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Use of Dynamic Compaction for Densifying MSW Landfills

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Abstract. Rapid industrialization and population explosion in recent times has led to the generation of large quantities of municipal solid waste (MSW), which has driven the MSW landfill sites to the brink of their design life. A viable option of extending the design life of these existing MSW landfills is through adoption of a suitable ground improvement methodology in a planned manner. The present study reports the effectiveness of Dynamic compaction (DC) for MSW landfills by using finite element (FE) based analysis in ABAQUS (ver. 6.14). The response of MSW is modelled by adopting the Drucker-Prager constitutive law and arbitrary Lagrangian-Eulerian (ALE) remeshing approach. The results indicate volumetric compression and densification of wastes under the impact of DC for various ranges of tamper energy, tamper radius and waste compressibility. An empirical equation is formulated based on optimized design parameters for obtaining DC induced settlement of MSW landfills in the field. The predictive design equation is subsequently validated by comparing the settlement values obtained using the equation with selected field case histories. Additionally, the effectiveness of DC in vertical landfill expansion or piggyback construction is investigated in the study and found to be effective. The present research thus explores the possibility of enhancing waste disposal capacity of MSW landfills for further waste disposal, or for reclamation of MSW sites for future infrastructure projects.

Keywords: Dynamic compaction, Municipal solid waste, Landfills, FE modelling, Piggyback landfills.

1 Introduction

Over the past few decades, dynamic compaction (DC) has gained popularity as an effective ground improvement technique for geomaterials in view of its simplicity, low-environmental impact and cost effectiveness. The method transmits kinetic energy onto the soil by allowing repeated dropping of heavy tamper from a height at regularly spaced intervals. DC is extensively applied in the field to improve the geotechnical characteristics of dry and saturated sands, silty sands, silts, peats etc. Another novel application of DC includes densification of municipal solid waste (MSW) landfills for future expansion. However, the highly complicated response of MSW under DC is still not properly understood, and very few analytical/numerical models or physical model studies have been undertaken to quantify volumetric compression of MSW landfills under DC-induced densification. The decisions have to be made depending mainly on several field trials and past experience, rendering the project as tedious and expensive. This necessitates a detailed investigation of settlement induced in MSW landfills under the impact of DC, and on the design parameters governing its efficiency. The relevance of the study is derived from the rapid industrialization occurring globally, which has resulted in massive generation of MSW in various cities across the world. As per the reports of Hoornweg and Bhada-Tata (2012) [1], the average waste disposal rate is growing globally by over 0.3% per annum on account of higher waste production. This has aroused interest in extending the life of MSW landfills using piggyback construction, which involves an increase in the height of existing landfills within their initial footprint area.

However, unplanned expansion induces additional surcharge loading on highly compressible MSW constituents, causing differential settlements and eventually affecting the liner integrity, as reported by Stuglis et al. (1996) [2], Ling et al. (1998) [3] and Viswanadham and Jessberger (2005) [4]. The present study thus explores the possibility of compressing the existing waste volume by DC before landfill expansion to mitigate the above difficulties. Numerical modelling is conducted to achieve the above using the commercial software ABAQUS, Dassault Systems, ver. 6.14 [5]. The effect of waste compressibility, energy and tamper radius is investigated. Based on optimized design parameters, empirical equations are established to aid in decision making regarding the implementation of DC to MSW landfills. Additionally, the effectiveness of DC in piggyback construction is investigated and found to be effective.

2 Mesh details and methodology adopted

The mesh adopted for the axisymmetric FE model is shown in Fig. 1, which consists of two separate entities, the tamper (width equivalent to the radius, *r*) and MSW domain comprising of 24 m depth and 14 m width (measured from center-line of tamper). The tamper is assumed to be a flat based mass with a circular cross-section. The contact between the moving tamper and MSW is modelled using the classical Coulomb friction law. In the initial step of analysis, geostatic stresses are induced in MSW to achieve a state of equilibrium with exiting in-situ stresses at zero deformations. This is followed by the simulation of the first tamper drop on MSW, performed using the approach outlined by Pan and Selby (2002) [6] and Ghassemi et al. (2010) [7]. The tamper nodes are assigned an initial velocity in this regard, computed from the free-fall equation presented in Eqn. (1), where V_o is the tamper velocity at the moment of contact with ground surface, h represents the drop height and g is the acceleration due to gravity (= 9.81 m/s^2).

