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Seismic characterization and dynamic site response of a municipal solid waste landfill in Bangalore, India

P Anbazhagan[1], GL SivakumarBabu[1], P Lakshmikanthan[2] and KS VivekAnand[1]

Abstract

Seismic design of landfills requires an understanding of the dynamic properties of municipal solid waste (MSW) and the dynamic site response of landfill waste during seismic events. The dynamic response of the Mavallipura landfill situated in Bangalore, India, is investigated using field measurements, laboratory studies and recorded ground motions from the intraplate region. The dynamic shear modulus values for the MSW were established on the basis of field measurements of shear wave velocities. Cyclic triaxial testing was performed on reconstituted MSW samples and the shear modulus reduction and damping characteristics of MSW were studied. Ten ground motions were selected based on regional seismicity and site response parameters have been obtained considering one-dimensional non-linear analysis in the DEEPSOIL program. The surface spectral response varied from 0.6 to 2 g and persisted only for a period of 1 s for most of the ground motions. The maximum peak ground acceleration (PGA) obtained was 0.5 g and the minimum and maximum amplifications are 1.35 and 4.05. Amplification of the base acceleration was observed at the top surface of the landfill underlined by a composite soil layer and bedrock for all ground motions. Dynamic seismic properties with amplification and site response parameters for MSW landfill in Bangalore, India, are presented in this paper. This study shows that MSW has less shear stiffness and more amplification due to loose filling and damping, which need to be accounted for seismic design of MSW landfills in India.

Keywords

MSW landfills, shear wave velocity, cyclic triaxial tests, ground motion, amplification, site response analysis

Introduction

Landfills located in seismic hazard zones are exposed to cyclic loads during earthquakes and the study of dynamic behaviour under such conditions is essential in the engineered design of landfills. Potential failure of a landfill during an earthquake not only produces seismic hazard-related losses but also causes health problems from the exposed waste. Failure of municipal solid waste (MSW) fills also affects functioning of other associated gas extraction facilities. Several seismic responses and stability analysis were carried out in India for typical civil/geotechnical-related projects. However, limited attempts have been made to characterize MSW landfill and to understand seismic response of the landfill waste mass. In this study site, response studies have been carried out by detailed *in situ* characterization of MSW in order to evaluate the seismic performance of the MSW landfills.

One-dimensional (1-D) site response analysis of MSW was performed by several researchers (Hashash and Park, 2001; Idriss, 1990; Idriss and Seed, 1968; Kramer, 1996; Roesset, 1977) in order to account for the effects of ground motion propagation during an earthquake. The assessment of dynamic properties of MSW is imperative for performing reliable seismic response analysis and efficient design of landfills. The seismic hazard at a place refers to the peak ground acceleration (PGA) at that location produced by a single earthquake or multiple earthquakes of different magnitude and occurrence. The most important MSW parameters required to perform seismic response analysis are shear wave velocity (V_s), unit weight of MSW and the strain-dependent normalized shear modulus reduction (G/G_{max}) relationships and the material damping ratio function. The shear modulus (G), which relates shear stresses to shear strains, is an important material property in the evaluation of dynamic response of MSW. The dynamic properties of MSW landfills are site specific and vary spatially across boundaries, with the respective waste treatment and management practices adopted. Though many researchers (Augello et al., 1998a; Matasovic and Kavazanjian, 1998; Zekkos et al., 2008) have studied the site response of MSW landfills by performing field tests or by back-calculations in several parts of the world, the present study is the first of its kind to be performed on Indian

[1]Department of Civil Engineering, Indian Institute of Science, Bangalore, India
[2]Centre for Sustainable Technologies, Indian Institute of Science, Bangalore, India

Corresponding author:
P Lakshmikanthan, Centre for Sustainable Technologies, Indian Institute of Science, Bangalore 560012, India.
Email: lakshmikanthancp@gmail.com

