Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-450

Long-term settlement model calibration based on field-monitored data at a multi-stage MSW landfill in South Korea

Y. S. Jo[1], W. Cha[2], D. Zekkos[3], Y. Kim[4], Y. S. Jang[5]

[1] Post-doctoral researcher, University of California at Berkeley, Berkeley, California, USA, email: ysjo_david@berkeley.edu

[2] Post-doctoral researcher, University of California at Berkeley, Berkeley, California, USA, email: wonjun.cha@berkeley.edu

[3] Professor, University of California at Berkeley, Berkeley, California, USA, email: zekkos@berkeley.edu

[4] Senior researcher, Korea Institute of Civil Engineering and Building Technology, Goyang-si, Gyeonggi-do, South Korea, email: kws@kict.re.kr

[5] Professor, Dongguk University, Seoul, South Korea, email: ysjang@dongguk.edu

ABSTRACT

An empirical model that incorporates mechanical creep, bio-compression, and residual settlement is proposed to enable the simulation of long-term waste settlement based on the hypothesis that the waste settlement mechanisms of the entire landfill are concurrent. The model is composed of two mathematical models (i.e., negative exponential decay and log-linear models) to simulate this superposed settlement behavior. The applicability and performance of the model were assessed based on field-monitored data measured over 21 years at a multi-stage municipal solid waste (MSW) landfill in South Korea. The model parameters were determined by error analysis and the model compatibility was evaluated by linear regression analysis based on the least square method. The results showed that the empirical model can adequately simulate the measured settlement curves, especially residual settlement.

Keywords: model, mechanical creep, bio-compression, residual settlement, negative exponential decay and log-linear models, multi-stage MSW landfill, long-term waste settlement

1 INTRODUCTION

Waste settlement varies depending on the water content, unit weight, amount of organic waste, the climate of landfill area, and landfill operation, rending the prediction of long-term waste settlement challenging (Durmusoglu et al., 2006; Edil et al., 1990; Ling et al., 1998; Sharma & De, 2007; Swati & Joseph, 2008; Wall & Zeiss, 1995). Several models have been developed over the past few decades to predict MSW settlement. These models have involved approaches based on Terzaghi's consolidation theory (Bjarngard & Edger, 1990; Hossain & Gabr, 2005; Sowers, 1973), unsaturated consolidation theory (Chen et al., 2012), critical state theory (Sivakumar Babu et al., 2010), landfill gas (LFG) production (Liu et al., 2006; Machado et al., 2008), composite compressibility models (Chen et al., 2010; Gourc et al., 2010; Liu et al., 2006; Marques et al., 2003; Park & Lee, 1997), as well as empirical or regression models (Edil et al., 1990; Ling et al., 1998; Yen & Scanlon, 1975), and the rheological model (Gibson & Lo, 1961). More recently, models that aim to capture the main physico-bio-chemical aspects of the biodegradation process and the associated settlements have been developed (Kumar et al. 2020; McDougall, 2007; Zekkos et al. 2021). The later ones more holistically capture the ongoing waste processes in landfills, but may require more complex parameter estimation.

Field data, especially measured for several decades are uncommon because of the challenges to collect long-term waste settlement data from the field- or pilot-scale landfills. Such challenges include the increase in management costs, the impact on landfill operations, and the damage to instruments. Jo & Jang (2022) assessed six settlement models using the field-scale data measured over 27 years at a multi-stage MSW landfill. In this study, a model that incorporates mechanical creep, bio-compression, and residual settlement is proposed and applied to the long-term waste settlement dataset measured at a multi-stage MSW landfill over 21 years after the post-closure. The term "multi-stage" is used to describe that the waste was buried at different times for each lift, and thus, the waste at each lift may be at a different stage of the settlement vs. time process. The model consists of two mathematical models (i.e., negative exponential decay and log-linear models). The model parameters are determined by error analysis and the model compatibility is evaluated by linear regression analysis.

2 METHODOLOGY

2.1 Studied area

The Gimpo Metropolitan Landfill (GML) is a multi-stage MSW landfill supported by buttresses constructed after landfilling to allow for subsequent waste fills. The GML covers an area of 14.63 km^2 in Gimpo of the Republic of Korea The buttresses were constructed on soft clay. The MSW was buried in the GML since 1992. The GML, composed of four landfills and two complexes, operates as a sanitary landfill (Fig. 1). Waste disposal in landfill #1, which is the focus of this study, was performed over 8 years, i.e., from 1992 to 2000 (GLC, 2022). During the waste disposal, MSW was buried in the eleven waste blocks (also known in the US as cells) (B, C, D, E, G, H, I, J, K, L, and M in Fig. 1) and sewage sludge, dredge sludge and construction and demolition (C&D) waste (i.e., industrial waste, construction waste, and textiles) was buried in three blocks. The organic waste content, unit weight of waste, and waste height for each block of landfill #1 are shown in Table 1. The organic waste content was determined by the following procedure; a) calculate the content of organic waste for each lift based on the waste disposal history. The annual organic waste composition was also utilized to calculate the content of organic waste; b) sum the content of organic waste for each lift; c) the sum is averaged for each block. Detailed information related to the proportions of MSW and C&D, waste disposal history, and annual organic waste composition is delineated in Jo et al. (2022). The unit weight of each block in Table 1 was also determined in the same way as the organic waste. Jo & Jang (2021) determined the annual unit weight of waste in landfill #1 using the data measured at earth pressure cells, and in this study these estimates are utilized. The organic wastes were composed of food, paper, wood, textiles, rubber, and leather. The ranges of organic waste and unit weight for each block were 63.15% ~ 64.95% and 10.97 kN/m^3 ~ 10.99 kN/m^3, respectively. The gravimetric water content of MSW is reported to be 113.7%, which is not an annually reported value. When waste disposal was completed, the waste height for each block ranged between 39.1 m and 44.1 m (41.7 m on average) (Table 1).

