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Estimation of short-term settlements of MSW landfill materials using shear wave velocity

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Article

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Abstract

Limited availability of simple yet adequately validated tools for estimating the deformation potential of municipal solid waste (MSW) material poses difficulty in planning and managing landfill operations. Estimation of settlement of MSW landfills has remained a challenge because of heterogeneity and time-varying mechanical behavior of MSW materials and difficulty of extracting representative samples and reconstituting them for laboratory testing. An empirical correlation is proposed here for estimating the short-term settlement of landfill materials. The relationship was developed by calibrating laboratory data from axial (1D) compression and consolidated drained triaxial tests against field-measured shear wave velocities from five landfill sites with varied waste compositions. The correlation was validated against three full scale load tests; one obtained in this research and two reported by others, and a field compaction study from a fourth landfill. Although the proposed correlation was more accurate than an alternative developed earlier, overall it underestimated settlements by about 12%. The proposed relationship could therefore provide a conservative guidance in MSW landfill design and operation.

1. Introduction

Landfill settlement may occur due to both mechanical compression and biological decomposition of the waste material. Typical field settlement data for Municipal Solid Waste (MSW) landfills indicate that settlements result from four physical processes: elastic deformation (Phase I); deformation due to time-rate independent reorientation and repositioning of fibrous, membrane-like, particulate and other MSW constituents under self-weight and other superposed loads (Phase II); deformation due to creep (Phase III); and deformation due to biodegradation, biogas compressibility and gas migration (Grisolia & Napoleoni, 1995). Phase I settlement typically develops over the first few days of fill placement and Phase II settlement develops over the initial 1 to 3 months of fill placement. The volume requirement and operational life of a landfill, for instance, is controlled by maximizing waste compaction during placement (Ham et al., 1978; Fang & Chaney, 2016), i.e., by minimizing the potential of settlements that develop in phases I and II. A reasonable estimate of settlements expected to develop in these phases would therefore be of help in the assessing the volumetric capacity of landfills at their design stages and in the operational management of the landfill operations. An empirical framework for estimating such settlements for a variety of MSW composition is the main focus of this paper. Compaction potential of MSW landfill materials and their primary compression sometimes could be as large as half of its original uncompacted thickness (Zekkos et al., 2016).

2. Differences in laboratory and field deformation behavior of MSW

The primary compression ratio, C'_c, that relates to the compression index, C_c, and initial void ratio, e_0, via $C'_c = C_c/(1+e_0)$ (Durmusoglu et al., 2006), is often used for estimating primary settlement, S_i, employing:

$$S_i = HC'_c \log\left\{\left(\sigma'_v + \Delta\sigma'_v\right)/\sigma'_v\right\} \quad (1)$$

where H is the waste thickness, σ'_v is the initial vertical effective stress and $\Delta\sigma'_v$ is the vertical stress increment that is causing the settlement. Since C'_c relates to the constrained

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modulus, M, of the waste undergoing settlement such that $M = 2.303\sigma'_v / C'_c$, M can also be used in settlement estimation instead of C'_c.

Characterizing MSW for C'_c (or M) by drilling boreholes or advancing a piezocone or other probes through the waste could be difficult due to the likelihood of premature refusal of the sounding on an impenetrable pocket of construction debris, metal pieces, or stretched plastic waste within the landfill. Such intrusive methods could also open up undesirable pathways for the migration of leachate, contaminants, and landfill gases. The field behavior of MSW depends mostly on its progressive compression and preferential alignment of constituents. So testing of relatively small-sized laboratory specimens prepared by reconstituting the waste materials extracted from drilling may not capture their field deformation behavior. Fibrous or membrane-like materials contained in the waste, for instance, align progressively perpendicular to the direction of compression (Zekkos et al., 2016) making its field deformation behavior stiffer than that inferred from laboratory tests (Bray et al., 2009; Ramaiah & Ramana, 2017). It should be mentioned here that the MSW materials having particle size greater than 20 mm are broadly classified as fibrous or membrane like materials (Bray et al., 2009). In general, they have long main axes and they are slender in nature. These materials show reinforcing effect when they undergo reasonable displacement.

