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Identification of initial settlement of municipal solid waste layers in Indonesian landfill

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Abstract

This study presents the measurement of municipal solid waste (MSW) compressibility and subsequent development of a landfill settlement estimation model incorporating a correction factor accounting for initial settlement prior to the addition of pressure/municipal solid waste layers. Three layers of municipal solid waste obtained from a temporary waste station in Bandung, Indonesia, were placed in each of three different lysimeters/treatments ($MSW_{organic}$, layer height 35 cm; $MSW_{mixed-1}$, layer height 70 cm; and $MSW_{mixed-2}$, layer height 35 cm), with a time lag of sample layer input of 2 days. Tests were then undertaken based on the ASTM D2435 test standard – Standard Test Method for One-Dimensional Consolidation Properties of Soils – revealing large immediate and secondary compression ratio values reflecting the high moisture and organic matter content of the analysed municipal solid waste. From the test results, it was also detected that the initial settlement of the analysed municipal solid waste was considerable even before the addition of pressure/further layers, ranging from 10% to 17%. Thus, a modification was made to the classical Sowers settlement estimation model in the form of a correction factor representing the initial settlement occurring prior to the addition of the municipal solid waste layers. This modification resulted in a decrease in the difference between estimated and actual settlement values, from 17% to 24% based on the Sowers equation model to below 5% using the proposed modified settlement model.

Keywords

Compressibility, compression ratio, landfill, municipal solid waste, settlement model

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Introduction

Waste settlement should always be considered in the design, operational and post-operational phases of any landfill site (Damanhuri and Tri Padmi, 2016). Settlement occurs owing to the compressibility of municipal solid waste (MSW) and is related to the capacity and integrity of the landfill. The magnitude and speed of settlement is determined by MSW compressibility, the addition of pressure owing to overlying layers, as well as mechanical creep and biocompression. Knowledge of compression behaviour is thus important in both the landfill operation and rehabilitation phases (Chen et al., 2010). Three major mechanisms are involved in the settlement process in landfills, namely: Immediate compression, mechanical creep and biocompression (Babu et al., 2010). Immediate compression is the initial mechanism that takes place owing to the increase in pressure on the MSW layer; this is then followed by mechanical creep processes as the cavity volume decreases between MSW materials, as well as anaerobic decomposition-related biocompression associated with the organic fraction of MSW (Bareither et al., 2012). The contribution made by each settlement component is thus important in estimating the MSW volumes that can be accommodated at any one landfill site (Babu and Lakshmikanthan, 2015).

The three main factors affecting MSW compressibility are its dry unit weight, moisture content and organic content, as reflected in the compression ratio (Basha et al., 2016). Whereas the immediate compression ratio (C_c') is used to predict strain occurring in the immediate compression phase (Oweis and Khera, 1990), the secondary compression ratio ($C\alpha$) is used to describe the strain occurring over time. Importantly, the methodology used in most soil mechanics research to identify the transition between immediate and secondary (time-related) compression cannot be applied to most landfill, because MSW is not in a saturated state (Bareither et al., 2012). However, the method introduced by Handy (2002) based on the first order rate equation (FORE) procedure can be

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used to determine the strain value at which immediate compression will end and time-related compression will begin, known as the end-of-immediate-compression-strain (ε_{EOI}). After identifying ε_{EOI} at each level of the addition of test pressure (σ_v), C_c' is determined based on the slope of the relationship between $\Delta\varepsilon_{EOI}$ and $\Delta\log\sigma_v$ (Bareither et al., 2012), while $C\alpha$ is determined from the slope of the relationship between the logarithm of time (log t) and strain/settlement per initial height (Bareither et al., 2012). Various descriptions of C_c' and $C\alpha$ have been used in terms of their relationship to the compressibility of MSW, including the following

- Increase with the maximum particle size (Hossain and Gabr, 2009).
- Correlate with moisture content, unit weight and percentage of biodegradable components (Bareither et al., 2012).
- Increase with the height of MSW layers (Ojuri, 2012).
- Negatively related to initial (dry) density (Chen et al., 2010).
- Vary according to the phases associated with biodegradation (Xu et al., 2015).
- Can be modelled in relation to waste composition, dry density, moisture content (dry basis) and percentage of biodegradable content (Heshmati et al., 2014).

