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ORIGINAL ARTICLE

Field-monitored settlement and other behavior of a multi-stage municipal waste landfill, Korea

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Abstract The behavior of the Gimpo #2 landfill, which is an active landfill and the largest in Korea, is analyzed using field measurement data obtained from various field instruments installed within the landfill. The data included in this analysis are the leachate head within the landfill, waste load data using soil pressure plate and settlement data from settlement plate on the surface of the waste of each stage fill including the settlement of the soft foundation clay soil. Landfill blocks are selected both near the embankment and in the center area of the landfill. The analysis of the field-monitored data showed that the leachate head increase was negligible near the embankment. It was significant in the central block as the waste loads increase and reached 15 m at the fourth stage of waste disposal. The reason that the leachate head is higher in the central block than near the embankment is due to the long drainage path and the loss of gradient of drain pipes. The range of unit weight of the waste converted from the measurement data of earth pressure cell was 0.91–1.24 t/m^3 and the average value was 1.05 t/m^3. The values reflect well the waste compositions recently buried in GML #2, since from 1998 the waste disposed in GML #2 did not contain food waste. The magnitude of final settlements that occurred in each stage loading of 5 m thickness in the peripheral block was very close to 120 cm. The settlement rate of the waste by dividing the thickness of waste was 24 %. This rate can be divided into 10 % by waste loading and 14 % by waste decomposition. The delay of settlements is recognized in each waste layer for second and third loading in the central block due to the accumulation of leachate within the landfill.

Keywords Waste · Landfill · Settlement · Field measurement · Clay · Leachate

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Introduction

For the successful design and management of landfill, field monitoring of the behavior of the landfill is important. In particular, accurate measurement of settlement can enable the use of void space, which is a concern in urban areas where available landfill sites are scarce (Yee 1999; McDougall 2007; Swati and Joseph 2008). Excessive settlement can lead to the failure of leachate management and the gas collection system. After the completion of landfill disposal, the landfill can be used for new development such as parks and golf courses. Long-term settlement is always a constraint in this case, because residual settlement after sports facilities are built can distort surface drainage and utility lines.

Settlement of municipal waste (MSW) landfill is a function of many factors, e.g., composition of waste material, degree of compaction, thickness of cover and status of landfill foundation. In Korea, MSW landfills have been built on seashore clayey soils, which can lead to long-term settlement of the landfill foundation. This may become another factor along with the location of the groundwater table, which influences the function of leachate and landfill gas collection systems.

Many scholars (Sowers 1973; Ling et al. 1998; Hossain et al. 2003) suggest that landfill settlements during the overall period of the landfill can be divided into primary settlement due to dissipation of the pore water and void gases in the leachate and secondary settlement due to creep of the waste skeletons and biological decay of the organic components of wastes. Gordon et al. (1986) reported that the long-term settlement of waste in landfills is caused by biological decomposition and the creep deformation of waste. Grisolia and Napoleoni (1996) suggested the settlement characteristics of waste, by mechanical and biological processes, progress through five stages as time passes: (1) initial settlement, (2) initial residual settlement, (3) secondary settlement by the creep and decomposition of waste, (4) completion of waste decomposition and (5) final residual settlement.

Landfill settlement of 40 % versus the initial thickness of the landfill waste has been reported due to decomposition on a long-term basis (Emberton and Parker 1987) and total settlements between 25 and 50 % of initial fill height are reported in untreated MSW landfill wastes (Wall and Zeiss 1995).

As prediction models of waste landfills, Ling et al. (1998) applied a hyperbolic model, which is often used in settlement prediction of embankment on soft soils, to predict long-term settlement of the waste landfill. Terzaghi's primary and secondary consolidation model has been tried for waste landfills by many researchers (Sowers 1973; Morris and Woods 1990; Wall and Zeiss 1995; Durmusoglu et al. 2005; Sharma and De 2007). Geotechnical parameters from the waste are suggested, e.g., compression index, C_c, and decomposition index, C_α, to quantify historical and observational waste settlement data from the field and laboratory. Bjarngard and Edgers (1990) suggested the prediction of landfill settlement based on field-measured settlement data.

In this paper, the behavior of leachate within the landfill and the settlements of waste, as well as the clay foundation is analyzed using 6 years of field measurement data for the No. 2 Gimpo Metropolitan Landfill (GML #2), an active landfill, where most of the waste near Seoul is disposed. The landfill is disposed stepwise up to eight stages and the settlement behavior has become complicated by the various wastes buried for long periods.

Settlement in this landfill is also influenced by the high leachate level within the fill and the soft clay foundation under the fill. Several points related to the settlement of waste and the leachate behavior within the wastes arising from the complexity of the landfill are discussed in the paper.

Settlement analyses are performed by separating the consolidation settlement of both waste and clay foundation by multi-stage waste load and the secondary settlement resulting from the decomposition of waste by the biological activity of micro organisms. The settlements of the waste in each stage of the landfill are predicted using Sowers model (1973), which is based on Terzaghi's model for primary and secondary settlements. Compression and decomposition indexes are obtained by fitting the primary and secondary settlements from the monitored data of settlement plates on the surface of each stage wastes. The field measurement data used are obtained from settlement plates, earth pressure cells and piezometers installed on the surface of each stage landfill and its clay foundation.

Site condition

Among the waste landfills built on soft soil, the GML of area about 20 km^2 in Korea is one of the largest landfills known worldwide. Landfills built on soft soil need management of the settlement of its foundation and waste as well as the stability of the landfill slope, while the clay foundation itself has the advantage of resisting the seepage of the leachate through the subsurface due to its low hydraulic conductivity.