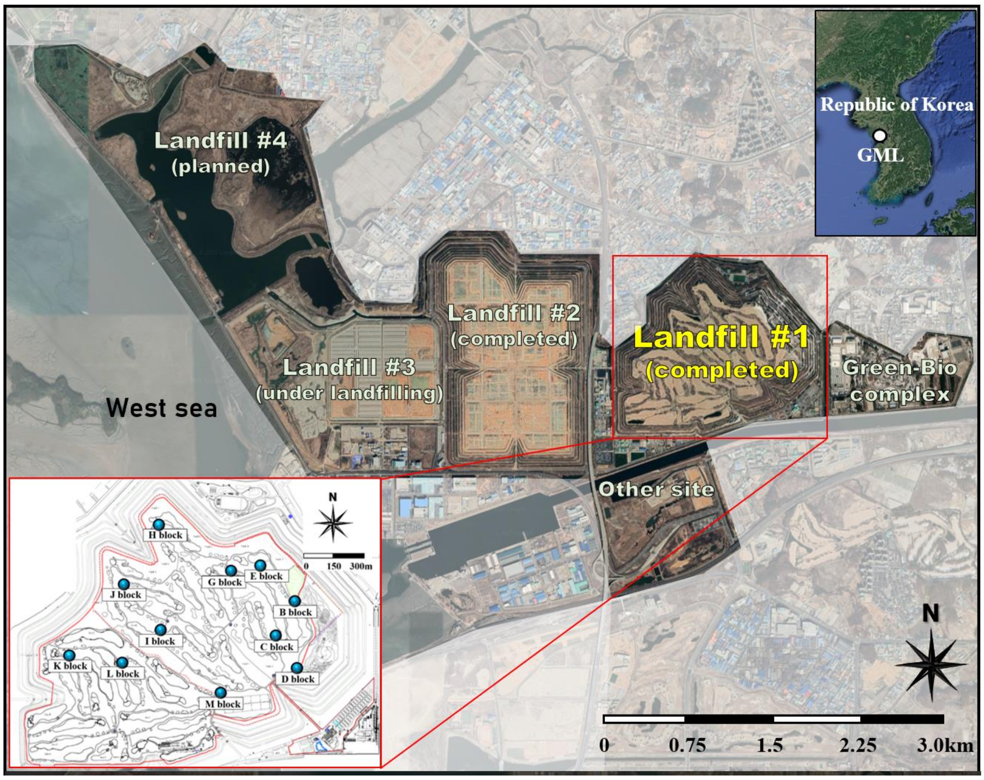

Figure 1. Location of Gimpo Metropolitan Landfill (GML) and landfill #1 where the waste disposal was completed; a) Layout of the GML and detailed location of each landfill; b) Location of settlement plates installed on the uppermost layer of landfill #1 after post-closure

Table 1. The organic waste content, unit weight, and waste height for each block of landfill #1 when the landfill was closed

Waste-blocks	B	C	D	E	G	H	I	J	K	L	M
Organic waste (%)	64.13	63.15	64.16	64.16	64.18	64.24	64.91	64.91	64.95	64.91	64.24
Unit weight (kN/m^3)	10.99	10.99	10.98	10.98	10.99	10.97	10.98	10.98	10.98	10.98	10.98
Waste height (m)	40.01	44.10	40.61	40.14	44.07	39.06	43.60	40.81	42.25	42.11	42.09

After landfill closure, stabilization operations, which include final covers and a biogas system to collect LFGs, were installed on the uppermost part of the landfill from September 2002 to December 2002. Currently, there is a golf course on the landfill surface as a public space. The detailed information (e.g., landfill design, initial thickness, area of landfill #1, quantity of landfilled MSW, and the waste block location and the landfill duration for each block) is delineated in Jo & Jang (2021).

Only eleven blocks (i.e., B, C, D, E, G, H, I, J, K, L, and M blocks) in which MSW was buried are used in this study, because waste disposal in three blocks (i.e., O, P, and Q blocks) was suspended due to the stability issues related to the dykes, associated with high pore pressures and high leachate levels. Waste landfilled in O, P, and Q blocks included dredge soils and sludge which have high water content.

