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SLOPE STABILITY OF MUNICIPAL SOLID WASTE LANDFILLS UNDER SEISMIC LOADING

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ABSTRACT

Design of municipal solid waste (MSW) landfills requires a considerable attention due to the undesirable environmental and socio-economical impact of a potential failure. Furthermore, recent research and engineering practice experience in developed countries characterized by high seismicity, like U.S.A and Japan, has shown that MSW landfills are vulnerable to the seismic threat. Despite the vivid interest worldwide on the seismic design of MSW landfills, there are certain topics that require more attention since current seismic codes seem rather incapable to cover fully the seismic design of MSW landfills, and other similar geo-structures. For instance, local site effects on ground shaking and slope stability of such geo-structures is either underestimated or even ignored. The current study aims to provide an insight into the parameters affecting the dynamic response of typical MSW landfills, like the selected geometry, the waste material's properties and excitation's characteristics, and furthermore to examine the basic seismic stability aspects. Therefore, two-dimensional finite element analyses were conducted, and the response (in terms of induced acceleration) was evaluated. Consequently, the two basic failure modes i.e. base sliding and slope instability, were examined utilizing simplified procedures (sliding block model) to assess the developed deformations.

Keywords: landfill, dynamic response, material nonlinearity, stability, permanent deformations.

INTRODUCTION

The main objective of the proper seismic design of municipal solid waste (MSW) landfills is the protection of human health and the environment. Seismic design of MSW landfills is commonly evaluated according to current methods used in embankment or earth-filled dam seismic stability analysis. The necessity of a proper earthquake–resistant design of MSW landfills has led several researchers to investigate the basic aspects influencing their seismic behavior. Analytical methods have been proposed for the evaluation of the dynamic response, based on the shear–beam approach (Ambraseys, 1960; Gazetas, 1987). Gunturi and Elgamal (1998), in order to estimate the response of hill-shaped landfills, have developed a nonhomogeneous shear–beam model of conical cross-section. Numerical analyses of typical landfill cross-sections performed by Rathje and Bray (2001) indicate that 1D analyses provide a rough estimate of maximum horizontal acceleration at the deck of the landfill, though the corresponding values for slope and crest are underestimated.

Currently, the basic categories of methods of dynamic stability analysis are: (a) pseudostatic analysis, (b) permanent deformation analysis, and (c) stress–deformation analysis. Although stress–deformation analysis is regarded as the most accurate, it is usually performed through finite–element analyses with

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the application of advanced constitutive models, which is rather impossible for waste material. On the other hand, pseudostatic methods neglect the actual dynamic inertia forces by providing stability evaluation in terms of a safety factor. Research on dynamic stability of landfills is generally focused on the estimation of the developed deformations along the geosynthetic interfaces at the liner systems based on permanent deformation analyses.

Assuming that the critical failure type is sliding of the cover liner, the impact of several parameters to the induced displacements has been investigated (Ling and Leshchinsky, 1997), as well as the validity of the basic assumptions of simple sliding–block method (Matasovic et al., 1998). Furthermore, Bray and Rathje (1998) investigated the base–sliding case and concluded that the basic factors influencing the permanent displacements include: the ratio of yield acceleration to maximum equivalent acceleration, dynamic response characteristics of landfill, and excitation characteristics. Moreover, the normalized equivalent acceleration (ratio of maximum horizontal equivalent acceleration to maximum horizontal acceleration) was found inversely proportional to normalized eigenperiod (ratio of eigenperiod of structure to mean period of earthquake) and 1D analyses were proven conservative for the estimation of maximum equivalent acceleration for base sliding. Permanent deformation analyses for sliding along the base liner have revealed that the decoupled procedure provides over-conservative estimates for lower eigenperiod of landfill and non-conservative estimates for soft failure masses (Kramer and Smith, 1997), a result further validated for nonlinear material behavior by Rathje and Bray (2000).