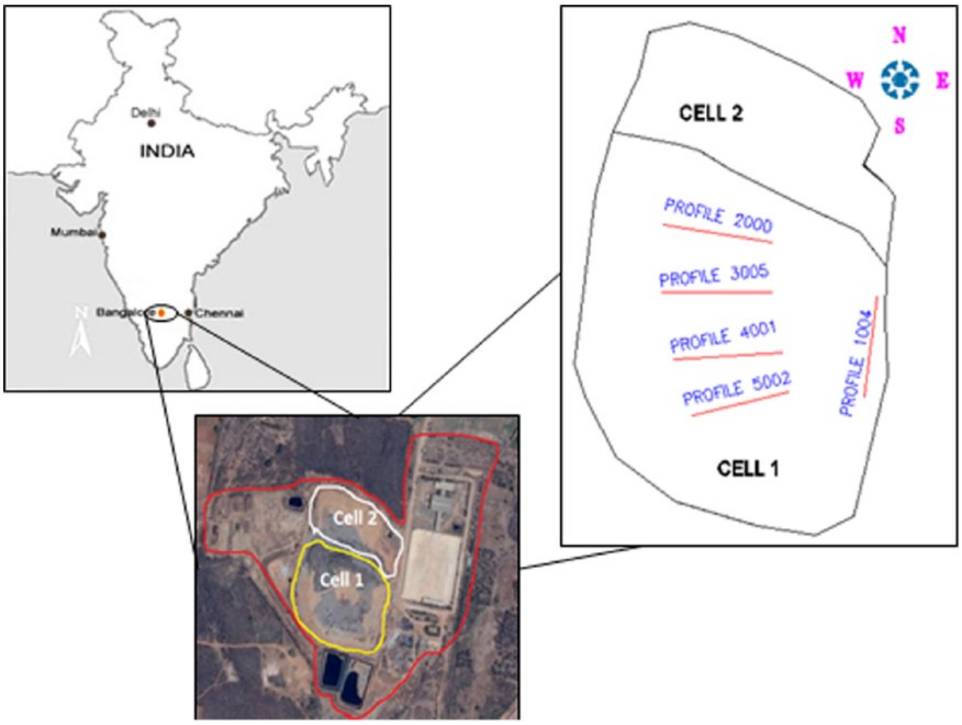

Figure 1. Google map image showing a Mavallipura landfill site with cell 1 and cell 2, and also showing the multichannel analysis of surface waves (MASW) test locations.

MSW landfills. The shear wave velocity is measured in the field using multichannel analysis of surface waves (MASW) in the present study. MASW is increasingly being applied to earthquake geotechnical engineering for microzonation and site response studies (Anbazhagan and Neaz Sheikh, 2012; Anbazhagan et al., 2010, 2013). Limited study has been done to characterize MSW landfill by MASW testing. Recently, Zekkos et al. (2014) presented shear wave velocity of MSW sites using spectral analysis of surface waves (SASW) and compared that with other methods too. In general, limited laboratory and field investigations are performed on MSW primarily due to the difficulties in performing such tests. Such difficulties include the health issues associated with testing waste material, sample disturbance and the large test specimens required in order to include the larger waste particles (Zekkos et al., 2006). Cyclic triaxial testing has been performed on MSW retrieved from Mavallipura landfill in the laboratory and the required MSW dynamic parameters are estimated. These include the field measurement using MSAW and about 50 laboratory cyclic triaxial tests. The MSW properties determined in the field and in the laboratory, and the recorded ground motions, are used as inputs to perform non-linear 1-D seismic response analysis. The waste behaviour is approximated using elastic shear modulus and viscous damping. DEEPSOIL software has been used in this study for performing 1-D non-linear site response analysis.

Site characteristics of MSW collection and field measurements

The MSW used in this study is the compost reject collected from the Mavallipura Landfill site, Bangalore, India (Figure 1), and is referred to as MSW in this paper. The site is spread over 30 acres and is divided into cell 1 (6 acres) and cell 2 (2 acres). The height of the landfill is more than 10 m. The landfill is covered with 10–20 cm of natural soil and the liner system consists of a clay layer according the landfill operators. Composting has been adopted as a potential pre-treatment method. Hand sorting of recoverable waste was followed by aerobic windrow composting for a period of 2 months. The compost reject had particle sizes varying from 4 to 35 mm. The particles of size >20 mm, mostly consisting of large plastics, rubber shoes, leather bags and other inert materials, were hand sorted or removed by other mechanical procedures. As it was difficult to separate particles <20 mm, these were filled directly. Therefore, particles of size <20 mm were used in the laboratory for characterization and testing. The compost reject contained 6.34% clothes, 28% plastics, 1.28% glass, 0.8% leather, 5.56% coconut, 1.96% stones, 0.88% rubber, 0.16% wood and 54.2% organic matter. The moisture content of the waste was calculated as the ratio of the weight loss of the weight that remained after heating at a temperature of 60°C until the specimen has dried to a constant mass. The natural water content of the sample was found to be 20%. The test for total volatile solids was performed according to the APHA 1965 (American Public Health Association) standard methods. The organic content of the compost reject <10 mm particle size was calculated as the ratio of the weight loss of the initial specimen weight after heating to a temperature of 550°C in a muffle furnace. The initial decomposable organic content of the waste was found to be 55% and the inerts constituted 45%.

Kavazanjian et al. (1996) measured the shear wave velocity profiles from eight California MSW landfills and the values ranged from 80 m s^{-1} near the surface to 300 m s^{-1} at a depth of 30 m. Sharma et al. (1990) studied the characteristics of San Pablo Bay landfill, Richmond, California, and reported an average shear wave velocity of 198.3 m s^{-1} at a depth of 15.3 m. Carey et al. (1993) reported a shear wave velocity ranging between 185 and 478 m s^{-1}. Most of the studies have revealed an increasing profile of shear wave velocity with depth of the landfill. The shear wave velocity (V_s) of MSW in a landfill can be measured *in situ* by various methods. The down-hole method, cross-hole method (SASW) and MASW are some methods successfully used in the determination of V_s. A summary of various methods used for measuring V_s of MSW is given by Zekkos et al. (2014) with a model to predict V_s as function of depth of MSW.