2.2 Waste settlement data

After the landfill was closed, from December 1999 to September 2000, new settlement plates were placed at the surface of eleven blocks (B, C, D, E, G, H, I, J, K, L, and M in Fig. 1) in order to measure the long-term waste settlements continuously and measurements were conducted using surveying equipment monthly. This study utilized settlement data collected over 21 years (i.e., after landfill closure to December 2021). During this period, the cumulative waste settlements measured from the settlement plates ranged between 5.91 and 9.06 m which corresponded to cumulative vertical strain ranging from 15.15% to 21.54% (17.21% on average). A golf course was constructed on landfill surface between September 2010 and September 2012. The waste settlement measured during this period ranged from 3.6 to 11.4cm, indicating that the additional stress on MSWs due to the construction of the golf course was negligible.

The waste settlement curves of the B, C, D, E, G, H, I, J, K, L, and M blocks are shown in Fig. 2. The waste settlement curves are similar in shape, with an initial steep slope and a gradual decrease that results in an inflection point. Since the waste was buried in eight lifts over eight years in landfill #1, the aging and settlement mechanisms of waste between the lower and upper parts of the lifts were significantly different. For this reason, after the landfill was closed, both mechanical creep and bio-compression were underway, making them hard to separate. In general, the initial steep slope before the inflection point is assumed to represent the coupled settlement mechanism, both mechanical creep and bio-compression. After that, beyond the inflection point, the residual settlement becomes the dominant settlement mechanism.

2.3 Model coupled with mechanical creep and biocompression and residual settlement

In this study, an empirical settlement model was developed to simulate the long-term waste settlement based on the hypothesis that the waste settlement mechanisms of the multi-stage MSW landfill where the wastes were buried for a long duration included mechanical creep, bio-compression, and residual settlement. This model is composed of two mathematical models, a negative exponential decay model and a log-linear model, as shown in Eq. 1a. In this equation, the negative exponential decay model represents the residual settlement due to final mechanical creep. The combination of the two models facilitates the simulation of superposed waste settlement mechanisms.

$$S_{T,AL} = H_{AL} \cdot \{\Delta\sigma' \cdot a \cdot (1 - e^{-\zeta \cdot t}) + \Delta\sigma' \cdot b \cdot \log^{(1-\zeta \cdot t)} \qquad (1a)$$

$$\mathrm{Log}(d\varepsilon/dt) = -0.434 \cdot (\zeta) \cdot t' + \log(\Delta\sigma' \cdot \kappa) \cdot (\zeta) \qquad (1b)$$

where, $S_{T,AL}$ is the total settlement after the post-closure, ε is the total strain after the post-closure. This strain has been determined based on waste thickness (Table 1) at the time the landfill was completed.

H_{AL} is the waste thickness after the post-closure, $\Delta\sigma'$ is the effective vertical stress at mid-depth of waste, a is the coefficient corresponding to settlement in which mechanical creep and biodegradation are mixed after the completion of landfilling (1/kPa) (= κ/a_{ref}), b is the coefficient corresponding to residual settlement (1/kPa) (= κ/b_{ref}), κ is the coefficient corresponding to secondary settlement after landfill closure (1/kPa), ζ are the constant rates (day^{-1}). κ and ζ were determined by linear regression (Eq. 1b) on the Log($d\varepsilon/dt$) – t graph. a_{ref} and b_{ref} are reference parameters determined by error analysis (see Section 3.2), t is the elapsed day after the completion of landfilling.