Based on MSW compressibility and landfill geometry, the magnitude of settlement at particular time intervals can be estimated, with four main types of settlement estimation model available: (a) soil mechanics-based models, (b) empirical models, (c) rheological models and (d) models related to biodegradation (Babu et al., 2010). One of the most well-known models based on the principle of soil mechanics was proposed by Sowers (1973) and is expressed as:

$$\Delta H = HC_c^* log\left(\frac{\sigma_0 + \Delta\sigma}{\sigma_0}\right) + HC_\alpha log\left(\frac{t_2}{t_1}\right) \quad (1)$$

where ΔH is the settlement owing to primary and secondary consolidation, H is the initial thickness of MSW layer, C_C* is the primary compression ratio, σ_0 is the the existing overburden pressure in the middle of the layer, $\Delta\sigma$ is the additional pressure due to MSW layer addition, $C\alpha$ is the secondary compression ratio, t_1 is the initial compression period time and t_2 is the time period studied in the model.

However, until now, no settlement-related studies have been conducted regarding Indonesian landfill sites, thus increasing uncertainty in landfill design and monitoring in the country. Indeed, as settlement is often ignored in landfill design and monitoring, their design lives are frequently too short. The purpose of the present research was thus to investigate MSW settlement at an Indonesian landfill site, as well as to modify the above-soil mechanics-based equation model by including the initial settlement taking place prior to the addition of pressure, thereby reducing uncertainty in the design and monitoring of landfill settlement, especially in Indonesia.

Materials and methods

MSW material

The MSW material used was typical of Indonesian landfill, with a large organic component and of conventional density (Damanhuri and Tri Padmi, 2016). Specifically, MSW samples were obtained from a temporary waste station in Bandung, Indonesia, and were characterised by high moisture and organic matter levels, with a moisture content of 69.05% (% wet weight), volatile content of 78.72% (% dry weight) and density (bulk) ranging from 0.41 to 0.64 t m^{-3}.

Scheme of the Lysimeter settlement measurement tool

In order to measure the settlement of the obtained MSW material, three lysimeters were constructed: Lysimeter$_1$, Lysimeter$_2$ and Lysimeter$_3$. All three lysimeters had an inner diameter of 0.82 m, with the heights of Lysimeter$_1$, Lysimeter$_2$ and Lysimeter$_3$ equal to 2 m, 3 m and 2 m, respectively. At the bottom of each lysimeter, a leachate channel was provided at two opposite points, with leachate collected in a container. Three variants of MSW were added to the lysimeters in three separate layers as follows – (a) Lysimeter$_1$: organic MSW with a layer height of 35 cm (MSW$_{organic}$); Lysimeter$_2$: mixed MSW with a layer height of 70 cm (MSW$_{mixed\text{-}1}$); and Lysimeter$_3$: mixed MSW with a layer height of 35 cm (MSW$_{mixed\text{-}2}$). Measuring plates were placed on the surfaces of Layer$_1$ and Layer$_2$, in order to view settlement in each of these two earlier layers. Settlement of Layer$_3$ was determined via a measuring meter based on the change in layer surface depth to the upper lip of the lysimeter.

The procedure employed to measure MSW settlement in the lysimeters proceeded as follows.