In the present study, surface wave-based method of active MASW survey has been carried out to develop a dispersion curve of MSW. The MASW system consisting of a 24-channel geode seismograph with 24 geophones of 2 Hz capacity is used in this investigation. The seismic waves were created by an impulsive source of 15 pounds (sledgehammer) with 300×300-mm size hammer plate with 10 shots. These waves are captured by the vertical geophones/receivers and further analysed by inversion. Twenty-four geophones are arranged linearly and the sources are kept on one side of the MASW line. Figure 2 shows the arrangement of geophones during a field survey along the lines shown in Figure 1 in cell 1. A geophone spacing of 1 m and source distances of 4, 8 and 12 m are used. Surface wave records are used to extract a dispersion curve and to estimate the shear wave velocity. A typical dispersion curve obtained from a multichannel record is shown in Figure 3. Shear wave velocities of each location were inverted from respective dispersion curves. The shear wave velocity obtained from MASW technique is comparable with the cross-hole and up-and-down-hole seismic methods with errors of 8–15% (Park et al., 1999). The shear wave velocity profile obtained from the MSW landfill is shown in Figure 4. The measured V_s varied from 53 m s^{-1} near the surface to 522 m s^{-1} at a depth of 70 m. This study shows that the investigated MSW has the lowest V_s value of 53 m s^{-1} at the surface and the highest V_s value of 125 m s^{-1} at 20 m depth. The depth of the MSW fill is not of uniform thickness, as the fill site was a valley before filling the MSW. The shear wave velocity values obtained from the Indian landfill are comparable with the lower side of the V_s values summarized by Zekkos et al. (2014). This lower value may be attributed to loose filling and the composition of MSW, which significantly affects the *in situ* V_s values. The composition of the waste at the site varies spatially and the waste fill was compacted using rollers. The site is sloped from the south towards the north side. In this study, an average shear wave velocity of 56 m s^{-1} at depth of 10 m was considered for the initial dynamic shear modulus (G_{max}) calculations and in developing normalized shear modulus curves.

Dynamic properties and model

Seismic response analysis of MSW requires representative dynamic properties and models, i.e. shear modulus reduction

Figure 2. Multichannel analysis of surface waves (MASW) system geophones set-up in the municipal solid waste (MSW) fill.

and damping ratio variation with strains. Many researchers have used cyclic triaxial or resonant column tests to derive shear modulus and damping parameters of soil samples, but very limited study has been carried to develop an MSW dynamic model. Augello et al. (1998b), Elgamal et al. (2004), Idriss et al. (1995), Matasovic and Kavazanjian (1998), and Morochnik et al. (1998) recommended strain-dependent normalized shear modulus reduction (G/G_{max}) and material damping relationships for MSW. Most of these studies were primarily based on back analysis of the seismic response of landfills and a summary of these studies can be found in Zekkos et al. (2008). Zekkos et al. (2008) carried out cyclic triaxial tests for different composites of MSW with a particle size <20 mm and presented dynamic properties and model by combining their study with previous studies.

Cyclic triaxial testing has been adopted as the test method in this study for the analysis of the dynamic properties of MSW in the laboratory. The testing instrument and samples tested are shown in Figures 5a and 5b. Strains in the range of 10^{-3}% to 1% can be measured in the cyclic triaxial apparatus. MSW samples of particle size <20 mm with a unit weight of 10.3 kN m^{-3} and moisture content 44% were used for laboratory testing. Stress-controlled tests with a sinusoidal loading pattern were conducted at two confining stresses (100 and 150 kPa) in the laboratory. More than 50 cyclic triaxial tests were conducted according to ASTM D 3999-91 and ASTM D 5311-92 in the laboratory to develop the normalized shear modulus reduction and damping ratio relationships.

Shear modulus and damping values estimated for each test have been compiled and normalized using initial low strain shear modulus and damping. These values are plotted in the existing shear modulus and damping curve summary. The normalized shear modulus reduction and damping ratio curves are presented in Figures 6a and 6b. The G/G_{max} values obtained in this study fall close to the upper bound of previous studies. Although the results are obtained from limited laboratory and field tests in this study,