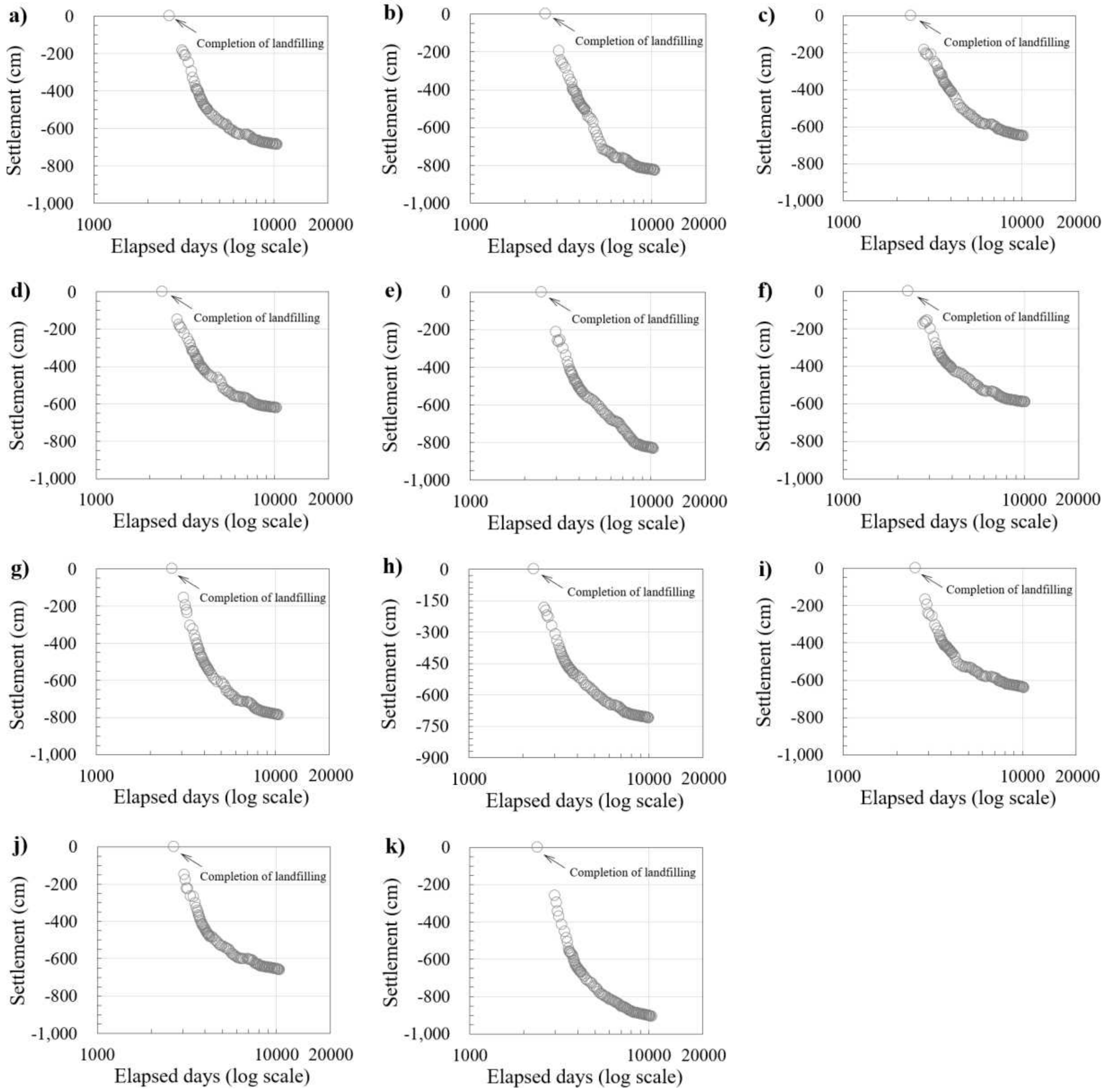

Figure 2. The waste settlement curves measured at each block of landfill #1 over 21 years after closure; a) B block; b) C block; c) D block; d) E block; e) G block; f) H block; g) I block; h) J block; i) K block; j) L block; k) M block

3 Model application and results

3.1 Model simulation

The model was calibrated against the field measurements. Model parameters (i.e., a, b, and ζ) were determined based on a parameter κ obtained from Eq. 1b and reference parameters (i.e., a_{ref} and b_{ref}). The error analysis was performed to determine and optimize the reference parameters. The procedure of model simulation is shown in the flow chart in Fig. 3.

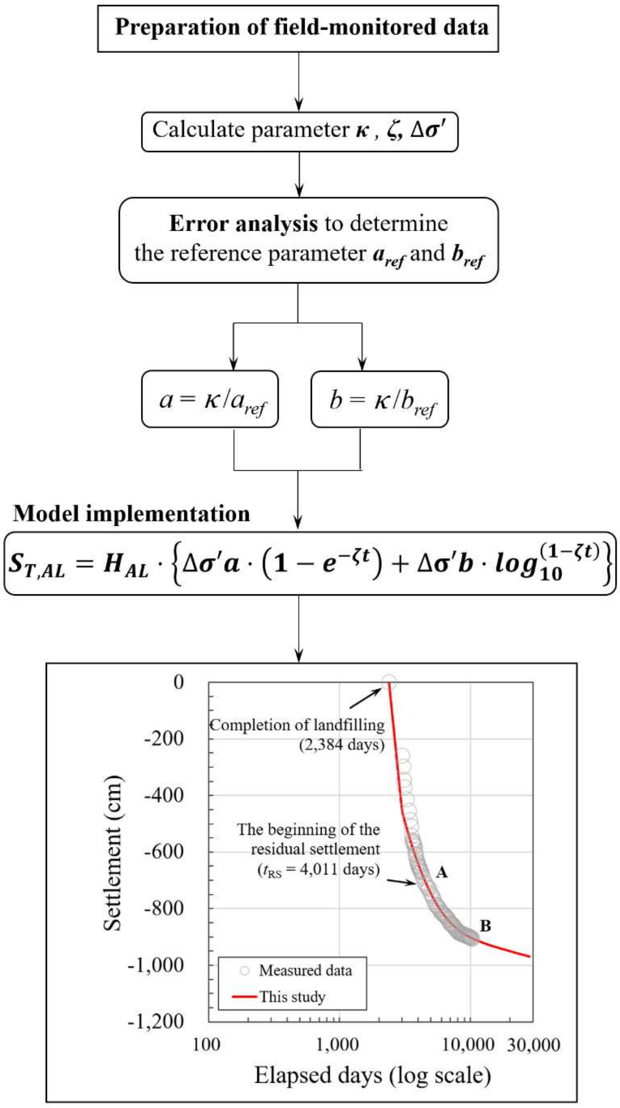

Figure 3. Flow chart for model simulation

The modeled settlement curves of each block are shown in Fig. 4 along with the measured settlement curves. The modeled and measured waste settlements were forced to be the same at point A (i.e., the inflection point in the settlement curve) in Fig. 4. Point A indicates the beginning date of the residual settlement and is the time at which the compression ratio begins to decrease with elapsed time (Jo et al. 2022). The modeled settlement was then extrapolated beyond point A. It is shown that the suggested model can adequately simulate the measured settlement curves. In particular, the long-term waste settlement and residual settlement are shown along with the measured settlement curve (see the red line in Fig. 4). The model fits well the field settlement data, especially the residual settlement. The model parameters are shown in Table 2.