GML is constructed in the west coastal reclaimed land located near Baekseok-dong, Seogu in Incheon (Fig. 1) and has been used from 1992. Disposal in the first landfill (GML #1) was continued for 8 years until 2000. Details of the landfill histories are introduced in Jang et al. (2010). GML #2, the second landfill of its capacity of 67 million ton, has begun to fill up since October 2000, and disposal is still continuing. The second landfill was planned with a height of 40 m, with a total of eight stages. The thickness of each stage landfill is designed as 5 m, in which the thickness of the waste is 4.5 m and the cover soil 0.5 m. However, the thickness of each fill has varied slightly between 5 and 9 m according to the condition of waste disposal. Stepwise disposal is repeated and the period of one step is about 10 months. GML #3 is in the design stage and planned to accept waste from 2015.

The layer of soils under the landfill is composed of a weak upper clay layer and a firm lower clay layer. The distribution of the thickness of clay layer in this site is plotted in Fig. 2. The clay layers are distributed from 15 to 25 m in the south block and below 10 m in the north blocks.

The foundation clay of the subject landfill is inorganic clay of medium compressibility and low plasticity. The average coefficient of consolidation ranges from 2.0×10^{-3} to 3.0×10^{-3} cm^2/s. The average compression index ranges from 0.15 to 0.25 (Jang et al. 2010). The in situ hydraulic conductivity of GML #2 ranges from 2.0×10^{-5} to 2.4×10^{-5} cm/s, and the laboratory hydraulic conductivity ranges from 1.0×10^{-7} to 5.0×10^{-7} cm/s (Sudokwon Landfill Site Management Union 1995).

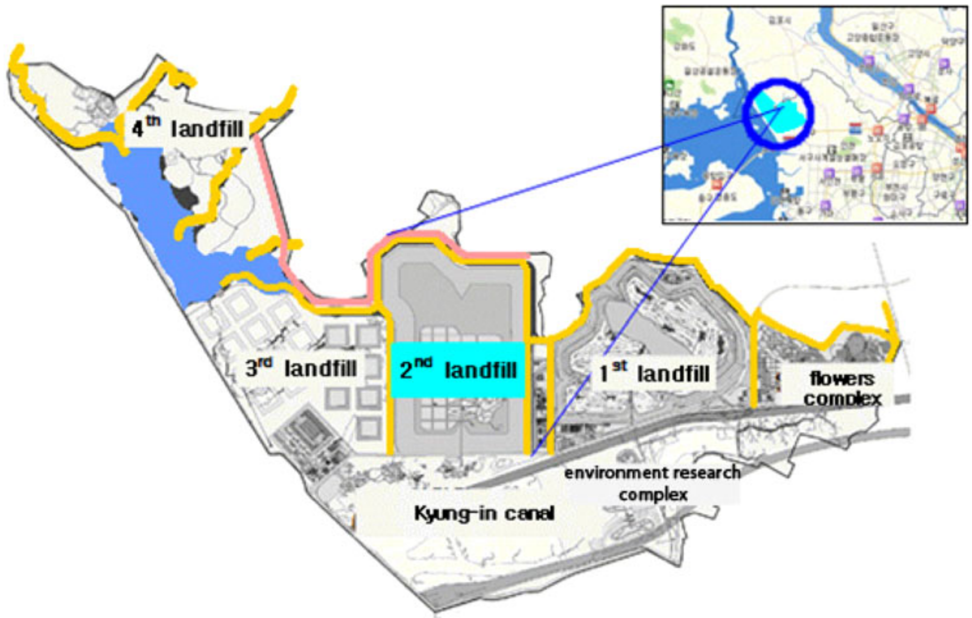


Fig. 1 Location and status of Gimpo landfill site (Jang et al. 2010)

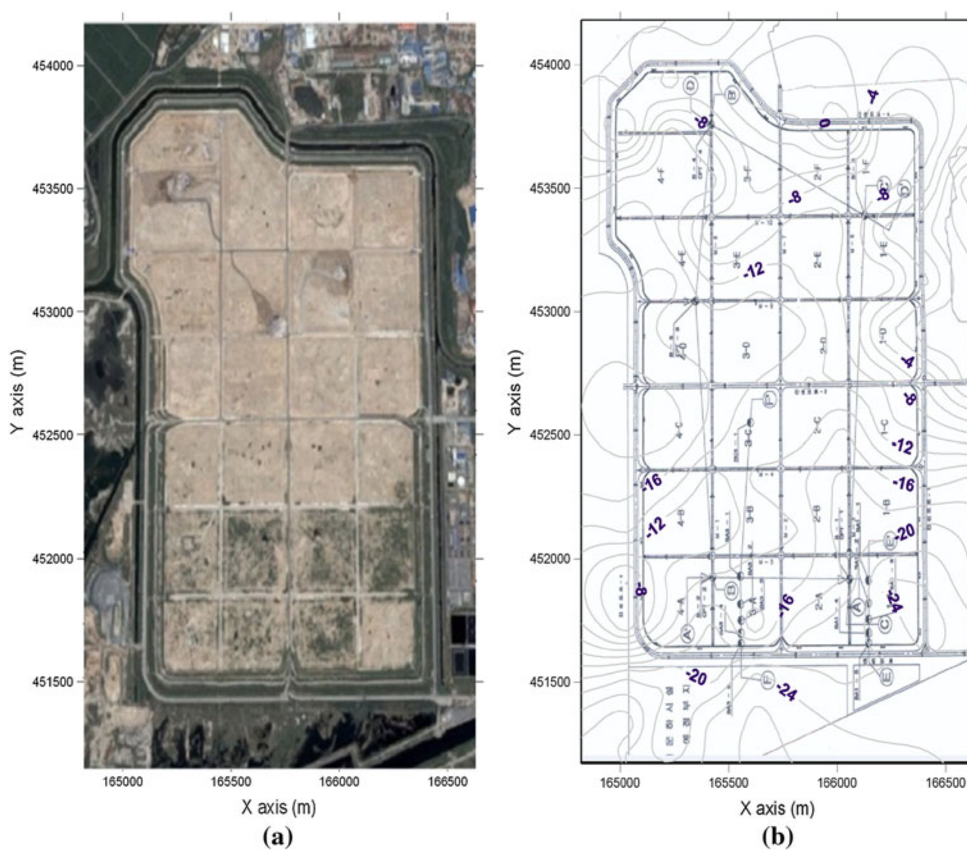


Fig. 2 Distribution of clay thickness under GML #2. **a** Air photo of GML#2, **b** Clay thickness contour (unit: m)