Consequently, laboratory-inferred C'_c has been noted to decrease with the physical size of specimens tested in the laboratory (Hossain & Gabr, 2005). A review of laboratory tests on MSW specimens with similar bulk unit weight, degradable waste content, and moisture content obtained by Wall & Zeiss (1995), Beaven (1999), and Reddy et al. (2009) also indicates that a 10-fold increase in the size of test specimen the average C'_c decreased by about 25%. A similar review by Gabr & Valero (1995), Jang et al. (2010), and Jang (2013) indicates that the average C'_c applicable in the field could be as small as a third of the laboratory-inferred value for MSW materials of similar characteristics. However, since the difference could be to an extent due to rearrangement and reorientation of waste contents developing over time, laboratory-derived C'_c may still provide a reasonable first-order estimate of primary settlements of MSW if a procedure partly based on laboratory tests is validated or calibrated against field observations.

As expected for a deformable material undergoing progressive compression, decomposition and content rearrangement, C'_c decreases with decreasing organic fraction (Hossain et al., 2003; Chen et al., 2009), with increased abundance of incompressible materials (Dixon et al., 2008; Kavazanjian Junior et al., 2013), with increasing depth of burial and age (Landva et al., 2000; Chen et al., 2009) and compaction during placement (von Stockhausen, 2007; Wong, 2009). The influence of moisture content on C'_c is somewhat complicated. Older (and therefore possibly partly decomposed) waste, for instance, has been noted to be more compressible when drier (Vilar & Carvalho, 2004; Durmusoglu et al., 2006), whereas relatively young waste is sometimes more compressible when wetter (Reddy et al., 2009).

3. Database

Laboratory test data from CME Gate and Dharma characterized in this study and Metropolitan Center, Suzhou, Yancheng, Okhla and Ghazipur dumpsites (Table 1) investigated by others were used for developing a C'_c-V_S correlation. The C'_c values were estimated from field stress-strain curves inferred by scaling laboratory deformation responses observed in one dimensional compression and consolidated drained triaxial tests on reconstituted waste materials to reflect the shear stiffness obtained from V_S and Poisson's ratio inferred from field-measured primary and secondary wave velocities (Figure 1). Figure 1 was developed based on the data from the Matasovic & Kavazanjian Junior (1998) and Landva et al. (2000). Details on five other dumps listed in Table 1, IIT-T1, IIT-T2, the Austin Community landfill (Zalachoris, 2010), Valdemingómez landfill (van Elk et al., 2014) and one in Michigan found in Hanson et al. (2010) were used to validate the C'_c-V_S relationship.

4. Landfill characterization and data reduction

CME Gate and Dharma, IIT-T1 and IIT-T2 landfills were characterized for their V_S with MASW employing six geophones placed at 1 m center-to-center spacing and 2 m offset between the source and the geophone nearest to it. The data were analyzed using factored wavelength inversion (Matthews et al., 1996) assuming penetration depth to be a third of the wavelength. The theoretical relationship between

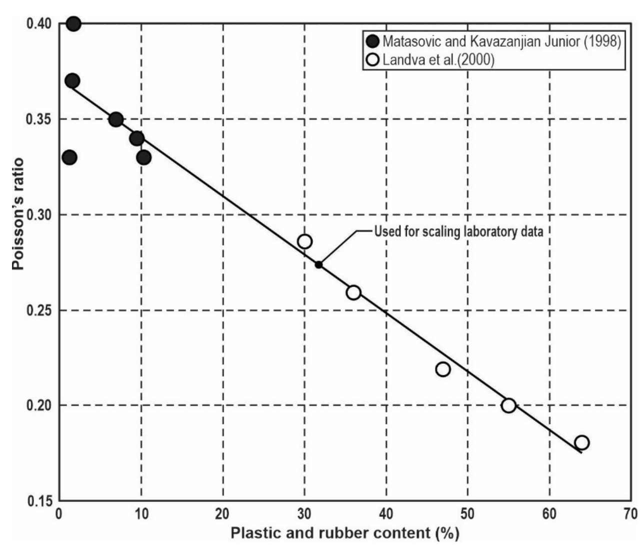

Figure 1. Poisson's ratio for MSW materials inferred from field body wave velocities.

Table 1. MSW data used in this study for correlation development and validation.