There are certain topics in seismic design of MSW landfills that require more attention. Apart from the uncertainties arising in geotechnical structures, like site effects and excitation's characteristics, there are parameters, like the waste disposal practice, the properties of the waste material (composition, age and compaction), the geometry of the landfill, and the liner systems (base and cover), which influence the dynamic response of landfills. A parametric study, utilizing the finite–element method, highlights the effect of the most important parameters on the linear and nonlinear dynamic response. Specifically, the factors examined are: the geometry, the waste–material properties, and the characteristics of the excitation. Moreover, the conducted frequency analyses aid on further determining the response characteristics of the structure and provide a complete representation of dynamic response of landfills. Since the seismic stability of circular slip surfaces (obtained from pseudostatic analyses, or examined in the static design of landfills) has not been yet proven to be less critical than base sliding along the liner, seismic stability assessment is performed in this study for both modes of instability.

DYNAMIC RESPONSE OF LANDFILLS

In the current study, in order to estimate the basic aspects of dynamic response of typical landfills, a series of parametric finite–element analyses was performed. For this purpose, three different geometries of typical above-ground landfills were examined (Figure 1). Model 1 and Model 2 are representative of above-ground landfills, while Model 3 represents a typical side-fill landfill. For all the examined models the slope inclination was selected to be 3:1 (horizontal to vertical), while the height of the landfills is equal to 20m. The finite–element modeling was performed utilizing the code QUAD4M (Hudson et al., 1994), which is a finite–element program capable to perform 2D plane-strain ground response analyses.

In QUAD4M material nonlinearity is taken into account using an iterative procedure according to which shear modulus and damping are consistent to the level of maximum cyclic shear strain. Models were discretized using finite elements, the size of which was tailored to the wavelength of interest, resulting to a finer mesh from rock to waste. Dynamic waste material properties have been commonly established through back-analysis procedures or in-situ testing (Singh and Murphy, 1990) and recently through laboratory-testing (Zekkos, 2005) (Figure 2).