1. MSW material was inserted into each lysimeter in three stages/layers. Sample input per stage/layer was carried out at 2-day intervals.
2. The load was given by the self-weight of the MSW material.
3. Settlement was detected based on the movement of graded measuring rods, whose bottom side was connected to the settlement measurement plates placed between Layer$_1$ and Layer$_2$ (Plate$_1$) and between Layer$_2$ and Layer$_3$ (Plate$_2$), as shown in Figure 1.
4. Each measuring rod moved downward with the measurement plates and relative to a motionless graded reference rod, based on which the total downward movement could be measured.
5. The downward movement of the measuring plates thus represents the settlement of the underlying layer, with the movement of Plate$_1$ indicating the settlement of Layer$_1$ and the movement of Plate$_2$ indicating the settlement of Layer$_2$.
6. The drop in the surface of Layer$_3$ was measured using a metre gauge.

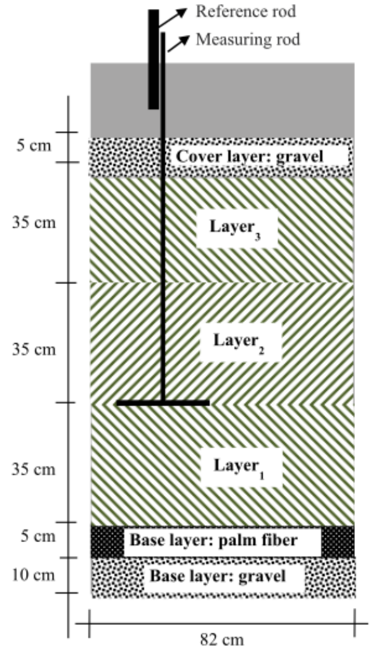

Figure 1. Scheme of lysimeter settlement plate.

MSW sample preparation

MSW samples were obtained directly from the temporary waste station in Bandung. Sampling was undertaken three times, to fill $Layer_1$, $Layer_2$ and $Layer_3$ in each lysimeter. Initial MSW density in lysimeters was considered as approximately equal to the MSW density with conventional compaction recorded in Indonesian landfill, i.e. around 0.4 to 0.6 t m^{-3} (Damanhuri and Tri Padmi, 2016). Sampling commenced in the morning and ended in the afternoon, with the MSW samples placed in the lysimeters the next day. On each sampling occasion, measurements of sample moisture and volatile content were carried out. The sampling procedure was as follows.

1. Samples of 500 L were collected randomly from several points around the temporary waste station.
2. In one 500-L sample, MSW composition was measured according to standard SNI 19-3964-1995.
3. Samples of 10–15 L were placed in plastic bags, the sample volume being minimised via the quadrant method, for the measurement of moisture and volatile content.
4. Samples of around 330 kg of mixed MSW were obtained to fill $Lysimeter_2$ and $Lysimeter_3$, with all material chopped to a maximum size of 5 cm prior to being placed in plastic bags.
5. Next, around 110 kg of organic MSW (non-organic component removed) was obtained to fill $Lysimeter_1$. Again, a maximum material size of 5 cm was ensured prior to placement in plastic bags.
6. Finally, samples were taken to the location of the lysimeters ready for insertion the following day.

Measurement of MSW settlement in lysimeters

MSW material was placed evenly in the lysimeters per layer at a target density of 0.4 to 0.6 t m^{-3}, in accordance with conditions at Indonesian landfill sites. Hourly measurements were made on the first day after initial sample/$Layer_1$ input, as well as on the first day after the addition of $Layer_2$. On every other day throughout the experiments, settlement measurements were carried out once a day. Settlement per layer was measured based on the measuring instruments placed in the lysimeter, as outlined above.

Results and discussion

Characteristics of the MSW samples

Table 1 presents the composition, moisture and volatile content of the MSW material placed in each layer in the lysimeters, with their initial height and density presented in Figure 2.

According to the measurement results (Table 1), the four main components in the analysed MSW samples are food waste, plastics, paper and leaves, exhibiting high moisture and volatile content as is typical of MSW in Indonesia. Similarly, the density of the MSW placed in the lysimeters ranged from 0.41 to 0.65 t m^{-3} (Figure 3), again corresponding to data recorded previously for Indonesian landfill (Damanhuri and Tri Padmi, 2016).