Landfill (References)	C_c', see Note *a*	V_S (m/s), see Note *a*	Waste composition (w/w %)	
			Plastic and rubber	Food, garden, paper/cardboard, textiles, metal, glass, wood, soil-like
CME Gate (this study)	0.250 - 0.310	90 – 110	17.2	−, 15.5, 3.2, −, −, 3.2, 64.1
Dharma (this study)	0.240	70	9.8	−, 3.4, 3.4, −, −, −, 81.6
IIT-T1 (this study)	*0.199 - 0.232*	40 - 150	7.8	−, 2.2, 2.1, 2.4, 3, 1.4, 81.1
IIT-T2 (this study)	*0.200 - 0.251*	60 - 230	19.4	−, 12.1, 0.1, 5.8, 2.3, 1.2, 59.1
Metropolitan Center (Machado et al., 2008; Machado et al., 2002)	0.072	*113*	23.8	36.1, 17.1, 2.6, 2.4, 3.5, 4, 10.5
	0.084	*153*	23.8	36.1, 17.1, 2.6, 2.4, 3.5, 4, 10.5
	0.193	*167*	23.8	36.1, 17.1, 2.6, 2.4, 3.5, 4, 10.5
	0.056	*134*	14	50.2, 5.2, 2.5, 5, 4.1, 5.6, 13.4
	0.125	*143*	14	50.2, 5.2, 2.5, 5, 4.1, 5.6, 13.4
	0.158	*201*	14	50.2, 5.2, 2.5, 5, 4.1, 5.6, 13.4
	0.296	*79*	19	55, 2, 3, 5, 2, 4, 10
	0.498	*95*	19	55, 2, 3, 5, 2, 4, 10
	0.741	*95*	19	55, 2, 3, 5, 2, 4, 10
Suzhou (Zhan et al., 2008)	0.200	*105*	16.6	14.75, 7.07, 0, 1.9, 0, 0, 59.65
Yancheng (Li & Shi, 2016)	0.223	*149*	15.2	53, 11.8, 5.2, 7.5, 4, 5.4, 6
	0.284	*189*	15.2	53, 11.8, 5.2, 7.5, 4, 5.4, 6
Okhla (Ramaiah & Ramana, 2017)	0.141	*77*	1	0, 0, 0.8, 0, 0, 98.2
	0.162	*118*	1	0, 0, 0.8, 0, 0, 98.2
	0.270	*147*	4	0, 0, 6.2, 0, 0, 89.8
	0.102	*213*	4	0, 0, 6.2, 0, 0, 89.8
Ghazipur (Ramaiah & Ramana, 2017)	0.066	*80*	0	0, 0, 0, 0, 0, 100
	0.090	*78*	0	0, 0, 0, 0, 0, 100
	0.154	*175*	0	0, 0, 0, 0, 0, 100
	0.127	*85*	3.3	0, 0, 4.5, 0, 0, 92.2
	0.217	*105*	3.3	0, 0, 4.5, 0, 0, 92.2
	0.413	*141*	3.3	0, 0, 4.5, 0, 0, 92.2
Austin Community (Zalachoris, 2010)	*0.22*	65 – 105	2.0	−, 5.0, −, −, 1.0, 92
Michigan Subtitle D (Hanson et al., 2010)	*0.34*	*49 – 71*	19.0,	25.0, 24.0, 6.0, 7.0, 6.0, 7.0, 6.0,
Valdemingómez (van Elk et al., 2014)	*0.22*	70 – 140	14.0	59, 6.0, −, 4, 8.0, −, 9

Note: *a*. Entries in normal typeface represent parameters representing corrected lab response or direct field measurements. Italicized entries are for C_c' obtained from the correlation developed in this study or V_S from Zekkos et al. (2014).

the velocities of Rayleigh and shear waves for isotropic, linearly elastic materials (Richart et al., 1970) were used to estimate the in-situ shear wave velocity with Poisson's ratio taken from Figure 1. Although there is some scatter in V_S inferred from MASW possibly due to material heterogeneity and consequent Rayleigh wave dispersion multimodality (Kausel et al., 2015; Zhang et al., 2016), their general increase with depth appears to capture the influence of compaction on V_S (Figure 2).

MSW materials from CME Gate and Dharma were subjected to vertical compression testing within a stiff metal cylinder of 600 mm diameter and 440 mm height. The observed deformation responses were corrected to reflect material stiffness inferred from body wave velocity measurements as discussed earlier. C_c' obtained in this manner with the corresponding MASW inferred values of V_S are listed in Table 1. These data were also used in developing the C_c' -V_S correlation proposed below.