Installation of field measurement instruments

The types of measurement instruments installed for analyzing the behavior and settlement of the landfill are settlement plates, earth pressure cells, piezometers, etc. The total number of instruments installed is about 290 and the location of installed instruments is plotted in Fig. 3. The schematic cross section of the measurement instruments is shown in Fig. 4 (Sudokwon Landfill Site Management Union 1998).

To compare the behavior of leachate within the landfill and its settlement, representative blocks are selected as 3-C

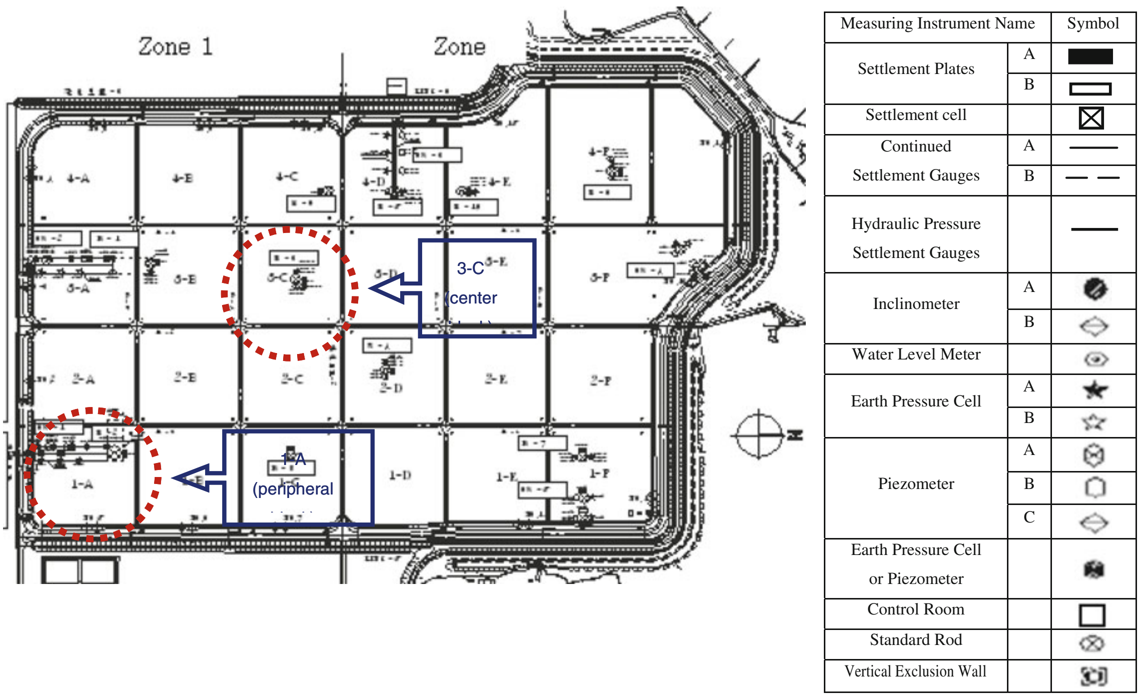
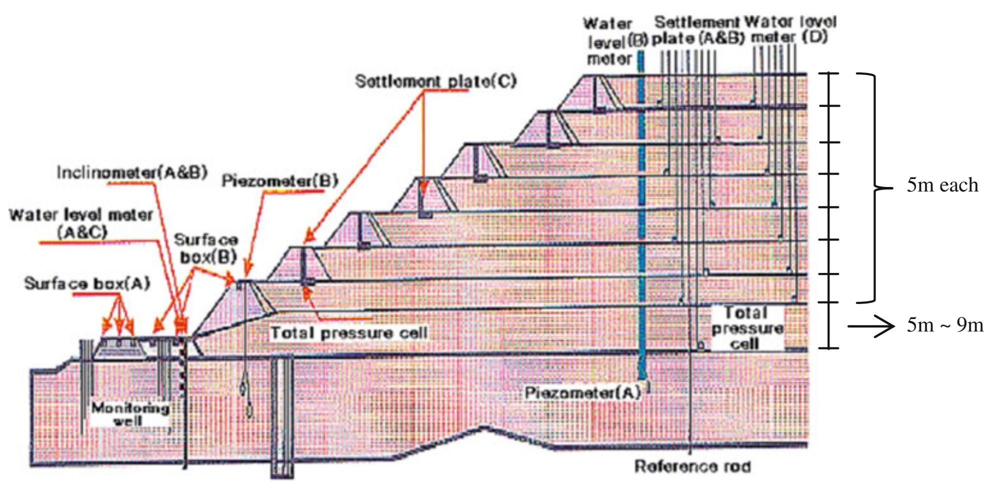


Fig. 3 Location map of measurement instruments in the landfill

Fig. 4 Representative cross section of measurement instruments (Jang et al. 2010)



in the central block and 1-A at the periphery of the landfill. In central block 3-C, a settlement plate, earth pressure cell and piezometer are installed and at block 1-A near the embankment, and a groundwater level checker is added to the same instruments in block 3-C. Most of the field instruments in the landfill are exposed to adverse surroundings, especially the settlement cells. After they are installed, settlement values are measured in parallel with disposal works and the instruments can easily be damaged and disappear. Hence, the field instruments need to be installed in sufficient numbers and to be able to be reinstalled if they are damaged or lost.