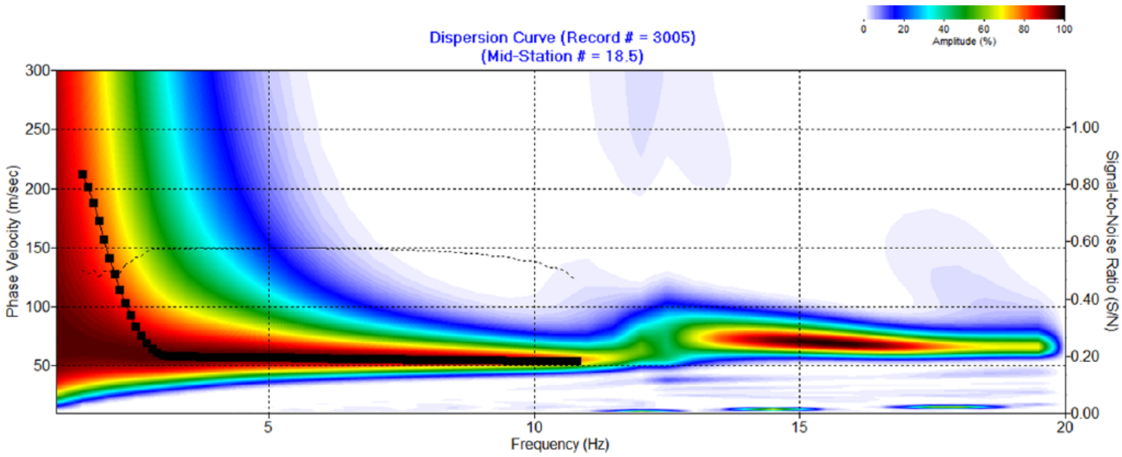

Figure 3. Typical dispersion curve from multichannel analysis of surface waves (MASW) survey.

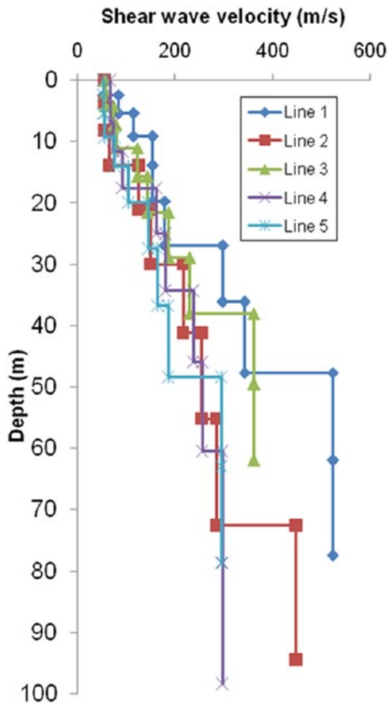

Figure 4. Shear wave velocity from multichannel analysis of surface waves (MASW) survey.

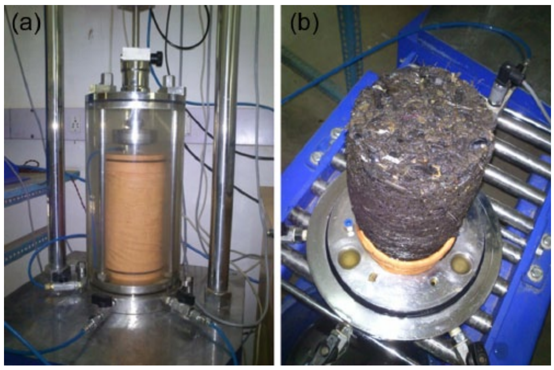

Figure 5. (a) Dynamic testing of municipal solid waste (MSW) sample in cyclic triaxial apparatus and (b) MSW sample in triaxial mould.

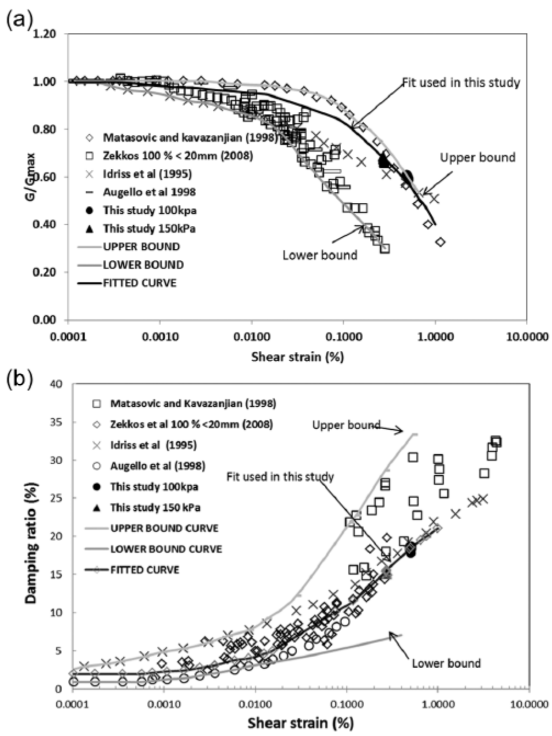

Figure 6. (a) G/G_{max} curves of the present study and previous studies; (b) damping ratio relationship of present study and previous studies.

a modulus reduction curve for the site has been artificially generated considering experimental results and previous studies. Figure 6a shows shear modulus reduction curve generated for the seismic analysis of MSW site and similarly damping values are also plotted along with the literature values in Figure 6b. Damping values of the site are average value of upper and lower bound values in the literature. In this study, the shear modulus and damping curve based on experimental results and literature values are used for site response study of MSW landfill.

Selection of input ground motions

It is generally recognized that the selection of appropriate input ground motion is one of the main aspects in a site response analysis of MSW landfill site. Several site response studies were carried

Table 1. Summary of input ground motions used in the study.