5. Correlation for primary compression ratio

Table 1 data indicate that C_c' may relate to V_S (taken in m/s) via the following relationship:

$$C_c' = a\exp\left(-bV_S\right) \quad (2)$$

in which parameters a and b were found to depend on mean normal effective stress, p', and atmospheric pressure, P_a, according to

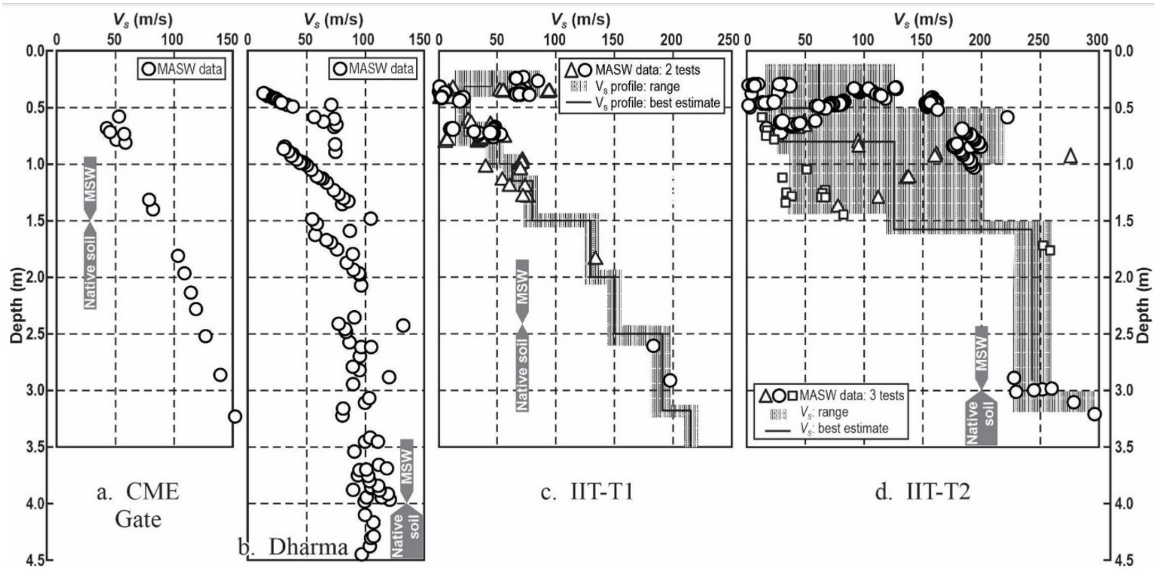

Figure 2. MASW-based shear wave velocity profiles at (a) CME gate landfill; (b) Dharma landfill; (c) IIT-T1; and (d) IIT-T2.

$$a = 2.56399 \times 10^{-1} \left(p'/P_a \right)^{\left(-0.76/\left(p'/P_a\right)\right)}$$
$$b = 8.5541 \times 10^{-3} \left(p'/P_a \right)^{\left(-0.36/\left(p'/P_a\right)\right)} \quad (3)$$

Although Equations 2 and 3 are functionally similar to Zekkos et al. (2014, 2016) correlations, instead of relying on laboratory deformation data, Equations 2 and 3 were developed using laboratory data calibrated for field-measured deformation moduli. Curve export professional 2.7.3 is used to develop these Equations 2 and 3 with $r^2 = 0.99$.

6. Validation

To validate the proposed relationship, field load test was performed at IIT landfill site that has been operating over the last five years as discussed in the following subsection. Measurements from another two field load tests and a compaction trial obtained by others were also used for validation.

6.1 Load test at IIT landfill

Two tanks, T1 and T2, of 1350 mm diameter were placed at the surface of a landfill at two locations with different waste compositions and filled rapidly with water after placement to impose 13.6 kPa surcharge. Waste thicknesses underneath T1 and T2 were 2.4 m and 3 m, respectively, below which saturated, firm to stiff silty clay was found. Over the subsequent 83-day of tank settlement was monitored using a system capable of delivering millimeter level accuracy. Water volume in the tanks were replenished to ensure that the surcharge remained constant over the settlement monitoring period.