Analysis of geotechnical data within GML #2 landfill

Through analysis of the field measurement data of GML #2, the pore pressure head changes are analyzed as the wastes are disposed stepwise in blocks 3-C and 1-A. The unit weight of the wastes is calculated using the data of earth pressure cells, which are installed on the surface of waste in each stage.

In the US and EU countries, firm and rigid foundations under landfills are regulated by law. Hence, the interest is on the settlement of the waste itself. However, in the settlement analysis of GML #2, consolidation settlements are classified into two types: settlement of the clay foundation of the landfill and settlement of the multi-stage waste in the landfill.

Through analysis of the field-measured settlement data, the consolidation settlement of subsurface clay and wastes due to stage loads of wastes themselves, and secondary settlement due to the decomposition of waste as time passes are analyzed in blocks 3-C and 1-A.

In addition, compression and decomposition indexes which describe the aforementioned two settlements of waste are calculated. These parameters are obtained for each stage waste layer, as the waste in each stage may vary in waste composition and time. The prediction model in this analysis is based on Terzaghi's one-dimensional consolidation model.

Initial void ratios of the subject soil and waste are necessary for the prediction model. Therefore, the void ratio of the waste is obtained considering the waste composition and its ratio. Specific gravities of waste components are measured in the laboratory and the component ratios are obtained from statistical data of annual waste components published in Sudokwon Landfill Site Management Corporation (2006).

Settlement of clay layer under the landfill

The settlements of the clay layer under GML #2 are plotted in Fig. 5. Settlement data were measured during the 5-stage waste disposal period from 2000 to 2009 (Sudokwon Landfill Site Management Corporation 2009). According to Fig. 3, the clay layer thickness is 20–24 m in block 1-A and 10–12 m in block 3-C.

In both blocks, it had taken about 4 years for completion of the fourth stage waste disposal. During that period, the settlement was about 70 cm in the peripheral block 1-A and 90–95 cm in the central block 3-C. In block 1-A, initial settlement of about 10 cm occurred right after each stage waste disposal, and the remaining slow rate settlements occurred until the next stage waste disposal. At the fourth stage, the settlement converged to 70 cm, when waste disposal was postponed until 2008.

In central block 3-C, the thickness of the first stage waste disposal was 9.07 m. Constant rate settlement occurred up to 50 cm, until the stage 2 disposal. Immediate settlement of about 15 cm occurred at the disposal of the third stage and continued at the fourth- and fifth-stage waste loading. Such a different behavior in settlement rate compared with that of block 1-A seemed to be related to the accumulation of leachate head within landfill block 3-C. This phenomenon is stated in the next leachate head section (Fig. 7).

Variation of leachate head within the landfill

The variation of the total head in the landfill is plotted in Fig. 6. Piezometers are buried both within the clay layer, i.e., EL. −13.99 and −14.1 m and near the surface, i.e., EL. −0.11 and 0.36 m at block 1-A. Elevation level (EL) is the marker of location based on the mean sea level in the Incheon area. Large negative values (−) of EL means that the piezometers are located deep beneath the surface of the upper clay layer.

The difference of total head by elevation of the upper and lower piezometers is recognized as about 14 m at block 1-A (Fig. 6a). Also at block 3-C, the total head difference due to elevation of piezometers is recognized as about 12 m. The influence on the total heads by each stage waste disposal is shown as the formation of the peak of total heads in both blocks. It can be recognized that total heads are quite constant at about 3–5 m in block 1-A, although a staircase increase of total heads is recognized in block 3-C.

The pressure head within the landfill, which is actually the same as the leachate level, is obtained by removing the elevation heads from the total heads. Pressure head changes as the time of landfill operation elapses are compared in Fig. 7 for the two blocks, 3-C and 1-A. It is clear that the leachate head increase is negligible near the embankment at block 1-A and the leachate head increase in the central block 3-C is significant as the waste loads are increased in stage and reach to 15 m at the fourth stage of waste disposal.

The pressure head from the piezometer within the clay layer, i.e., EL −8.26 m was shown as 20 m at the fourth-stage waste loading and is consistently higher than the pressure head in the piezometer at the surface layer, i.e., EL 1.73 m. It can be recognized that the piezometer within the clay layer reflects the excess pore pressure in the clay layer which is caused by the staircase waste loading. The pressure head in the piezometer at the surface layer is close to the leachate head within the landfill at the central block 3-C. The reason that the leachate head is higher in the central block than near the embankment is the availability of drainage. Due to the short drainage path, the drainage of leachate in the landfill is easier near the embankment than in the central blocks. At the central blocks, the drainage of leachate is reduced due to the long drainage length and the loss of gradient of the drain pipes formed on the surface of the clay layer. The loss of pipe gradient is caused by the settlements of clay foundation as the consolidation of the clay proceeds by the staircase waste loading.