To assess the goodness of fit of the model results to the field measurements, the ratio of modeled to measured settlement (*hereafter* RMMS) in percentage is calculated and is shown in Table 2. RMMS values above 100% indicate a higher modeled settlement compared to the measured settlement. The RMMS value was calculated at point B of Fig. 4, which is the last measured value of settlement. The RMMS values vary from 98.8% to 100.6%, indicating a good match of the data.

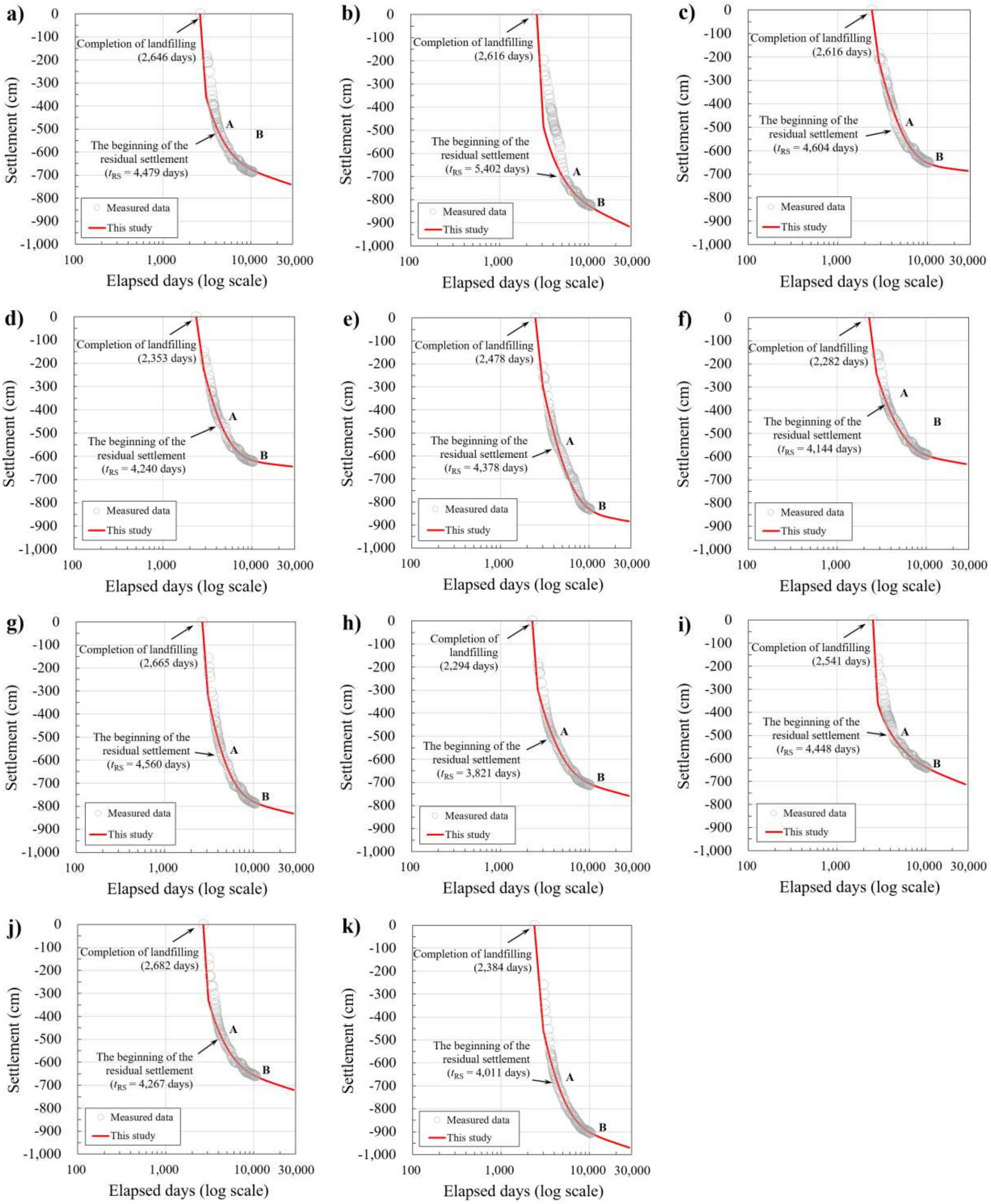

Figure 4. Comparison of measured and modeled settlement curves for each block; a) B block; b) C block; c) D block; d) E block; e) G block; f) H block; g) I block; h) J block; i) K block; j) L block; k) M block

Table 2. Model parameters (i.e., Δσ', κ, a, b, a_{ref}, b_{ref}, and ζ) related to the suggested model, the measured and modeled waste settlements, the ratio of measured and modeled settlement (RMMS), and the results of linear regression analysis (i.e., R^2 and S.E.) for each waste block of landfill #1 (continued)