Detection of initial settlement before MSW layer addition

Observation of the three lysimeters revealed a significant compression phenomenon taking place in the first 2 days prior to the addition of pressure caused by the placement of another MSW layer. Figure 3 shows the presence of an initial settlement mechanism in the MSW layer owing to the latter's self-weight, before the addition of the next layer.

Comparing the settlement with the height of the initial layer (Figure 4) indicates a significant settlement of between 10% and 17%; as a result, such initial settlement occurring before the addition of pressure must be included in any landfill settlement estimation model.

Determination of MSW sample compression ratio

Determination of immediate compression ratio (C_c') of MSW samples. The value of the immediate compression ratio was calculated for $Layer_1$ in all three lysimeters using the first order regression equation/FORE method (Handy, 2002); using this method, values of C_c' could not be determined for the remaining two layers as linear regression based on the relationship of $\Delta\varepsilon_{EOI}$ vs $\Delta\log\sigma_v$ required four point values of ε_{EOI}, with the gradient of the linear regression line representing the value of C_c' (Figure 5). The total pressure received by each $Layer_1$ was the self-weight of the three MSW sample layers and the cover layer (a 5 cm thick

Table 1. Composition, moisture and volatile content of the tested MSW samples.

Parameter	$Sampling_1$	$Sampling_2$	$Sampling_3$	Average
Density (t m^{-3})	0.2419	0.2909	0.3005	0.2778
Composition				
Food waste	69.99%	55.45%	53.11%	59.52%
Plastic	11.82%	13.11%	11.80%	12.24%
Paper	11.82%	18.15%	15.34%	15.10%
Garden	4.54%	12.14%	15.34%	10.68%
Glass	0.90%	0.15%	0.15%	0.40%
Rubber	0.00%	0.00%	0.00%	0.00%
Metal	0.24%	0.34%	0.00%	0.20%
Textile	0.30%	0.00%	0.73%	0.34%
Hazardous waste	0.39%	0.66%	3.52%	1.52%
Moisture content (% wet weight)	70.71%	71.29%	65.14%	69.05%
Volatile content (% dry weight)	82.03%	74.08%	80.06%	78.72%

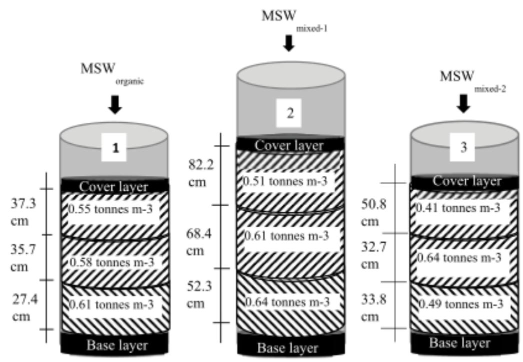

Figure 2. Initial density and height of lysimeter MSW layers.

gravel layer). Table 2 presents the values of C_c' calculated for all three treatment variants.

Analysis of Table 2 reveals that the C_c' values of the analysed MSW samples are large, reflecting their high moisture and organic matter content, since the value of C_c' increases with increasing levels of moisture (Reddy et al., 2009; Vilar and Carvalho, 2005) and organic material (Chen et al., 2009; Swati and Joseph, 2008).

Determination of secondary compression ratio (Cα) of MSW samples. The secondary compression ratio indicates time–bound settlement (Lambe and Whitman, 1969), typically expressed in days (Babu et al., 2010). Just as for the determination of the immediate compression ratio, the secondary compression ratio was also calculated only for $Layer_1$ in all three lysimeters. Analysis of Figure 6 reveals the onset of a stable linear decline from the 10th day, with the value of $C\alpha$ being the slope gradient of the strain vs log t graph (Figure 7). The $C\alpha$ values obtained in the present study are large, again in accordance with MSW characterised by high moisture and organic matter levels (Chen et al., 2009; Reddy et al., 2009; Swati and Joseph, 2008; Vilar and Carvalho, 2005).