Settlements of waste within the landfill

The mechanism of the waste settlement is divided into (1) mechanical settlement and (2) biological settlement. Mechanical settlement is developed by compaction, and compression due to the waste load and occurred in a relatively short period. Biological settlement is caused by the

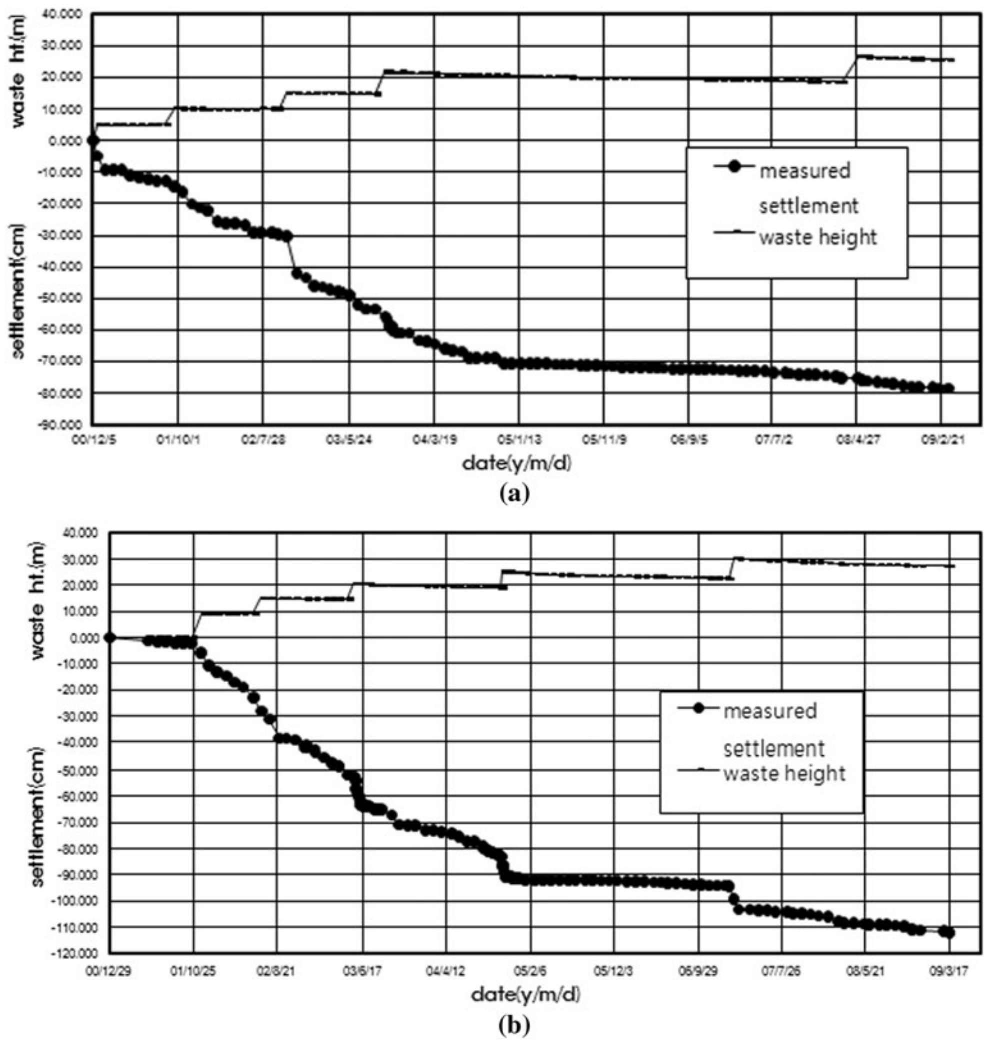


Fig. 5 Variation of settlement of clay layer under the landfill. **a** Block 1-A, **b** block 3-C

disintegration and decomposition of the waste and progresses in the long-term period. The biological settlement depends on the degradable solid amount and the time of disposal.

In this section, the settlements of waste at each stage of loading are plotted in Fig. 8 with the waste heights for the two blocks, 1-A and 3-C. In the case of the peripheral block 1-A, the waste load of 5 m thickness causes 50 cm settlement immediately after the first- and third-stage loadings and at the second-stage loading, a twice longer time was needed to reach a 50-cm settlement. Once the initial 50-cm settlements occurred after the first loading in the waste layers of each stage, additional settlements caused by the next stage loading were negligible. This means that mechanical settlements of the waste occurred mostly at the initial stage of waste loading, when the void ratios of the disposed waste are high.

Between the stage loadings, constant rate settlements of the wastes develop as time passes. It can be indentified that the settlement that occurred immediately after the waste disposal can be grouped into primary settlement caused by waste loading and constant rate settlement belonging to secondary settlement, by the bio-chemical decomposition of waste.

The magnitude of final settlements counted by summing up the two type settlements in each stage loading was very close to 120 cm. The settlement rate of the waste calculated by dividing the settlement by the thickness of waste was 24 %. This rate can be divided into 10 % by primary settlement from waste loading and 14 % by secondary settlement by waste decomposition.

In the case of the central block 3-C, initial settlement immediately after the second-stage loading in the first waste layer was about 60 cm. The primary settlements in the next stage loading were negligible and, instead, constant rate settlement occurred. About 60 cm settlement re-occurred at the fourth-stage loading. The total settlement of the first waste layer was 2.1 m. As the thickness of the first waste layer disposed was identified as 9.07 m, the total settlement rate to the fourth stage loading was 23 % which

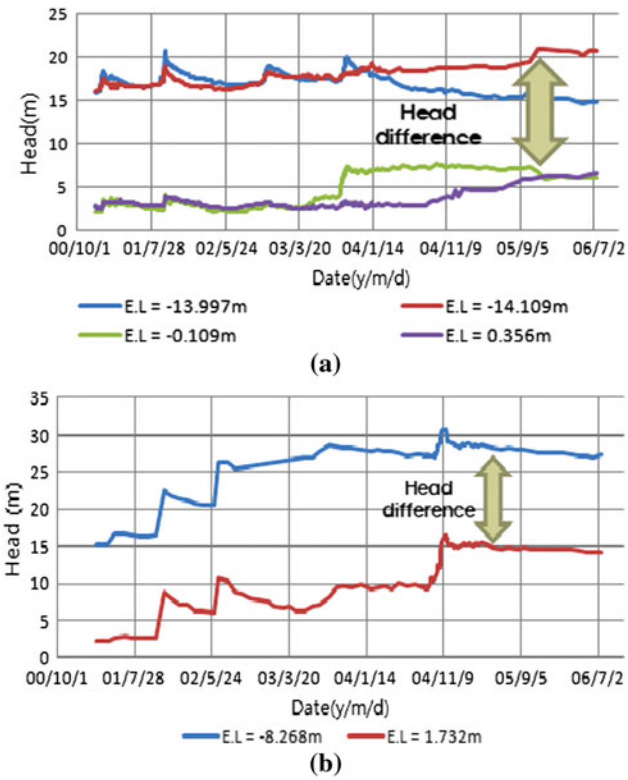


Fig. 6 Total head reflecting the elevation head. **a** Block 1-A, **b** block 3-C