Earthquake name	PGA (g)	Epicentre Distance (km)	Magnitude (Mw)	File names used
Saguaney 1988	0.121	115.827	5.6	a1_enr
Saguaney 1988	0.051	147.615	5.6	a2_enr
Saguaney 1988	0.174	105.068	5.6	a7_ent
Saguaney 1988	0.124	124.192	5.6	a8_enr
Saguaney 1988	0.056	164.996	5.6	a9_en2
Saguaney 1988	0.057	148.398	5.6	a10_ent
Saguaney 1988	0.126	112.940	5.6	a20_enr
Quebec 2005	0.070	29.696	5.4	A61-2005
Quebec 2005	0.084	13.300	5.4	A21-2005
Virginia 2011	0.098	53.500	5.8	Virginia

Note: PGA values are at 2% probability of exceedance in 50 years.

out in MSW, but most of them were carried for sites in the inter plate region. In this study, for the first time a site response study of a MSW landfill in an intraplate region was attempted. The selection of time histories includes records that closely match the site tectonic environment, controlling earthquake magnitudes and distances, local site conditions, response spectral characteristics, and for geotechnical evaluations, duration of strong ground shaking. The study area is close to Bangalore, which is a part of the 'stable continental region' (SCR) and South India. There are significant damaging earthquakes in this 'stable' region of Peninsular India (PI), e.g. Bhuj (2001, Mw 7.6), Koyna (1967, M 6.5), Latur (1993, Mw 6.1) and Jabalpur (1997, Mw 5.8) (Anbazhagan and Neaz Sheikh, 2012; Anbazhagan et al., 2012, 2014). Anbazhagan et al. (2009) carried out a probabilistic seismic hazard analysis of Bangalore city and suggested a PGA value of 0.121 g corresponding to a 2% probability of exceedance in 50 years. These were intraplate earthquakes and are reported in previously unknown seismic activity regions or unknown faults. These earthquakes also caused considerable damage close to the epicentre and far distance. However, recordings of these earthquake events are not available due to poor instrumentation, except the Bhuj event, which was recorded at a building. There is literally no acceleration time history data available in Peninsular India that can be used for site response and amplification estimation in SCR sites. Hence, in this study, intraplate recordings from around the world have been screened and recordings suitable for the study area are selected. About 10 intraplate ground motion records available in the range of PGA values were identified and used in this study. A summary of selected ground motions are given in Table 1. It can be noted here that these data were well distributed with respect to rock level PGA values and duration. These data are given as input at each MSW column and its site-specific response has been estimated at the surface of MSW.

Identification of dynamic parameters

MSW properties required for seismic analysis are unit weight, shear wave velocity and the normalized shear modulus reduction and damping curve relationships. Determination of the site-specific unit weight of the MSW column in a landfill is necessary. The unit weight in the field varies according to the composition of MSW and the compaction efforts adopted. Generally, field tests are performed in order to find the unit weight profile of MSW in landfills. Matasovic and Kavazanjian (1998) reported unit values ranging of 14–18 kN m^{-3} down to a depth of 10 m. Zekkos et al. (2006) compiled large-scale *in situ* unit weight test data from MSW landfills of different countries and reported that the majority of values ranged between 8 and 16 kN m^{-3} down to a depth of 60 m. It was observed from the present study that the unit weight of MSW increased with depth and a similar trend was reported by Zekkos et al. (2008) and Matasovic and Kavazanjian (1998). In this study, the unit weight of MSW was assumed based on the shear wave velocity, which is well within the Zekkos et al. (2008) recommendation. The densities of geotechnical materials are estimated considering shear wave velocity and density relationship proposed by Anbazhagan et al. (2015). These values also concur with Boore (2007) density values in the unpublished report. Shear wave velocity and density are used to generate a 1-D column for site response analysis. Each column consists of MSW and is followed by composite material taken as sand and hard stratum or rock layer. Five 1-D columns generated from the data are shown in Figure 7. It can be noted from Figure 7 that the MSW at the site has a thickness varying from 13 to 27 m, followed by sandy soil having a thickness of 22–42 m, below which is a hard stratum or rock layer having a V_s value of about 300 m s^{-1}. Dynamic models for MSW, i.e. the normalized shear modulus reduction (G/G_{max}) and damping ratio curves developed from the laboratory cyclic triaxial test results and literature values, are shown in Figure 8. The developed G/G_{max} curve is comparable with the results of Zekkos et al. (2008). The difference in damping value may be attributed to waste composition in Indian MSW. Most of the waste in MSW landfill is biodegradable and has high damping values. Five subsurface profiles with dynamic model and input ground motions are used to estimate the seismic response parameters, as discussed in the next section.