Development of settlement estimation model

As stated earlier, both Figures 4 and 5 illustrate the existence of an initial settlement mechanism in $Layer_1$ of each lysimeter, prior to being loaded by the next MSW layer. This mechanism is noteworthy as it suggests that MSW layers in Indonesian landfill sites are not subjected to additional pressure instantaneously, but rather experience a grace period before being re-loaded. Considering this initial settlement, the classical settlement estimation model based on the principle of soil mechanics should be modified, as it has always been assumed that settlement starts immediately owing to the addition of pressure, followed by secondary settlement over time. In the present study, such a modification is proposed that includes an initial correction factor in the settlement estimation equation that takes account of the observed initial settlement.

The formula to be modified is that proposed by Sowers (1973), as presented earlier in equation (1). By including an initial correction factor, the updated settlement estimation model is expressed as follows:

$$\Delta H = E_0 + HC_c^{*}log\left(\frac{\sigma_0+\Delta\sigma}{\sigma_0}\right) + HC_\alpha log\left(\frac{t_2}{t_1}\right) \quad (2)$$

where E_0 is the correction owing to initial settlement occurring prior to the addition of pressure.

To identify E_0, regression analysis of strain vs log t was applied, as in the detection of $C\alpha$ values, for data covering the first 2 days before the addition of the next MSW layer. The first group of data included the initial settlement of the three layers in $Lysimeter_1$ (i.e. $MSW_{organic}$, Figure 8), and the second group of data the initial settlement of the three layers in each of $Lysimeter_2$ and $Lysimeter_3$ (i.e. mixed MSW ($MSW_{mixed\text{-}1}$ and $MSW_{mixed\text{-}2}$) (Figure 9)).

Based on the regression equation y = bx + a, it was found that strain (ε) = C_0.log t + a, where C_0 is the initial compression ratio

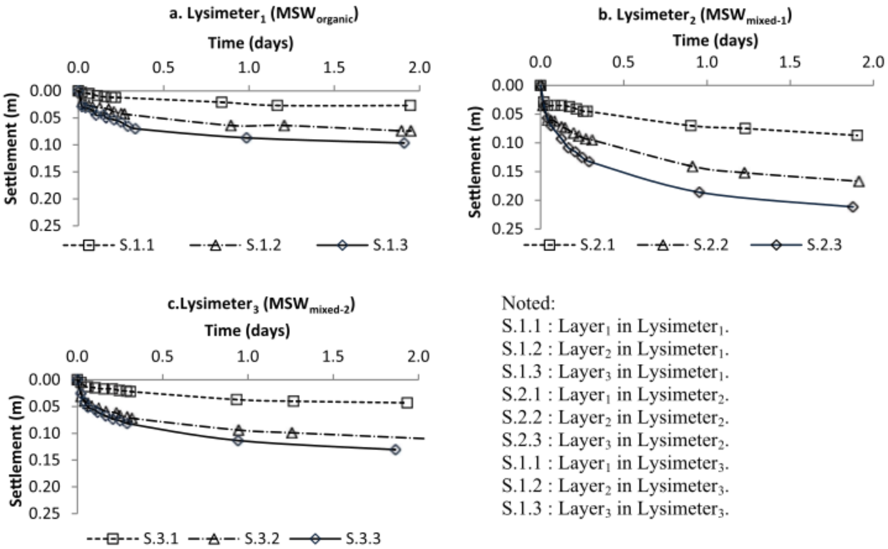

Figure 3. MSW settlement before adding pressure in: (a) Lysimeter$_1$, (b) Lysimeter$_2$ and (c) Lysimeter$_3$.