$$V_0 = (2gh)^{0.5} \tag{1}$$

As the tamper hits the MSW surface, it decelerates from initial velocity (V_0) to a stationary position, thereby completing one blow. The above process is repeated to model subsequent blows on MSW deposits. Further, to account for massive strains generated during DC based on the findings of Poran and Rodriguez (1992) [8] and Zekkos et al. (2013) [9], Arbitrary Lagrangian-Eulerian (ALE) remeshing approach within ABAQUS/Explicit module is adopted.

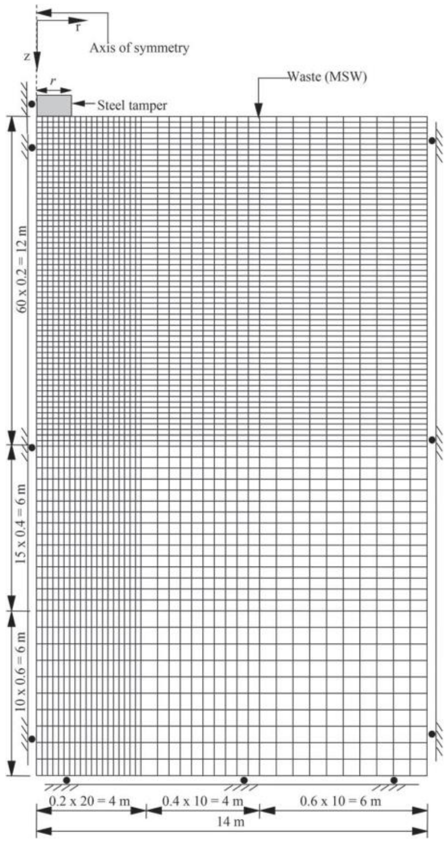

Fig. 1. FE mesh adopted in the study

3 Constitutive Law and Material properties

The physical and mechanical properties of waste materials are generally investigated by extending the concepts of conventional soil mechanics, owing to complexities involved in modeling diverse MSW refuse. Gu and Lee (2002) [10] and Ghassemi et al. (2010) [7] proposed an elasto-plastic constitutive law developed initially by DiMaggio and Sandler (1971) [11] for modeling impact loading on soils. The above constitutive law has been chosen in this study. The elasto-plastic constitutive law with volumetric hardening cap replicates the increase in material stiffness with successive tamper blows. As the above constitutive law is not in-built in ABAQUS, user-defined subroutine coded in FORTRAN language was fed as input in the analysis. The yield surface comprises of primarily two parts, a non-hardening Drucker-Prager shear yield surface (f_s) and an elliptical volumetric hardening cap (f_h). Within the yield surface, MSW is modelled as a non-linear elastic material using the bulk modulus (K) parameter. Details of the constitutive law are discussed in Kundu and Viswanadham (2016, 2018) [12, 13].

The above constitutive law involves parameters related to hardening cap (D, W, R), elastic behavior (ν, κ), Drucker-Prager yield surface (α, k) and initial void ratio (e). Derivation of the above parameters necessitate laboratory triaxial tests or hydrostatic tests on MSW. An alternative approach was adopted in the study as proposed by Gu and Lee (2002) [10] for DC on dry sands, wherein the constitutive parameters were determined through numerical simulation of 1D compression tests. It involves an iterative process using a wide range of hardening and elastic parameters until the vertical strain (ε_v) vs log vertical stress (σ_v) curves obtained from numerical and laboratory 1D compression tests coincide.

Table 1. Model parameters adopted in the FE analyses.