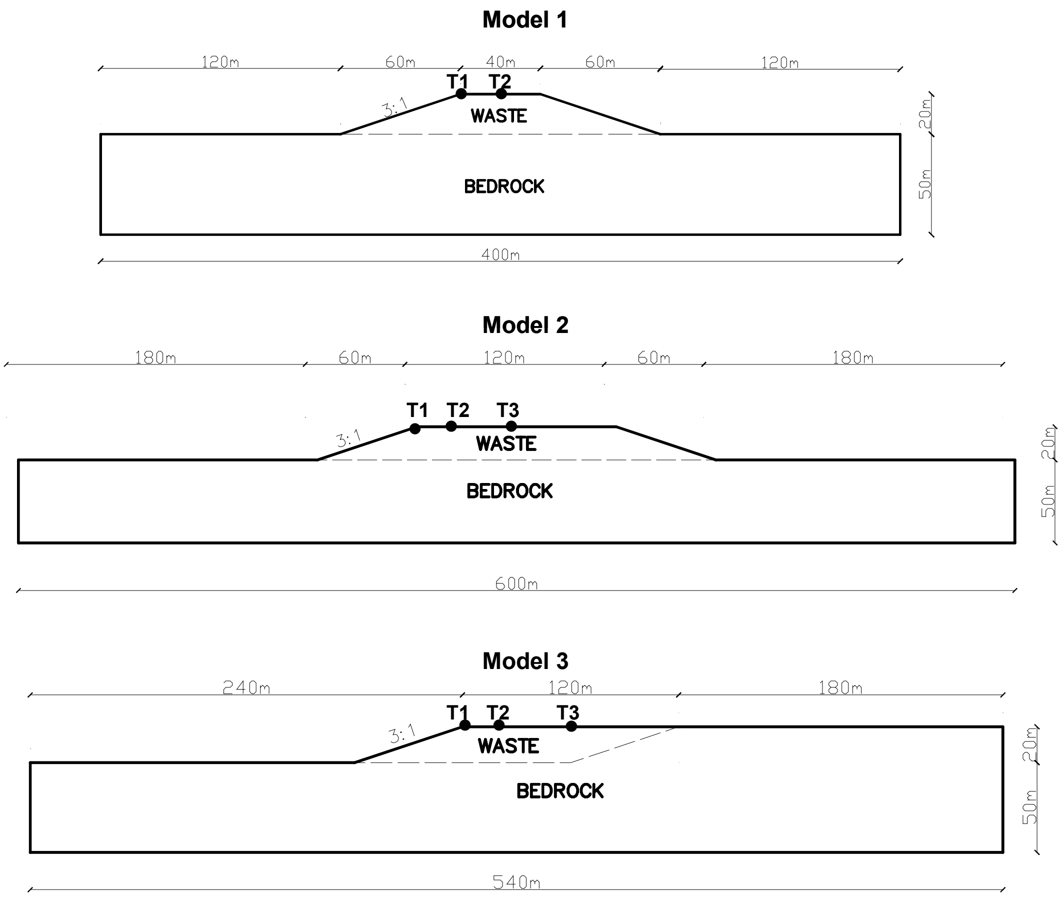

Figure 1. Geometry of the three models examined in the current study. T1, T2, T3 are the points of interest

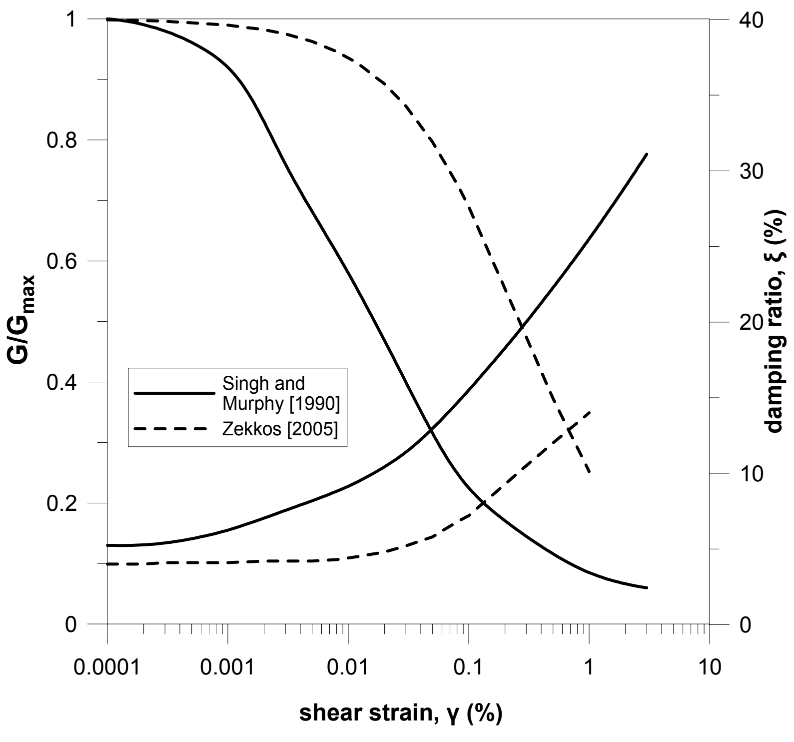

Figure 2. Shear modulus reduction curves and damping variation curves proposed by various researchers for waste materials

Table 1. Frequency characteristics of the three excitations

Excitation	Predominant period (sec)	Mean period (sec)
Ricker pulse (f_0 =2Hz)	0.32	0.34
Aegion	0.50	0.47
Kobe	0.38	0.66