The settlement at T1 estimated from Equation 2 using V_S profile of Figure 2c and p' estimated from Zekkos et al. (2014) and Schmertmann et al. (1978) approach exceeded the 83-day observed settlement by about 25 mm (Figure 3a). The corresponding estimate for T2 based on Figure 2d V_S profile, on the other hand, was smaller than the 83-day observation by about 80 mm.

6.2 Load test at Austin community landfill

A 230 mm thick footing of 900 mm diameter was constructed on the surface of the Austin community landfill and footing settlements were recorded with three linear potentiometers placed around the footing that resulted from a series of static vertical loads applied statically with a Vibroseis truck (Zalachoris, 2010). MASW geophones were positioned around the boundary of the footing, and four V_S profiles were obtained with a maximum coefficient of variation of 9.7% with its mean V_S profile. MSW composition and mean V_S values from the field load test location can be found in Table 1. For the mean V_S profile the settlements were estimated from Equation 2 adhering to Schmertmann et al. (1978). The results indicate that the proposed method overestimated the settlement at a 45 kN load by about 14% (Figure 3b).

6.3 Trial compaction at Michigan (subtitle D) landfill

Full-scale field compaction tests were performed over a test cell of about 200 m^2 area at a landfill in Michigan, USA by placing the waste in 500 mm loose lifts and compacting them with 530-kN BOMAG BC 1172RB waste compactor (Hanson et al., 2010). The reported unit weight of waste at placement was 3.3 to 6 kN/m^3. As indicated in Table 1, the corresponding shear wave velocities are expected to range between 49 m/s and 71 m/s (Zekkos et al., 2014). Assuming a tangential contact between the compactor and native ground

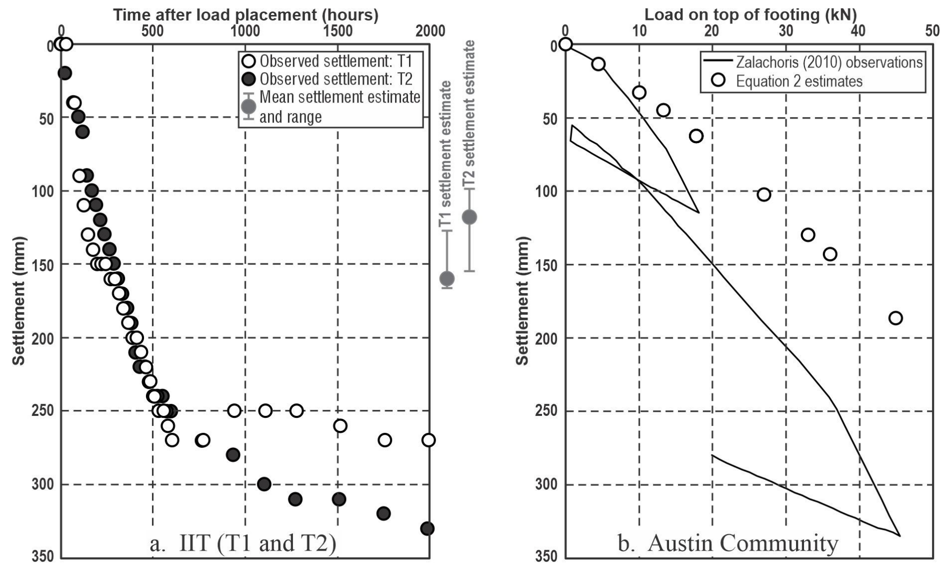

Figure 3. Observed and estimated settlements at (a) IIT –T1 and IIT- T2 landfill; and (b) Austin landfill.

or underlying compacted layer, the compaction is likely to have imposed a $\Delta\sigma_v'$ of about 52 kPa. Assuming an effective stress friction angle of about 30° and zero cohesion for the waste layer at placement (Zekkos et al., 2012), the ultimate bearing capacity that the poorly compacted layer of MSW would have mobilized under compactor wheels would have been about 48 kPa; a value quite close to the estimated stress increment. While the settlement estimate for $\Delta\sigma_v' = 52$ kPa and C_c' from Equation 2 exceeded the corresponding observation in one instance by as much as 73% and was smaller than observation by as much as 28% in another, the majority of observations were in approximate agreement with Equation 2 estimates (Figure 4).