	Properties						
Waste type	$^*D$ (m^2/kN)	$^*W^a$	$^*R^a$	$^\#\alpha^a$	$^\#k$ (kPa)	κ^a	υ^a
MSW_HC [C_{ce} = 0.43]	0.008	0.55	4.33	0.22	40.96	0.0066	0.2
MSW_MC [C_{ce} = 0.19]	0.004	0.24	4.33	0.22	40.96	0.0050	0.2
MSW_LC [C_{ce} = 0.04]	0.004	0.05	4.33	0.22	40.96	0.0010	0.2

*: Work-hardening parameters; $^\#$: Drucker-Prager parameters; κ: Slope of the unloading line in the e-log p' curve; υ: Poisson's ratio; -^{a}: Dimensionless parameter; Lateral earth pressure coefficient (K_0) = 0.6.

Similar methodology was adopted, except that the vertical strain (ε_v) - log vertical stress (σ_v) plot is derived in this case from characteristic unit weight profile of MSW landfills suggested by Zekkos et al. (2006) [14] as an alternative to laboratory test data. Three waste compressibilities (C_{ce}) are considered in this case, viz. high (MSW_HC) (C_{ce} = 0.41), moderate (MSW_MC) (C_{ce} = 0.21) and low (MSW_LC) (C_{ce} = 0.04) with representative unit weights (γ_i) of 5, 10 and 15.5 kN/m^3 respectively. The material parameters involved in the constitutive model are derived in Kundu and Viswanadham (2020) [15] and are defined separately for each MSW type in Table 1. The mild steel tamper is modeled as an elastic material with Young's modulus of 210 GPa and Poisson's ratio of 0.303, as observed in the case of standard steel [13].

4 Parametric Studies

The following section investigates the effect of waste compressibility, tamper energy and tamper radius in optimizing the response of MSW landfill sites to DC-induced densification. At the outset, it is imperative to determine the optimum number of blows to be delivered in the field for different MSW compressibilities, as the efficiency of blows reduce with successive drops. As reported by Mayne et al. (1984) [16], the number of blows usually lie in the range of 8 to 12, although values as low as 2 to 5 have been reported. As reported in Kundu and Viswanadham (2020) [15], the optimum number of blows for wastes with C_{ce} = 0.41, C_{ce} = 0.21 and C_{ce} = 0.04 are 12, 8 and 5 respectively. The same is adopted in subsequent parametric studies.

The influence of MSW compressibility is investigated in terms of crater volume (V_c), as shown in Fig. 2. The energy, momentum and tamper radius are varied (range: 75 - 400 t-m for energy; 86 - 400 t-m/sec for momentum and 0.8 m - 2.4 m for radius) to observe the corresponding change with waste compressibility. A similar trend can be observed in each case irrespective of the magnitude of DC design parameters. This is followed by investigation of the effect of tamper energy on induced crater volume. As suggested by Lee and Gu (2004) [17], the momentum delivered during tamper drop plays an equally important role in governing the overall efficiency of DC. Hence, in this study, the significance of energy and momentum is studied in conjunction with each other, corresponding to various compressibility ratios of wastes. The results are presented in Fig. 3, which indicate that the effect of momentum is more pronounced across different energy levels and waste compressibility. The radius of the base area of tamper used in DC is also an important design parameter guiding the efficiency of the process. The corresponding variation of crater volume with radius is shown in Fig. 4, which depicts an increasing trend of 11% - 43% with an increase in tamper radius. However, beyond a radius of 1.6 m, the reduction in waste volume is marginal. The optimized design parameters thus obtained are used to develop an empirical equation [Eqn (2)] indicating the probable crater volume in the field.

$$V_c = 1.64\ C_{ce}^{1.5}\ m^{1.05}\ h^{0.6}\ r^{0.3} \quad (2)$$

In Eqn (2), V_c is the crater volume in m^3, C_{ce} is the compression ratio of MSW and m, h and r represent the mass (in t), the height of fall (in m) and radius (in m) of tamper respectively. Finally, the settlement induced at the ground surface (δ_s) is calculated based on computed crater volumes and area of influence (A) as presented in Eqn (3).

$$\delta_s = V_c/A = (1.64/A)\ C_{ce}^{1.5}\ m^{1.05}\ h^{0.6}\ r^{0.3} \quad (3)$$