Seismic response analysis of MSW

Site response analysis is used to predict the response of each subsurface layer subjected to an earthquake ground motion. Several

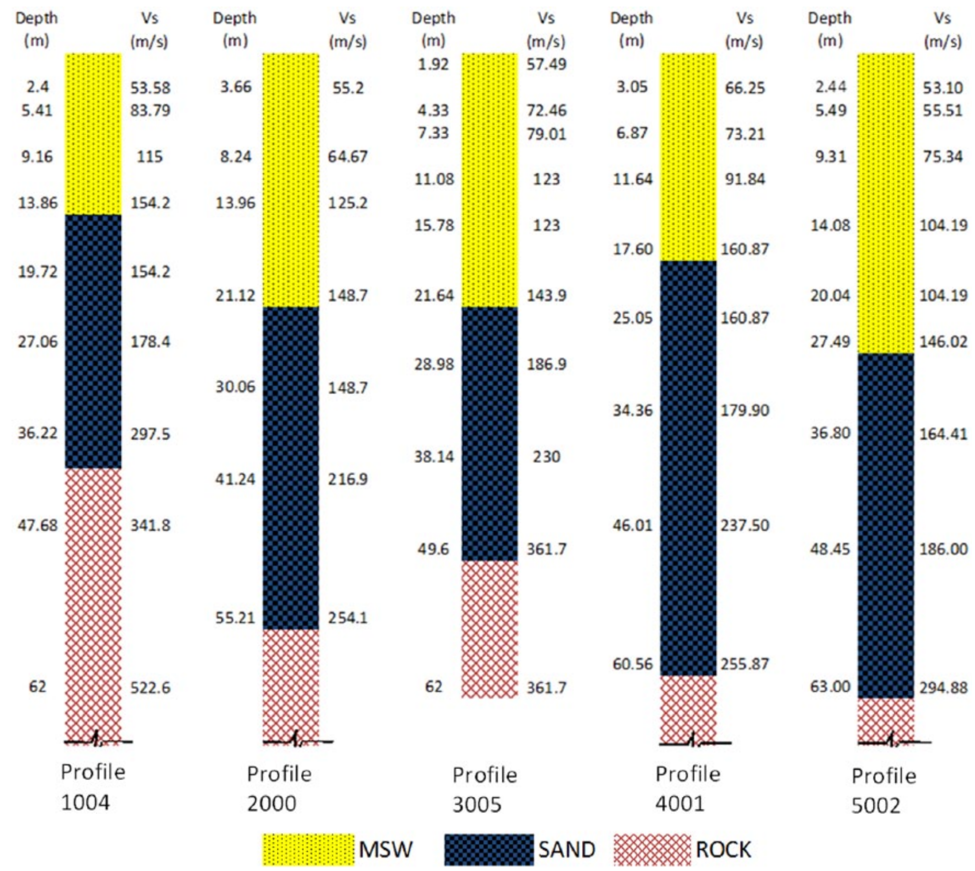

Figure 7. Municipal solid waste (MSW) columns generated for site response analysis.

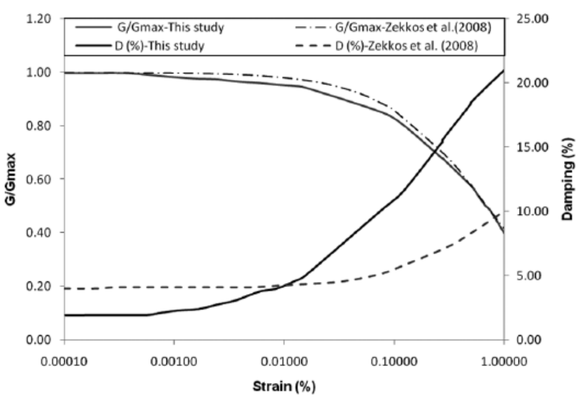

Figure 8. G/G_{max} and damping ratio curves from the present study and Zekkos et al. (2008).

site response studies were carried out on subsurface soil profiles and very limited studies are available for response estimation of MSW landfill sites. An MSW landfill site consists of MSW fill followed by a filled soil layer and hard stratum. The response analysis of MSW sites is expected to be different from routine soil site response studies, as there is a significant change in MSW dynamic properties and dynamic models when compared with soils. Even though dynamic response parameters are required for the safe design of landfills and associated amenities, systematic dynamic response analysis of MSW sites is very limited. The seismic response of MSW landfills is a function of the height of the fill, stiffness of the fill, dynamic properties of refuse, presence of clay liners, refuse geometry and the characteristics of the base motion (Singh and Sun, 1995). These findings were also confirmed by Bray et al. (1995) through equivalent linear analysis of several MSW sites with different foundation conditions and rock motions. Rathje and Bray (2001) carried out the 1-D and 2-D dynamic response analysis, and found that 1-D equivalent linear analysis provides a conservative estimate of the seismic loading; however, caution is warranted for shallower sliding surfaces where topographic amplification is enhanced during seismic loading. Psarropoulos et al. (2007) highlighted that dynamic response of MSW landfills is a complex dynamic soil–structure interaction problem and proper seismic design of landfills requires site-specific seismological conditions, the specific local site conditions and the individual characteristics of each landfill. Choudhury and Savoikar (2009) carried out equivalent linear analysis of typical MSW landfills considering different acceleration and periodic ground motions. They have reported that the assumption of constant unit weight and shear wave velocity for landfills underestimates the variation of maximum horizontal acceleration (MHA), normalized stresses and amplification ratio. It can be noted from the literature that most of the MSW response analyses were carried out by considering the equivalent linear approach and highlighted the importance of the site-specific study. In this study, for the first time an attempt has been made to estimate the seismic response of MSW landfills by non-linear analysis with site-specific data.