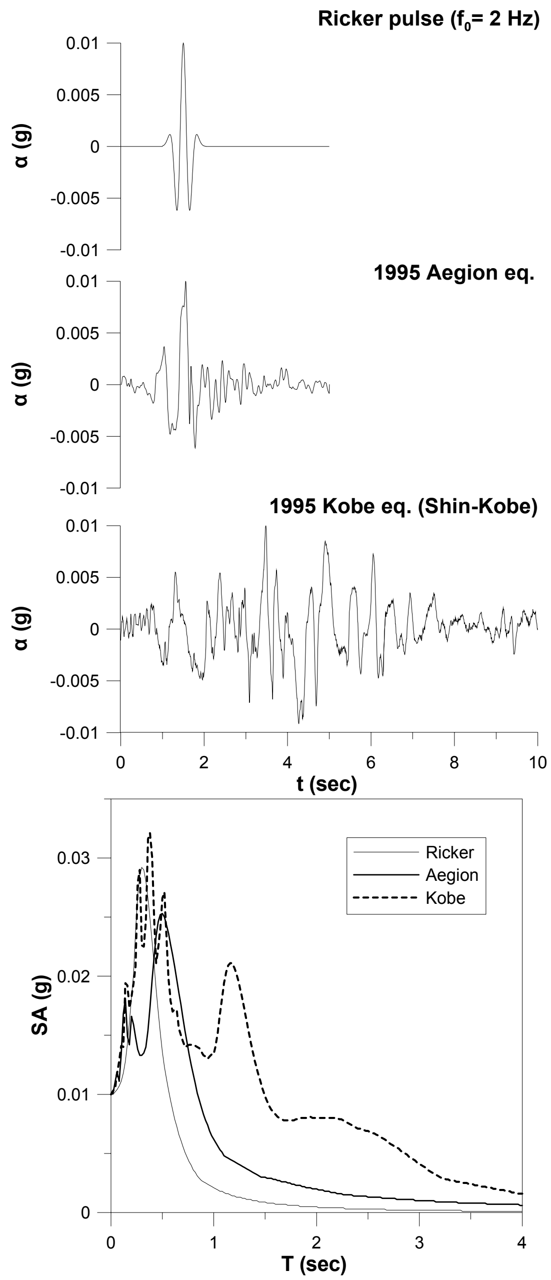

Figure 3. The acceleration time–histories and the corresponding response spectra of the three excitations used in the analyses; all scaled to the minimum PGA level (=0.01g)

Taking into account the uncertainties concerning the material properties of waste, three different cases of initial (low–strain) shear–wave velocity, V_S, were considered: 160 m/sec (Type A), 250 m/sec (Type B), and 400 m/sec (Type C). Unit weight of waste material, γ, was set equal to 10kN/m^3, while for the shear-modulus reduction and damping-increase the curves proposed by Singh and Murphy (1990) were selected (see Figure 2). Three different base horizontal excitations were used in the analyses. Specifically: a) a simple Ricker pulse with central frequency f_0 = 2Hz, b) the record from the

1995 Aegion earthquake, and c) the Shin-Kobe record from the 1995 Hyogoken–Nanbu (Kobe) earthquake. In this way a broad frequency range was covered. Ricker pulse, despite the simplicity of its waveform, covers a range of frequencies up to $3f_0$. The acceleration time histories and the corresponding response spectra of the three excitations are given in Figure 3, while in Table 1 the predominant (T_d) and the mean period (T_m) are presented. The latter is estimated by the following equation:

$$T_m = \frac{\sum_i C_i^2 \cdot \left(\frac{1}{f_i}\right)}{\sum_i C_i^2} \tag{1}$$

where C_i are the Fourier amplitudes, and f_i represent the discrete Fourier transform frequencies between 0.25 and 20 Hz (Rathje et al., 1998).

In order to examine the response of the three landfills, under both linear and nonlinear conditions, all accelerograms were scaled to three levels of peak ground acceleration (PGA): 0.01g, 0.1g, and 0.36g. in the frequency analyses, the finite–element code ABAQUS (2003), and specifically the Lanczos eigenvalue extraction method, was utilized. The models used in the frequency analyses were identical to the ones of the dynamic analyses. Note that the response characteristics were determined not only for the linear cases, but for the nonlinear ones as well, by taking into account the modified material properties of the equivalent-linear procedure.

Geometry effect

The dynamic behavior of the three models is examined through the Transfer Function (TF) of the top deck points of interest, revealing the frequency characteristics of the response in the examined points (see Figure 4). TF is defined as the ratio between the Fourier amplitudes of the dynamic response at the points of interest and of the base excitation. In order to provide the basic characteristics of the response, the following reference points (see Figure 1) selected for each model are:

- T1, the crest point,
- T2, the midpoint of Model 1, located in 20m distance from crest for Model 2 and Model 3, and
- T3, the midpoint of Model 2, located in 60m distance from crest or the projection of the toe of inclined base–rock foundation for Model 3.

As shown in Figure 4, the response of the top deck points for each model is characterized by the same value of fundamental frequency, though comparing the fundamental frequencies between the three models the difference is obvious. Model 1 exhibits the lowest value of first eigenperiod (compared to the other models), while Model 2 exhibits the highest value of first eigenperiod. The same trends were also observed in the frequency analyses. Furthermore, though referring to the same material properties the maximum value of amplification observed is the highest for Model 3, while Model 2 leads to the lowest value, compared to the other models. In Model 1 and Model 3 the transfer function receives higher values at point T2 than other points at deck, while the same trend is observed at point T3 for Model 2. The amplification values in the range of fundamental frequency for Model 3 decrease at point T3 and increase for a second frequency. The trend of a second significant frequency but now closer to the first one appears too at point T2 for Model 2 and Model 1.