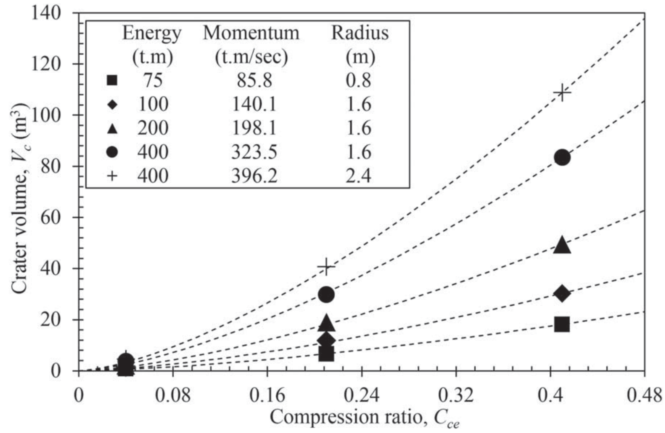

Fig. 2. Influence of MSW compressibility

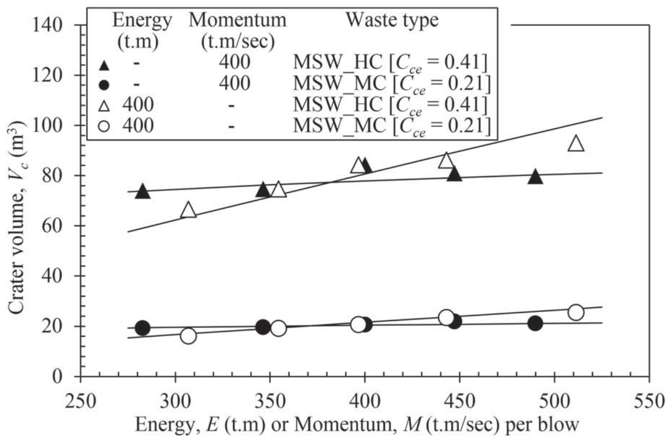

Fig. 3. Influence of tamper energy and momentum

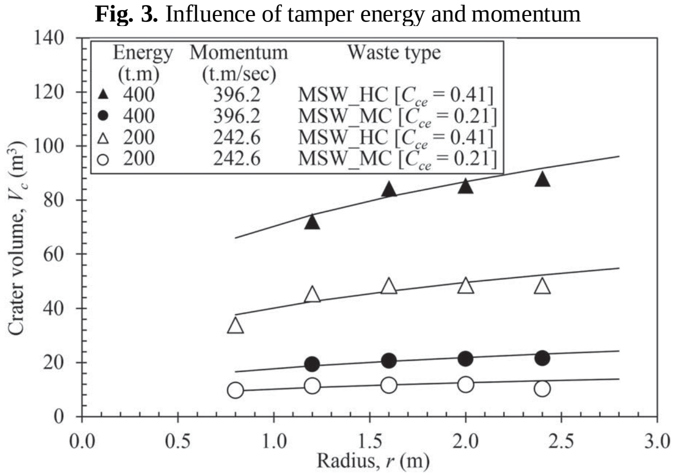

Fig. 4. Influence of tamper energy and momentum

5 Validation of Predicted Results with Field Case Studies

In order to examine the validity of the proposed empirical equation, the settlement values of waste materials computed on the basis of Eqn (3) are compared with field observations presented in Table 2, based on selected case histories compiled by Zekkos et al. (2013) [9]. In this case, compression ratios (C_{ce}) specific to the cases investigated were not mentioned in the research database, although the corresponding age of MSW was presented. Hence, compression ratios have been assumed based on the correlation between MSW age and C_{ce} as outlined in Chen et al. (2009) [18]. As evident from the results compared in Fig. 5, majority of the fitted data points lie above the linear trend line of 1V:1H inclination, implying that the empirical equation is predicting conservative settlement values. The scattering of few data points may be attributed primarily to the heterogeneous nature of MSW existing at the site, exhibiting variable compressibility with depth, and on the assumption of C_{ce} values on the conservative side based on the findings of Chen et al. (2009) [18]. However, as the scattering is observed above the 1V:1H line, the design approach is considered to be conservative, and can be accepted for all practical purposes in the field. Utilizing the above concept, an overview of the effectiveness of DC in facilitating vertical landfill expansion is discussed subsequently.