Waste blocks	B	C	D	E	G
Δσ' [a] (kN/m^2)	219.85	242.33	222.95	220.37	242.16
κ	6.47×10^{-2}	6.77×10^{-2}	6.06×10^{-2}	6.91×10^{-2}	6.32×10^{-2}
a (1/kPa)	2.70×10^{-4}	1.93×10^{-4}	5.51×10^{-4}	5.32×10^{-4}	5.74×10^{-4}
b (1/kPa)	1.29×10^{-4}	1.50×10^{-4}	4.66×10^{-5}	4.46×10^{-5}	5.74×10^{-5}
a_{ref}	240	350	110	130	110
b_{ref}	500	450	1300	1550	1100
ζ (1/day)	5.69×10^{-4}	5.65×10^{-4}	5.00×10^{-4}	5.76×10^{-4}	4.49×10^{-4}
Measured [b] (cm)	686.00	826.60	650.70	621.70	831.70
Modeled [c] (cm)	677.75	830.26	653.51	619.23	833.17
RMMS [d] (%)	98.80	100.44	100.43	99.60	100.18

[a] Effective vertical stress that is calculated by multiplying waste height and unit weight. The waste height and unit weight for each waste block are shown in Table1; [b] Measured waste settlement; [c] Modeled waste settlement; [d] Abbreviation of the ratio of measured and modeled settlement

Table 2. Model parameters (i.e., Δσ, κ, a, b, a_{ref}, b_{ref}, and ζ) related to the suggested model, the measured and modeled waste settlements, the ratio of measured and modeled settlement (RMMS), and the results of linear regression analysis (i.e., R^2 and S.E.) for each waste block of landfill #1

Waste blocks	H	I	J	K	L	M
Δσ [a] (kN/m^2)	214.24	239.36	224.05	231.97	231.18	231.07
κ	6.13×10^{-2}	7.15×10^{-2}	6.55×10^{-2}	4.80×10^{-2}	5.62×10^{-2}	7.64×10^{-2}
a (1/kPa)	4.38×10^{-4}	4.47×10^{-4}	3.85×10^{-4}	1.23×10^{-4}	2.44×10^{-4}	4.78×10^{-4}
b (1/kPa)	7.21×10^{-5}	7.95×10^{-5}	1.01×10^{-4}	1.37×10^{-4}	1.12×10^{-4}	1.18×10^{-4}
a_{ref}	140	160	170	390	230	160
b_{ref}	850	900	650	350	837.65	650
ζ (1/day)	5.18×10^{-4}	5.74×10^{-4}	5.46×10^{-4}	5.02×10^{-4}	5.39×10^{-4}	5.60×10^{-4}
Measured [b] (cm)	591.80	787.30	711.20	640.60	660.10	905.80
Modeled [c] (cm)	595.33	784.41	705.52	640.55	659.59	904.87
RMMS [d] (%)	100.60	99.63	99.20	99.99	99.92	99.90

[a] Effective Vertical stress that is calculated by multiplying waste height and unit weight. The waste height and unit weight for each waste block are shown in Table1; [b] Measured waste settlement; [c] Modeled waste settlement; [d] Abbreviation of the ratio of measured and modeled settlement

3.2 Assessment of model parameters and modeled waste settlement

Datasets can augment the ability of settlement models (e.g., prediction), but also require long and costly measurements. In particular, in terms of the model parameters, sufficient field-monitored data should be collected to improve the accuracy of models. In this study, we determined the reference parameters (i.e., a_{ref} and b_{ref}) that are needed to calculate model parameters a and b (see Eq. 1a) by conducting error analysis by calculating the average squared error (Eq. 2). The parameters a and b represent different waste settlement mechanisms. The error function (Eq. 2) is used to evaluate the sensitivity and invertibility of reference parameters (i.e., a_{ref} and b_{ref}) and search the optimized combination of model parameters a and b for given settlement data to estimate the long-term waste settlement. Note that the partial derivative of the error function with respect to the model parameters (i.e., a and b) yields the gradient that drives the convergence to the optimum value of the parameter.

$$\text{Average squared error } \left(\mathrm{E_{sqr}}\right) = \sqrt{\frac{\sum_i e_i^2}{n}} \tag{2}$$

where, e_i is the error for settlement, $e_i = (\hat{s_i} - s_i)$, $\hat{s_i}$ is the modeled waste settlement and s_i is the measured waste settlement.

The error between modeled and measured waste settlements is minimized (i.e., local minima) for the optimum model parameters a and b. Convergence to the optimum parameter set can be observed by taking slices of the 3-dimensional error surface across the optimal value for each parameter. Fig. 5 shows the 3-dimensional error surface of the L2 norm and slices of the error surface for model parameters a and b, related to the D block. In which, the L2 norm stands for E_{sqr} in Eq. 2. The invertibility of model parameters depends on the curvature of the selected error function to each parameter, and the gradient captures it. The model parameter a shows higher invertibility, but the analysis is limited due to the dimensionless feature of parameters. The model parameters (i.e., a, b, a_{ref}, and b_{ref}) determined by this procedure are shown in Table 2.