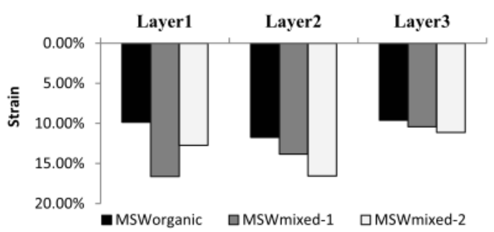

Figure 4. Strain (settlement per initial height of sample layer) before adding pressure.

and a is a constant describing the strain at $t=1$ day ($\log t=0$). It thus follows that:

$$\varepsilon = \frac{\Delta H_{(initial)}}{H} = C_{0.}log.(t) + a^{\circ} \rightarrow {}^{\circ}\Delta H_{(awal)} \\ = E_0 = H.(C_0.\log t + a) \tag{3}$$

where $\Delta H_{(initial)}$ is the amount of initial settlement observed before the addition of the next MSW layer, which is the definition of the initial correction factor (E_0) in equation (2).

Thus, by combining equations (2) and (3), we obtain the following MSW settlement estimation equation:

$$\Delta H = H.(C_0 logt_0 + a) + H, C_c^{'} log\left(\frac{\sigma_0 + \Delta\sigma}{\sigma_0}\right) \\ + H.C_\alpha log\left(\frac{t_2}{t_1}\right) \tag{4}$$

where C_0 is the initial compression ratio (0.0461 for organic MSW and 0.0585 for mixed MSW), t_0 is the time interval between layer i and the layer above and a is the constant describing strain when $t=1$ day (0.934 for organic MSW and 0.1231 for mixed MSW).

Testing of the modified settlement estimation model

The settlement of Layer$_1$ in all three lysimeters was estimated using both the Sowers equation (equation (1)) and the modified equation (equation (4)), with these estimates then compared with the actual settlement data recorded during the experiments. Values of the immediate and secondary compression ratios are presented in Figures 5 and 7, geometry and pressure data in Figure 2, and the initial compression ratio and constants forming the initial correction equations in Figures 8 and 9. Estimations were carried out for the period running from 0 to 35 days, according to available settlement data.

Analysis of Figures 10–12 reveals that the estimated settlement values calculated using equation (4) are closer to the actual settlement than those obtained using equation (1), with the difference between estimated and actual settlement decreasing to under 5% from 17%–24%, respectively.

Conclusion

Under conventional density conditions, large immediate and secondary compression ratios were recorded in the analysed Indonesian MSW samples, reflecting their high moisture and organic matter contents. Furthermore, significant initial settlement was also identified, taking place prior to the addition of pressure after the placement of further MSW layers. Owing to the time lag occurring between layer additions, this phenomenon must therefore be included in any landfill settlement estimation

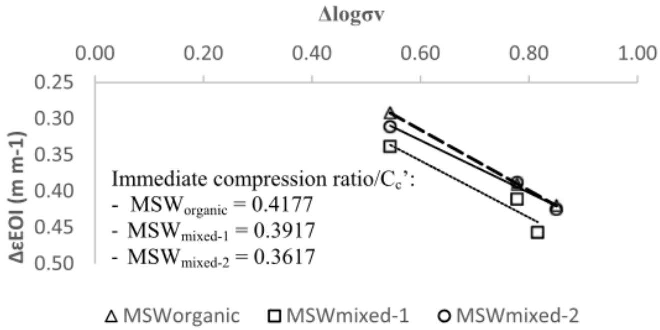

Figure 5. Determination of C_c values for the three MSW treatment variants.

Table 2. Values of C_c' for the $MSW_{organic}$, $MSW_{mixed\text{-}1}$ and $MSW_{mixed\text{-}2}$ treatments.

Sample code	Treatment	Sample description	C_c'
$MSW_{organic}$	$Lysimeter_1$	Organic MSW, height per layer ~ 0.35 m	0.4177
$MSW_{mixed\text{-}1}$	$Lysimeter_2$	Mixed MSW, height per layer ~ 0.70 m	0.3917
$MSW_{mixed\text{-}2}$	$Lysimeter_3$	Mixed MSW, height per layer ~ 0.35 m	0.3615

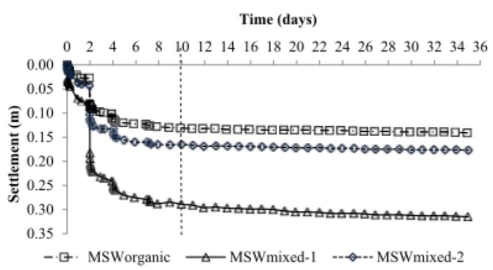

Figure 6. Measured settlement in $Layer_1$ in all three treatment variants.