6.4 Valdemingómez landfill load test

A surface surcharge was placed on a 33-m high landfill in Madrid, Spain by placing soil over a rectangular area measuring 39 m in length and 20 m in width (van Elk et al., 2014). Maximum height of the fill was 4 m. Settlements were monitored near the middle of the north and south edges of the fill at various distances from the fill slope toe. MSW composition and mean V_S values inferred from Rayleigh wave measurements for test location are presented in Table 1.

Settlements estimates from Equation 2 were within +9% and −44% of observations with observations by and large exceeding those from Equation 2 marginally (Figure 4).

6.5 Bias and accuracy

Overall, observed short term settlements were found to be larger than Equation 2 estimates by about 12% with the observation clustering within +78% and −42% of estimates (Figure 4). In comparison, the Zekkos et al. (2016)

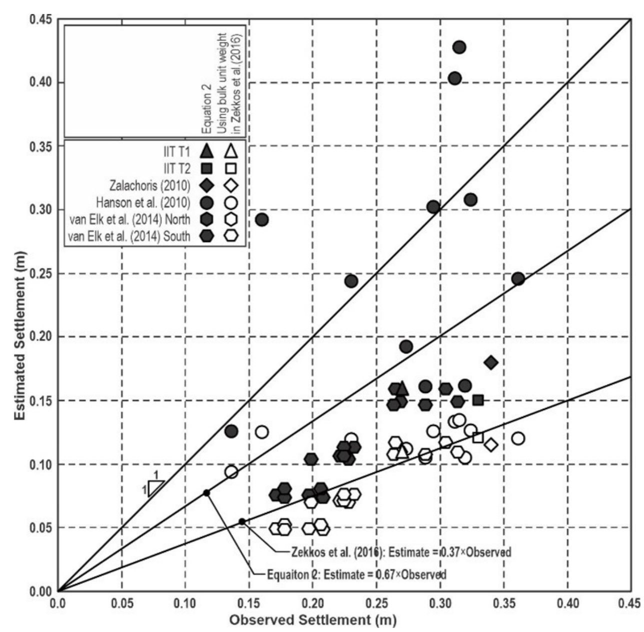

Figure 4. Comparison of settlement estimates with observations.

framework underestimated settlements overall by about 63% with observations exceeding the corresponding estimates by between 28% and 330%.

7. Conclusion

A reliable estimate of short term settlements of MSW materials is an essential input in proper design and operation of MSW landfills. Laboratory testing for obtaining such settlements may not always be feasible due to the difficulty in extracting representative MSW samples and reconstituting them within the small confines of typical laboratory setups.

An empirical procedure has been proposed in this paper for estimating short-term settlements of MSW materials using field-measured shear wave velocity. The relationship was developed by calibrating laboratory deformation test data to reflect field conditions using field-measured primary and secondary wave velocities, calculating the compression ratio from the calibrated deformation response and relating the compression ratio to field-measured shear wave velocities. Data from four MSW landfills characterized in this study and six sites investigated by others were used to develop the correlation. The settlements estimated using the proposed framework were then compared with observations from four full-scale field load tests and a compaction study. Load tests at two locations were conducted in this study and the other three datasets used in this exercise were from published literature. The results indicated that the short-term settlement estimates obtained from the correlations were about 12% less than observations.

The results obtained in this study suggest that short term compaction or deformation potential of MSW landfills could be reasonably estimated from laboratory compression or triaxial test data scaled to reflect the stiffness obtained from field-measured primary and secondary wave velocities. In the absence of laboratory data, the correlation proposed in this study may also provide a reasonable but somewhat conservative option for estimating short term settlements of MSW materials.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Nagendra Kola: data curation, visualization, testing, formal analysis, validation, writing – original draft. Debasis Roy: conceptualization, methodology, supervision, funding acquisition, writing – review & editing. Debarghya Chakraborty: supervision, writing – review & editing, funding acquisition.

Data availability

The datasets produced and analyzed in the course of the present study are available from the corresponding author upon reasonable request.

List of symbols

e_0	initial void ratio
p'	mean normal effective stress
C_c	compression index
C_c'	primary compression ratio
H	waste thickness
M	constrained modulus
P_a	atmospheric pressure
S_i	immediate or short-term settlement
V_S	shear wave velocity
σ_v	initial vertical effective stress
$\Delta\sigma_v'$	vertical stress increment

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