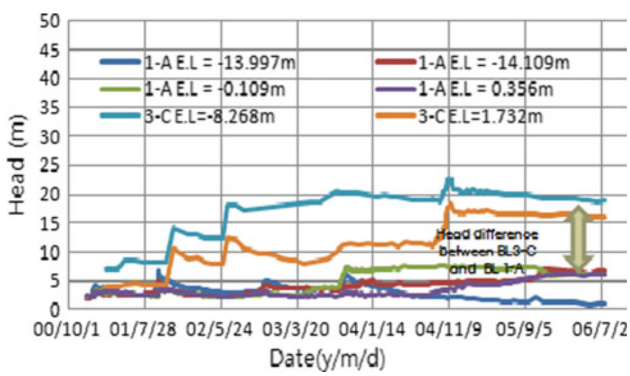


Fig. 7 Comparison of pressure head in the central block 3-C and the peripheral block 1-A

is close to the settlement rate of waste disposed in the peripheral block of 1-A.

The settlement patterns of second and third waste layer were superimposed closely up to the third-stage loading and the primary settlement of the second and third waste layer was about 60 cm. The thickness of the second and third waste layer was identified as 6.27 and 5.83 m, respectively, and the settlement rates of the second and third waste layer were about 20 %.

The delay of settlements in each waste layer for second and third loading in the central block 3-C seems to be related to the accumulation of leachate within the landfill. As the unit weight of waste and cover soil buried in each layer is in the range of 1.0–1.3 t/m^3 (average 1.13 t/m^3; refer to Fig. 2), wastes under 10–15 m leachate level exert very small effective stresses which can cause negligible primary settlements in the second and third stage loading. At the fourth stage loading, the waste load was fully converted to effective stress on waste layers, which caused 60 cm primary settlements in each waste layer.

Variation of the pressure and unit weight of waste

The unit weight of the waste varies depending not only on the compositions of waste, but also the degree of waste compaction and the amount of cover soils within the waste. The thicknesses of cover soils in Korea are 15 cm for daily covers, 30–50 cm for medium covers, i.e., per 6- to 10-month period and 150 cm for final covers. For the medium covers of the stage landfill in Korea, the volume of soils within the disposed waste is about 10 %, since the thickness of medium soil cover is 50 cm. The amount of soil volume in the waste can significantly influence the primary settlement of waste landfills, as the increase of soil volume can give higher weights of waste in the landfill.

As explained in the former section, earth pressure cells are installed on the surface of each waste layer. For block 1-A, an earth pressure cell is also installed on the surface of the bottom clay layer. The pressure of waste as the waste height increase in stages is plotted with time for the two blocks 1-A and 3-C in Fig. 1 (ESM only).

From Fig. 1, it can be recognized that waste pressure increases as the waste height increases stepwise. The pressure of waste layer disposal was about 5 t/m^2 as the waste layer of 5 m thickness is disposed. At block 1-A, the waste pressure decrease after the fourth stage loading at the cell installed on the surface of the second waste layer was caused by malfunction of the earth pressure cell which often occurs in the field (Fig. 1a, ESM only). For block 3-C, the earth pressure cells are working fine and the stepwise pressure increase is identified for each stage of the waste loading.

The variation of the unit weight of the waste is plotted with respect to time (Fig. 2, ESM only). The unit weight of waste is calculated using Eq. (1) in which the waste pressures are divided by the thickness of the waste.

$$\gamma_t = \frac{\sigma_t}{H} \tag{1}$$

where γ_t unit weight of the waste, σ_t pressure of waste read from the earth pressure cell, and H thickness of the waste.

The range of unit weight of the waste with cover soil was calculated as 1.0–1.3 t/m^3, and the average value of the unit weight of the waste and cover was 1.13 t/m^3.