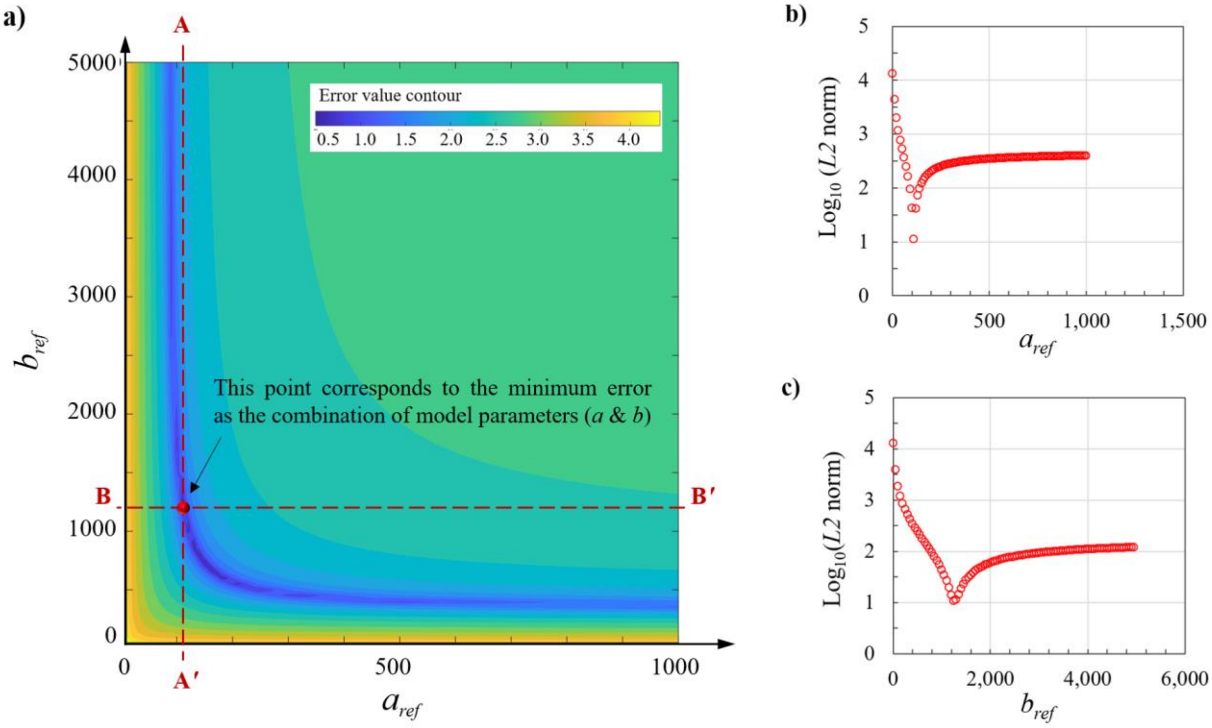

Figure 5. L2 norm error surface for the D block. the red dotted lines (i.e., A-A' and B-B') capture the optimum parameters a and b set for the model; a) Error surface contour map; b) the changes in L2 norm for a given range of a_{ref} (b_{ref} = 1300) (A-A' section in Fig. 5a); c) the changes in L2 norm for a given range of b_{ref} (a_{ref} = 110) (B-B' section in Fig. 5a)

4 CONCLUSIONS

In this study, a model that incorporates mechanical creep, bio-compression, and residual settlement was proposed and implemented by using a long-term waste settlement dataset measured at a multi-stage MSW landfill in South Korea over 21 years. This model is composed of two mathematical expressions, a negative exponential decay model and a log-linear model. Each expression describes the combination of mechanical creep and bio-compression and the residual settlement due to mechanical creep only. As the two expressions are combined, this model can simulate each waste settlement mechanism of the multi-stage MSW landfill in that the waste was buried at different times for each lift.

Model parameters (i.e., a, b, and ζ) were determined based on a parameter κ and reference parameters (i.e., a_{ref} and b_{ref}). The error analysis was performed to determine and optimize the reference parameters. The modeled waste settlement curves were along with the measured waste settlement curves. The model fits well with the waste settlement data, especially the residual settlement. In addition, to assess the accuracy of the model, the ratio of modeled to measured settlement (RMMS) in percentage is calculated. The RMMS values vary from 98.8 % to 100.6 %, indicating a good match of the data. Based on this result, the proposed model is considered to be able to simulate the measured waste settlement well, especially post-closure behavior and residual settlement as well as mechanical creep and biological degradation.

REFERENCES

Bjarngard, A., & Edger, L. (1990). Settlement of municipal solid waste landfills. In: Proceedings 13th Annual Madison Waste Conference, University of Wisconsin, (pp.192-205), USA

Chen, Y., Ke, H., Fredlund, D.G., Zhan, L., & Xie, Y. (2010). Secondary compression of municipal solid waste and a compression model for predicting settlement of municipal solid waste landfills. Journal of Geotechnical and Geoenvironmental Engineering, 136, 706-717.

Chen, K.S., Chen, R.H., & Liu, C.N. (2012). Modeling municipal solid waste landfill settlement. Environmental Earth Sciences, 66(8), 2301-2309.