Table 2. Summary of MSW parameters used in validation.

Sl. No.	Reference	Energy (t-m)	Momentum (t-m/sec)	[a]Radius (m)	Age of waste (years)	[b]C_{ce}
1	Charles et al. (1981) [19]	196	232	1.4	40	0.11
2	Charles et al. (1981) [19]	300	297	1.4	15	0.16
3	Charles et al. (1981) [19]	300	297	2.0	17.5	0.16
4	Welsh (1983) [20]	504	422	1.3	6	0.21
5	Lukas (1985) [21]	69	90	0.6	30	0.13
6	Swain and Holt (1987) [22]	225	257	1.4	20	0.15
7	Perelberg et al. (1987) [23]	251	287	2.3	10	0.18
8	Perelberg et al. (1987) [23]	167	234	2.3	10	0.18
9	Perelberg et al. (1987) [23]	167	234	2.3	10	0.18
10	Perelberg et al. (1987) [23]	167	234	2.3	10	0.18
11	Perelberg et al. (1987) [23]	251	287	2.3	10	0.18
12	Gifford et al. (1992) [24]	300	297	1.7	20	0.15
13	Schexnayder and Lukas (1992) [25]	233	288	0.9	8	0.19
14	Woodward-Clyde (1995) [26]	800	626	1.3	44	0.11
15	Yee (1999) [27]	280	277	1.9	5	0.22

[a]$r = S/3.5$: S is print spacing; [b]Based on age of wastes as per Chen et al. (2009) [18]

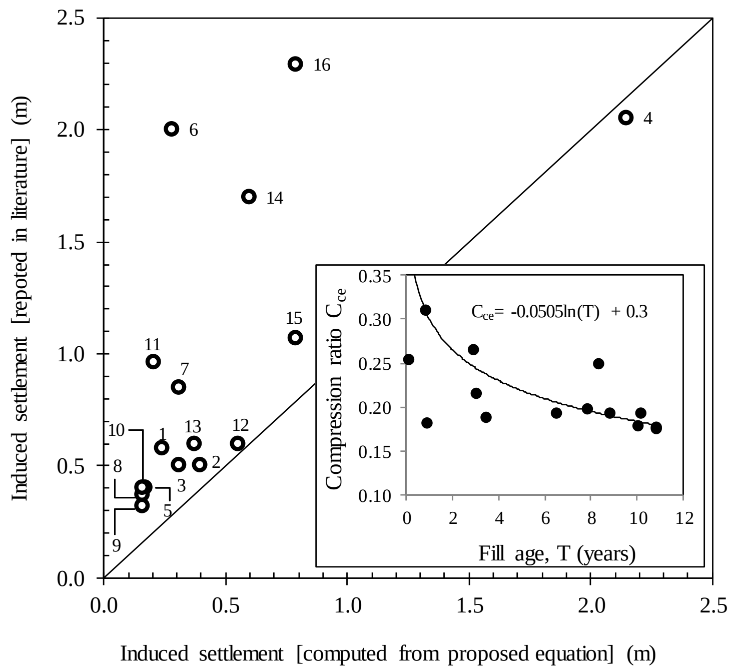

Fig. 5. Comparison of settlement values in MSW landfills with field results

6 Efficacy of DC in vertical landfill expansion

The effectiveness of DC in piggyback landfill construction has been demonstrated in the present study with the help of a case study reported by Chen et al. (2009) [18]. The study involves primarily the settlements anticipated in an existing landfill in Qizhishan region, China as a result of possible vertical expansion of 40 m height within the initial footprint area of the existing landfill system. As reported by Chen et al. (2009) [18], subsequent application of surcharge pressure on the uncompacted landfill in league with piggyback construction can result in huge settlements of about 5.8 m corresponding to a C_{ce} value of 0.20 for the underlying MSW, which is detrimental as far as landfill liner integrity issues are concerned. With an aim to reduce the settlements incurred due to landfill expansion, five possible cases of DC are considered in the present study on the existing MSW landfill by varying the energy, momentum and radius of tamper to replicate different field conditions. The average settlements predicted from Eqn (3) for the landfill under consideration in all the five cases after execution of DC is plotted in Fig. 6, which indicates that, by choosing various ranges of energy, momentum and tamper radius close to actual field conditions, substantial settlement can be induced by DC in the existing landfill system prior to application of vertical surcharge due to piggyback expansion.