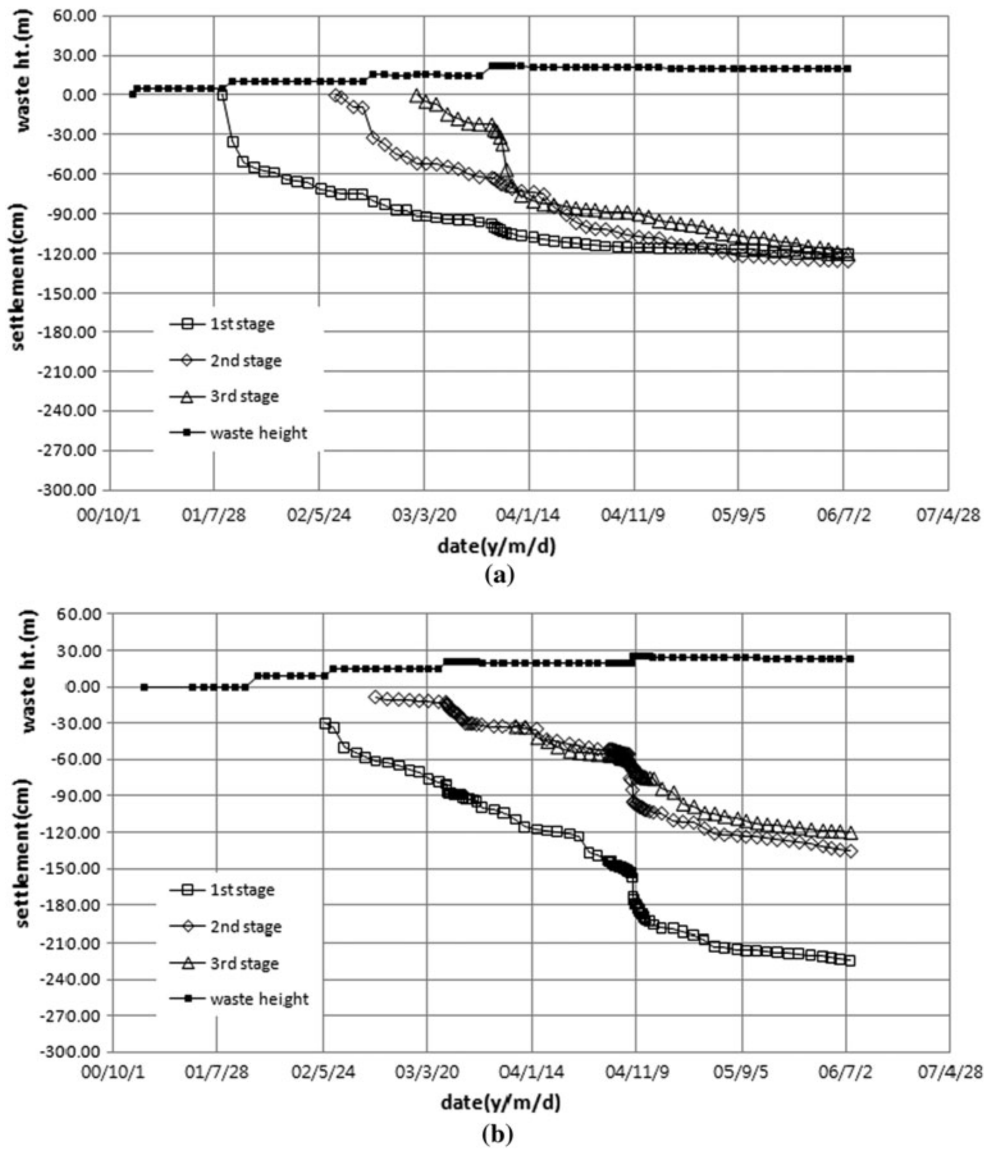


Fig. 8 Changes of settlements of the waste layers within the landfill with respect to the time of disposal. **a** Block 1-A, **b** block 3-C

Considering the percentage of cover soils in the waste layer as 10 %, the calculated unit weight of wastes without cover soils turned out to be as 0.91–1.24 t/m^3, and the average value of the unit weight of waste was 1.05 t/m^3. The type of cover soil used in GML is mostly weathered granitic soil and its unit weight after compaction is assumed as 1.8 t/m^3.

The range of the unit weights calculated is close to the range of values, 0.86–1.24 t/m^3, suggested by the Sudokwon Landfill Site Management Corporation (2001) and is a little higher than the range of values 0.92–1.07 t/m^3 suggested by Fasset et al. (1994) for well-compacted wastes. It is judged that the calculated values reflect well the waste recently buried in GML #2. The waste disposed in GML #2 did not contain food waste, after executing the "food waste resource recovery general plan" of the Ministry of Environment of Korea from September 1998 (Jang et al. 2010).

Prediction of settlement within the landfill

Settlements of waste in GML #2 are predicted using the formula suggested by Sowers (1973). Sowers' formula for predicting settlement can predict the primary settlement developed by waste loading and the secondary settlement from waste decomposition.

As GML #2 is the stage landfill, the settlements of waste layers in each stage are predicted by separating the primary settlement, which occurred right after the waste disposal from the secondary settlement, which developed by continuous decomposition of the waste.

Calculation of the compression and the decomposition indexes

The properties related to the settlement of waste fills are the primary compression index (C_c) related to waste load and the secondary compression index (C_α). These indexes change with the disposed time and locations of the waste within the landfill. The Sowers model used for calculating the two indexes is the following:

$$S_{total} = S_{pri} + S_{sec} = C_c \frac{H}{1+e_0} \log \frac{p_0 + \Delta p}{p_0} + C_\alpha \frac{H_1}{1+e_0} \log \frac{t_2}{t_1} \quad (2)$$

where S_{pri} and S_{sec} the primary and secondary settlements, H the initial thickness of the waste fill in each stage, H_1 the thickness of the waste fill after removing S_{pri}, C_c Compression index, e_0 initial void ratio of waste, C_α Decomposition index, p_0 initial pressure of the waste fill in each stage, Δp additional pressure by the stepwise waste disposal, t_1 starting time of waste decomposition, t_2 time of occurring S_{sec}.

The compression index of the waste is obtained by transforming the formula of primary settlement, S_{pri}, as the following equation:

$$C_c = \frac{\Delta H(1+e_0)}{H \log\left(\frac{p_0+\Delta p}{p_0}\right)} \quad (3)$$

in which ΔH is the primary settlement S_{pri} and the remaining parameters are the same as those in Eq. (2).