The site-specific data discussed in the previous sections are modelled in DEEPSOIL to obtain 1-D non-linear response parameters. Fully non-linear analysis are preformed in the time domain, where shear modulus (G) and damping (ξ) vary throughout the duration of loading. DEEPSOIL also includes: (1) a non-linear constitutive model developed by Matasović and Vucetic (1993); (2) a pressure-dependent hyperbolic model (Hashash et al., 2011), used to obtain the fitted non-linear curves for the site-specific shear modulus-reduction and damping ratio curves given in Figure 8; and (3) estimation of the reduction factor, developed by Phillips and Hashash (2009) that modifies the extended Masing hysteretic behaviour to match the shear modulus-reduction and damping ratio curves simultaneously over a wide range of shear strains (Kaklamanos et al., 2015). The seismic response is studied by examining surface acceleration time history, response spectra and the maximum strain at each location of the landfill. The input ground motion and estimated surface acceleration time history are compared with the predicted responses generated for the five profiles and 10 ground motions. Figure 9 shows the typical input and surface ground motion for profile 5. It can be observed from Figure 9 that input motion has undergone considerable amplification, and changes in amplitude, frequency and duration are noticed. A similar phenomenon is also observed for all remaining profiles and input motions. The response spectra for five sites and with 10 input response spectra are given in Figure 10. Figure 10 shows that MSW column modifies the input motion considerably and results in amplification. It can be observed from Figure 10 that the peak spectral acceleration is noticed before 0.5 s in the input motion as well as in surface motion, which is different from the spectral signature of interplate MSW sites. A few input motions show multiple spectral peaks at the surface due to shallow hard stratum reverberation. This study shows that amplification and spectral signature of intraplate MSW fill is different from interplate MSW sites, which need to be accounted for in seismic design of intraplate MSW landfill sites. An intraplate earthquake occurs in the interior of a tectonic plate, whereas an interplate earthquake is one that occurs at a plate boundary. The input motion and response acceleration with depth for a typical ground motion are shown in Figure 11. The plot of acceleration on top of each layer shows that the input acceleration is lightly amplified due to the composite layer at bottom of the MSW. Considerable amplification is noticed from the top of composite layer to the top of the MSW. The presence of a composite layer, i.e. medium to dense soil above bedrock, is enhancing the amplification of MSW, which was also highlighted by Choudhury and Savoikar (2009). Repetto et al. (1993) reported that the higher MHA values were observed at the top of landfills when compared with the bedrock MHA values for low levels of excitation <0.2 g, particularly for low landfill with heights less than 30 m, and suggested that permanent deformations may occur

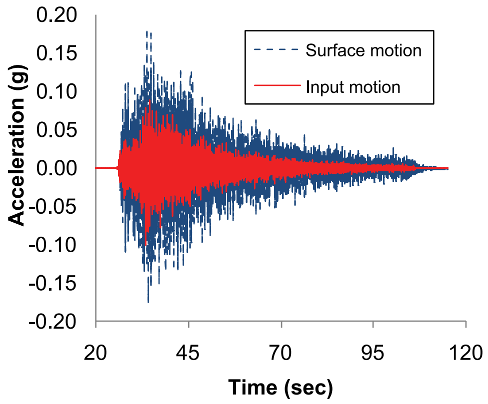

Figure 9. Typical input and surface ground motion for intraplate municipal solid waste (MSW) site.

in the waste cover system than in the bottom liner system. A site response study of intraplate landfill site response also showed similar conclusions, but the spectral signature of intraplate MSW sites is different from Repetto et al. (1993). This study shows that the landfill underlined by a composite layer and rock can cause amplification for lower and intermediate levels of shaking. Amplification values observed in the present study are comparable with shallow bedrock site amplification values reported by Anbazhagan et al. (2011) and are different from 30-m-based amplification values. Although the results obtained from this study are similar to other seismic site response studies with respect to amplification, the response analysis of the several MSW sites is required in order to arrive at the amplification factor and spectral signature of intraplate MSW sites.

Conclusions

The lack of data availability of the dynamic properties of MSW and site response of MSW landfills in Indian has led to the execution of this work. A 1-D non-linear site response study was carried out at five MSW column profiles at Mavallipura landfill. Seismic analysis of MSW landfills required the determination of the dynamic properties of MSW such as the unit weight, shear wave velocity, and the normalized shear modulus reduction and damping ratio curve relationships. The cyclic characteristics of the MSW were established based upon field and laboratory testing. The shear wave velocity profile for the MSW was measured using an MASW survey and the waste density was estimated considering V_s values. The unit weight profiles of MSW and underlying layers were calculated based on the shear wave velocities measured in the field. The normalized shear modulus reduction and damping ratio curves for MSW were developed based on a combination of laboratory cyclic triaxial test results and published literature values. Ten intraplate input motions were selected considering seismicity of the study area in Bangalore, India, and were used for site response analysis. A 1-D non-linear site response was carried out and surface spectral parameters are estimated. This study shows that shallow MSW fill undergoes