Durmusoglu, E., Sanchez, I.M., & Corapcioglu, M.Y. (2006). Permeability and compression characteristics of municipal solid waste samples. Environmental Geology, 50(6), 773-786.

Edil, T.B., Ranguette, V.J., & Wuellner, W.W. (1990). Settlement of municipal refuse. In: Landva, A.O., Knowles, G.D. (Eds), Geotechnics of Waste Fills-Theory and Practice, STP 1070, ASTM, West Conshohocken, (pp.225-239). PA, USA.

Gibson, R.E., & Lo, K.Y. (1961). A theory of soils exhibiting secondary compression. Norges Tekniske Vitenskapsakad.

GLC (2022). Book of annual statistics for Gimpo Metropolitan Landfill. Gimpo Metropolitan Landfill Corporation.

Gourc, J.P., Staub, M.J., & Conte, M. (2010). Decoupling MSW settlement into mechanical and biochemical processes-Modelling and validation on large-scale setups. Waste Management, 30(8-9), 1556-1568.

Hossain, M.S., & Gabr, M.A. (2005). Prediction of municipal solid waste landfill settlement with leachate recirculation. In: Proceedings Geo-Frontiers, GSP No. 142, Waste Containment and Remediation, ASCE. (pp. 1-14), Austin, Texas, USA.

Jo, Y.S., & Jang, Y.S. (2021). Comparison of waste settlement characteristics for two landfills disposed in long sequential periods. Waste Management, 131, 433-442.

Jo, Y.S., & Jang, Y.S. (2022). Assessmenet of waste settlement models based on the long-term settlement data measured at a multi-stage MSW landfill in Korea. Journal of Material Cycles and Waste Management, 24(6), 2328-2340.

Jo, Y.S., Yoo, W.K., Hwang, S.P., & Kim, C.Y. (2022). Coupled mechanical creep and bio-compression and residual settlement in a multi-stage municipal solid waste landfill, Korea. Scientific Reports, 12(19058), 1-9.

Kumar, G., Reddy, K.R., & McDougall, J.R. (2020). Numerical modeling of coupled biochemical and thermal behavior of municipal solid waste in landfills. Computers and Geotechnics, 128(103836), 1-23.

Ling, H.I., Leschchnsky, D., Mohri, I., & Kawabata, T. (1998). Estimation of municipal solid waste landfill settlement. Journal of Geotechnical and Geoenvironmental Engineering, 124(1), 21-28.

Liu, C., Chen, R., & Chen, K. (2006). Unsaturated consolidation theory for the prediction of long-term municipal solid waste landfill settlement. Waste Management, 24, 80-91.

Machado, S.L., Vilar, O.M., & Carvalho, M. (2008). Constitutive model for long term municipal solid waste mechanical behavior. Computers and Geotechnics, 35(5), 775-790.

Marques, A.C.M., Filz, G.M., & Vilar, O.M. (2003). Composite compressibility model for municipal solid waste. Journal of Geotechnical and Geoenvironmental Engineering, 129(4), 372-378.

McDougall, J. (2007). A hydro-bio-mechanical model for settlement and other behaviour in landfilled waste. Computers and Geotechnics, 34(4), 229-246.

Park, H.I., & Lee, S.R. (1997). Long-term settlement behavior of landfills with refuse decomposition. Journal of Solid Waste Technology and Management, 24(4), 159-165.

Sharma, H.D., & De, A. (2007). Municipal solid waste landfill settlement: Postclosure perspectives. Journal of Geotechnical and Geoenvironmental Engineering, 133(6), 619-629.

Sivakumar Babu, G.L., Reddy, K.R., Chouskey, S.K., & Kulkarni, H.S. (2010). Prediction of long-term municipal solid waste landfill settlement using constitutive model. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management, 14(2), 139-150.

Sowers, G.F. (1973). Settlement of waste disposal fills. Proceedings 8th International Conference on Soil Mechanics and Foundation Engineering. (pp.207-210), Moscow, Russia.

Swati, M., & Joseph, K. (2008). Settlement analysis of fresh and partially stabilized municipal solid waste in simulated controlled dumps and bioreactor landfills. Waste Management, 28(8), 1355-1363.

Wall, D.K., & Zeiss, C. (1995). Municipal landfill biodegradation and settlement. Journal of Environmental Engineering, 121(3), 214-224.

Yen, B.C., & Scanlon, B.S. (1975). Sanitary landfill settlement rates. Journal of the Geotechnical Engineering Division, 101(5), 475-487.

Zekkos, D., Datta, S., & Fei, X. (2021). Coupled process modeling for energy generation from municipal solid waste degradation: Laboratory-scale and field-scale simulations. 3rd International Symposium on Coupled Phenomena in Environmental Geotechnics, Japanese Geotechnical Society Special Publication. 9(11), 485-503.

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 9th International Congress on Environmental Geotechnics (9ICEG), Volume 4, and was edited by Tugce Baser, Arvin Farid, Xunchang Fei and Dimitrios Zekkos. The conference was held from June 25th to June 28th 2023 in Chania, Crete, Greece.