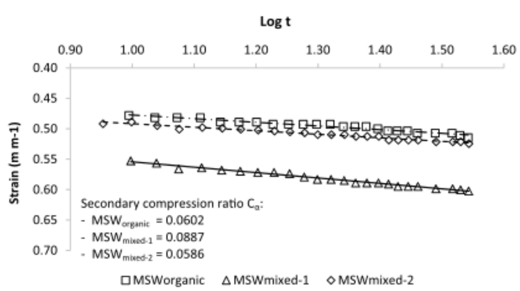

Figure 7. Determination of Cα values for all three treatment variants.

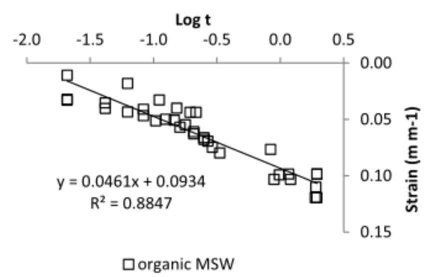

Figure 8. Determination of E_0 for organic MSW.

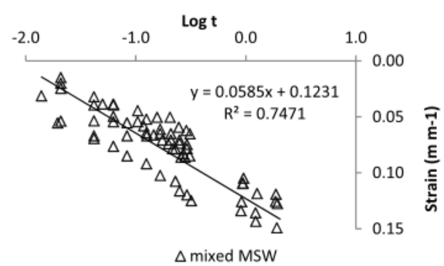

Figure 9. Determination of E_0 for mixed MSW.

model. Here we have proposed that this initial correction should account for the relationship between strain (ε = settlement per initial height, $\Delta H/H$) and the logarithm of time (log t). Linear regression was employed to obtain the value of the initial compression ratio (C_0), which is bound to the log t parameter, and a free constant that describes settlement at t = 1 day (log t = 0), thus forming an initial correction equation. Modification of a classical settlement estimation model was carried out by combining the proposed initial correction with the equation first published by Sowers (1973). Comparative analysis revealed that the modified settlement estimation model is able to significantly decrease the difference between estimated and actual settlement values.

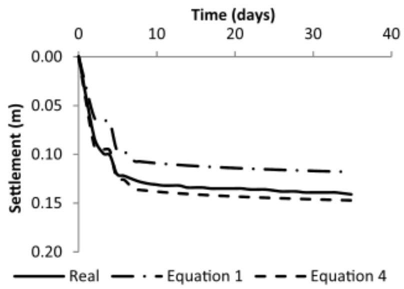

Figure 10. Actual and estimated settlement for $MSW_{organic}$.

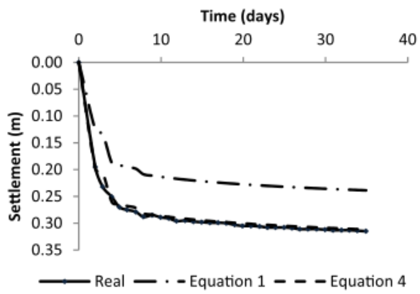

Figure 11. Actual and estimated settlement for $MSW_{mixed-1}$.

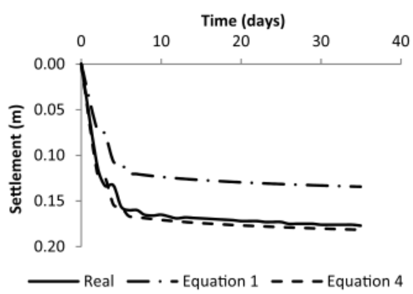

Figure 12. Actual and estimated settlement for $MSW_{mixed-2}$.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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