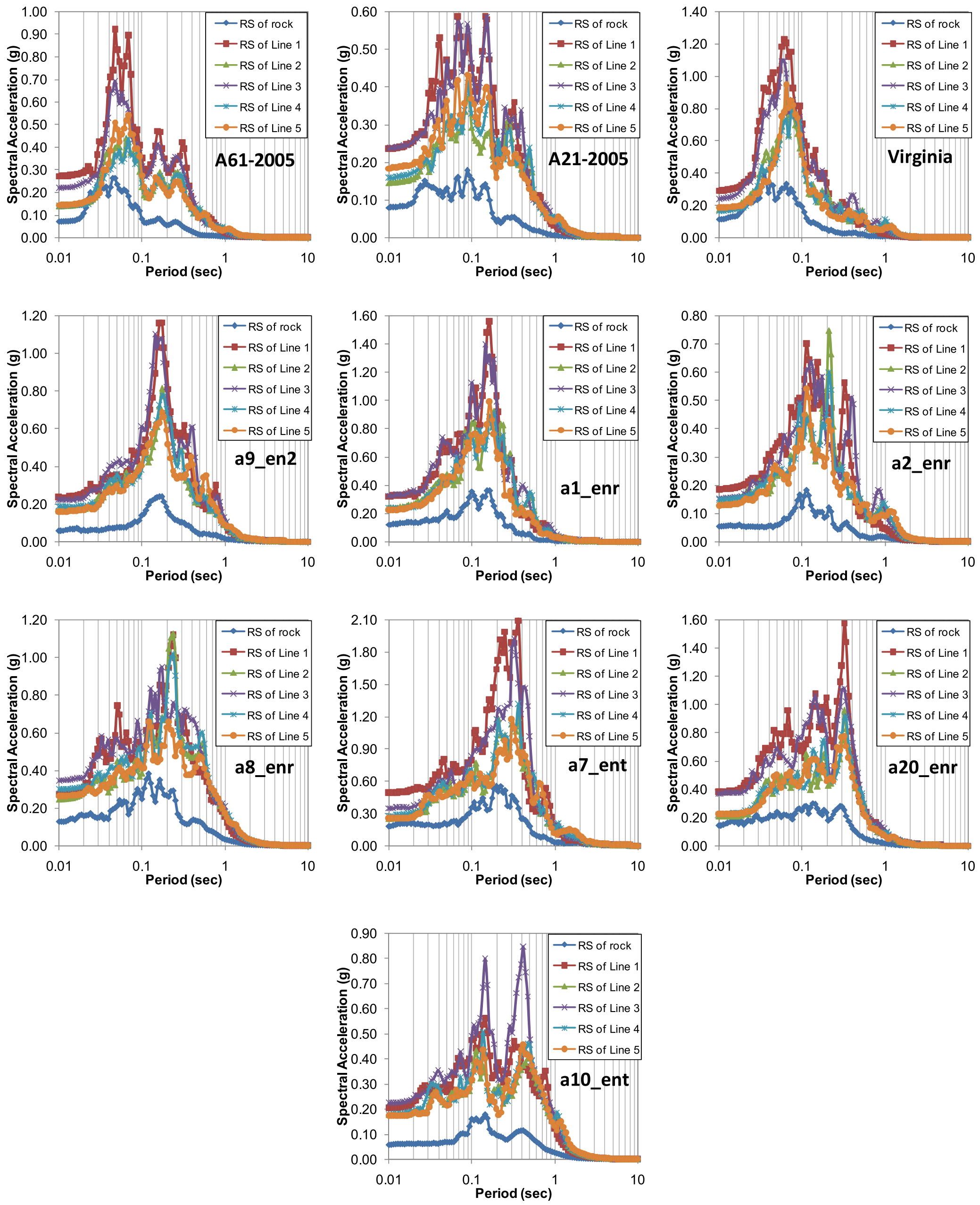

Figure 10. Input and surface response spectrum for 10 intraplate municipal solid waste (MSW) sites.

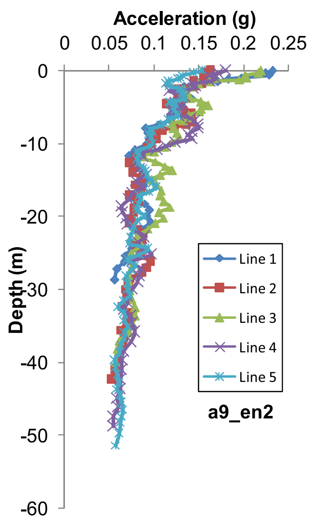

Figure 11. Typical depth versus acceleration for selected motion.

considerable seismic amplification for ground motion of less than 0.2 g. The amplification factor and spectral signature of intraplate MSW sites are different from interplate MSW sites studied earlier. The results indicate the potential of the amplification of surface ground motions by the waste situated above a composite layer of soils and bedrock at the bottom of the waste column. Hence, the stability of landfill cover system due to seismic ground motion amplifications is an important aspect in landfill design.

Declaration of conflicting interests

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