The primary settlement of the first stage waste layer in block 1-A is plotted as the waste load of the second, third and fourth stage waste disposal, which is given on the surface of the first stage waste layer (Fig. 3, ESM only). The compression index C_c calculated using Eq. (3) was 0.201.The decomposition index of the waste is obtained by transforming the formula of secondary settlement, S_{sec}, as Eq. (4).

$$C_\alpha = \frac{\Delta H(1+e_0)}{H \log\left(\frac{t_2}{t_1}\right)} \quad (4)$$

in which ΔH: the secondary settlement, S_{sec}, after removing the primary settlement, S_{pri}, and the remaining parameters are the same as those in Eq. (2).

The secondary settlement of the first stage waste layer in block 1-A is plotted versus the time after the first waste layer is disposed (Fig. 4, ESM only). The decomposition index C_α calculated using Eq. (4) was 0.211. In Fig. 4, the basis time t_1 was selected as the starting time of the second stage waste disposal, July 18, 2001, and the measurement data collected until June 14, 2006 was used. The total elapsed time for monitoring was 1,789 days. At the initial stage of the waste disposal in Fig. 4, the measured secondary settlement and the predicted settlement using the decomposition index, C_α from the formula of secondary Eq. (4) are not consistent; however, they become well fitted as time elapses.

The initial void ratio of waste, waste heights and compression/decomposition indexes are summarized with respect to the disposed blocks-stages and the time of waste disposal, in Table 1.

The initial void ratio of the waste was higher at the first waste layer during the year 2000–2001. The values reduced continuously as time passes after the waste disposal of GML #2 is started.

The compression index of the first waste layer in block 1-A is higher than that of the first layer in block 3-C. This phenomenon occurs because the accumulation of leachate head in the peripheral block 1-A is much smaller than in the central block 3-C. Instead, the decomposition index of the first layer in the central block 3-C, i.e., 3-C-1 in Table 1, was very high because the settlement of waste layer 3-C-1 showed the pattern of secondary settlement, instead of primary settlement (refer to Fig. 8b). The settlement of waste layer 3-C-1 counted mostly as the decomposition settlement.

The variation of the initial void ratio of the waste is similar, where the compression indexes also reduced slightly, as the time of disposal passes. This means that the composition of the waste becomes denser as the food waste was prohibited from being disposed in GML #2. The range of compression index is calculated as 0.11–0.20 and that of the decomposition index is 0.17–0.23. The decomposition index of waste layer 3-C-1 is not included in the range, because it seems to be an unusual value, caused by the leachate accumulation effect in the central block 3-C. The ratio of the two indexes, i.e., C_α/C_c is in the range of 105–177 % omitting the unusual ratio of 234 %.

Conclusion

In this paper, the behavior of the leachate within the landfill and the settlements of the waste as well as the clay foundation are analyzed using the 6 years of field measurement data of GML #2. The settlement in clay strata under the landfill is measured during the 5-stage waste disposal period from 2000 to 2009. The settlements of the waste in each stage landfill are predicted based on the Terzaghi model of consolidation. The following points are derived from the analyses:

The magnitude of final settlements of wastes by summing up the primary and secondary settlements in each stage loading of 5 m height was very close to 120 cm. The settlement rate of the waste by dividing the thickness of waste was around 24 %, which can be divided into 10 % by primary settlement from waste loading and 14 % by

Table 1 Compression and decomposition indexes w.r.t. the disposed blocks and stages

Block-stage[a]	Starting time of disposal	Finishing time of disposal	Initial void ratio (e_0)	Waste height H (m)	Compression index (C_c)	Decomposition index (C_α)	C_α/C_c (%)
1-A-1	2000-12-18	2001-02-16	1.624	5.124	0.201	0.211	105
1-A-2	2001-07-18	2001-10-18	1.274	5.798	0.149	0.230	154
1-A-3	2002-09-24	2002-11-27	1.131	5.655	0.110	0.194	177
3-C-1	2001-05-16	2001-12-18	1.500	9.071	0.144	0.336	234
3-C-2	2002-05-28	2002-07-25	1.470	6.265	0.155	0.171	110
3-C-3	2003-04-24	2003-06-02	1.276	5.828	0.106	0.179	169

[a] Naming example 1-A-1 means 1-A block and the 1st waste layer

secondary settlement from waste decomposition. The magnitude of the settlement rate was lower than the rate of settlements suggested in the literature, e.g., 25–50 % for untreated waste fills. This small rate seems to be caused by the time elapsed after disposal as well as the types of waste disposed in the landfill. Some residual settlement is expected after the time of prediction. The "Food waste resource recovery plan" of Korea executed from September 1998, prohibited the disposal of food waste in GML #2, and this influenced the reduction of settlement.

The leachate head increase was negligible near the peripheral embankment of GML #2 and was significant in the central block as the waste loads are increased. The height of leachate head reached to 15 m at the fourth stage of waste disposal. The reason that the leachate head is higher in the central block, than near the embankment, is the damage of the drainage path and gradient. It can be recognized that settlement of the soft clay foundation under the fills may have caused the malfunction of drainage pipes on the landfill liners in the central block of the landfill.

The delay of settlements is recognized in each waste layer for second and third stage loading in the central block due to the accumulation of leachate within the landfill. Wastes under 10–15 m leachate level give very small effective stresses which can cause negligible primary settlements in the second and third staged loading. At the fourth staged loading, the waste load was fully converted to the effective stress of the waste layer, which caused 60 cm primary settlements in the waste layers.

The range of the unit weight of the waste converted from the measurement data of earth pressure cell was 0.91–1.24 t/m^3, and the average value was 1.05 t/m^3. The values reflect well the waste compositions recently buried in GML #2, as the waste disposed in GML #2 did not contain the food waste from 1998. The initial void ratio of the waste was higher at the first waste layer during the year 2000–2001. The values reduced continuously as the time passed after the waste disposal of GML #2 started. The compression indexes also reduced slightly, as the time of waste disposal progressed. This means that the composition of the waste became denser compared with the initial period of waste disposal in GML #2.

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