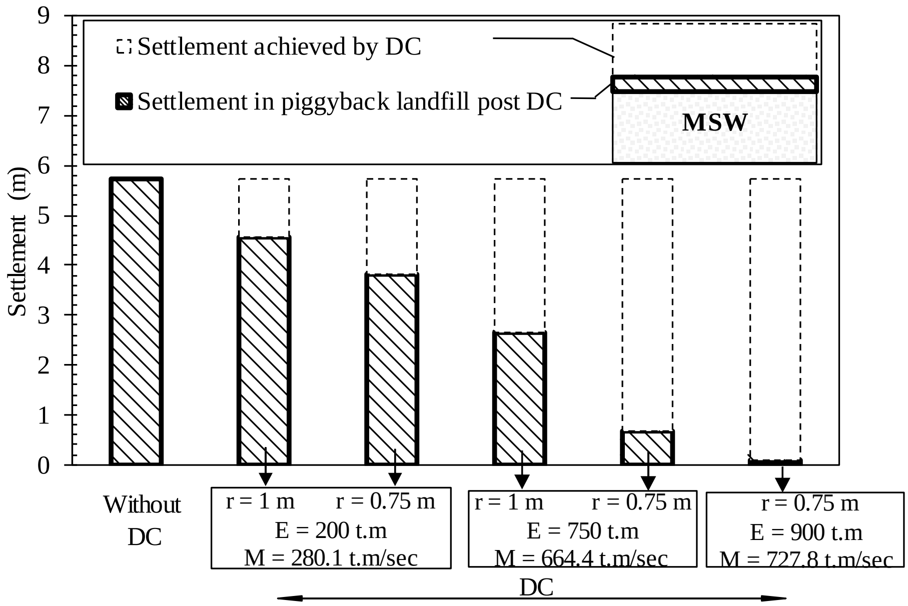

Fig. 6. Effectiveness of DC in vertical expansion of landfills (C_{ce} = 0.2)

As for example, for this particular MSW landfill site, the average settlement induced by DC for an energy level (*E*) of 900 t-m, momentum (*M*) of 727.8 t-m/sec and tamper radius (*r*) of 0.75 m is close to 5.8 m, which is equal to the settlement expected in uncompacted landfill after piggyback construction. The study hereby highlights that if the existing landfill system is subjected to DC induced settlements prior to expansion, application of subsequent surcharge loading for piggyback landfill construction will lead to negligible compression of underlying MSW, and overall stability of the system will be retained. As a consequence, the settlement experienced by the bottom liner will be almost negligible, thereby maintaining its integrity.

7 Conclusions

The present study aims at investigating the efficacy of DC process in reducing the volume of MSW accumulated with time. The study is especially relevant in the contemporary world owing to acute shortage of space encountered within the urban areas, which makes it challenging to find new landfill sites for further waste disposal. Finite element based studies was conducted in this regard using the commercial software ABAQUS (ver. 6.14), by employing the Drucker-Prager constitutive law and arbitrary Lagrangian-Eulerian (ALE) remeshing approach. The results indicated volumetric compression and densification of wastes under the impact of DC for various ranges of tamper energy, tamper radius and waste compressibility. An empirical equation was developed based on optimized design parameters to provide an insight regarding the mass of tamper and height of fall to be chosen at the site to achieve a desired level of waste reduction in a typical MSW landfill. The equations aid in focussing the efforts of expensive field trials, thereby economizing the project. The validity of the developed equation in predicting DC induced settlement of MSW landfills was established by comparing the predictions with selected field case histories. Additionally, the effectiveness of DC in vertical landfill expansion or piggyback construction was investigated and found to be effective. The present research thus establishes applicability of DC in enhancing the storage capacity of MSW landfills for further waste disposal, thereby extending the design life of existing landfills. Additionally, it explores the possibility of reclamation of MSW sites for future infrastructural projects.

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