Nonlinear response results to stiffness degradation of the material and increase of viscous damping. Consequently, the nonlinear eigenperiod is expected to increase, while on the contrary the amplification levels are in general expected to decrease. The aforementioned trends are verified in Figure 5, which presents the transfer functions for the same deck points of the three models examined in the elastic case. The maximum value of amplification is now observed in Model 3 (as in linear case), while the lowest value is observed in Model 1. In the range of fundamental frequency (around 1.5Hz) the higher amplification levels are observed at point T3 in Model 2, while for Model 3 and Model 1 at point T2, like in the linear case (see Figure 4 for comparison).

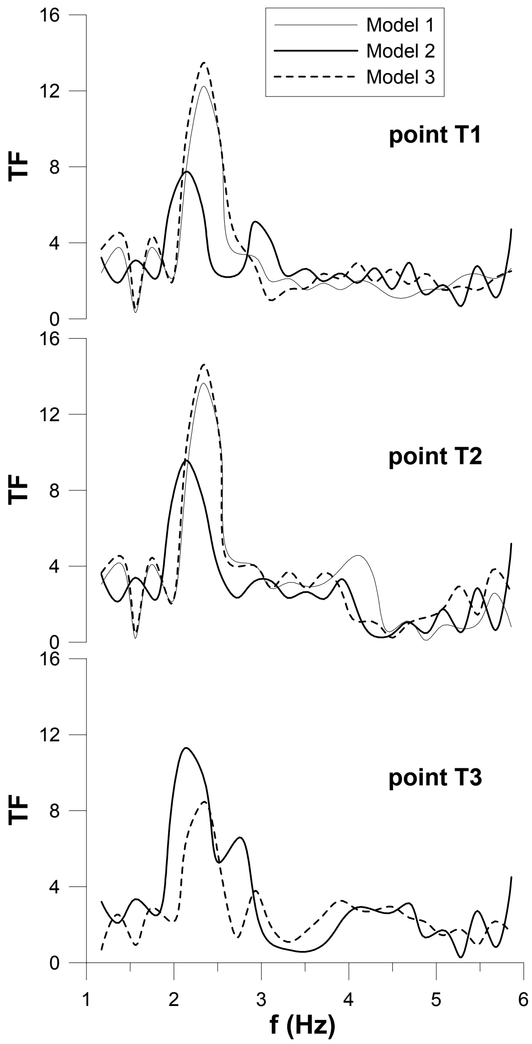

Figure 4. Transfer Functions (TF) defined as the ratio between the Fourier amplitudes of the dynamic response at points of interest (T1, T2, T3) and the base excitation. Here only the elastic case (PGA=0.01g) with material Type A is presented

Material effect

The effect of the material properties on the elastic response is also examined. This effect is strongly related to the excitation's characteristics. As the small shear strain modulus increases the landfill's eigenperiod receives lower values. Consequently, this may lead to a detrimental effect on response (when approaching resonance) or beneficial (when the eigenperiod becomes higher than excitation's period). These phenomena are more complicated in nonlinear case, since the response is dominated by the shear-modulus reduction and the damping increase curves. Comparing the response (TF) calculated via the shear-modulus reduction and damping increase curves proposed by Singh and Murphy (1990), with the corresponding obtained using the more realistic curves proposed by Zekkos (2005), the results indicate that the latter leads to higher amplification levels, mainly due to the substantially lower material damping (see Figure 1). On the other hand, the higher values of shear modulus result to less intense decrease of fundamental frequency due to material nonlinearity. These phenomena are evident in Figure 6. The geometric characteristics of MSW landfills imply that as observed in surface irregularities, generation of a "parasitic" vertical acceleration is unavoidable. Examining the effect of the material properties on the aforementioned developed "parasitic" vertical acceleration for the linear case, the maximum value of vertical acceleration is observed to decrease with higher material stiffness. The vertical acceleration increases for in nonlinear case for initially stiffer material (Type B and C) while decreases for initially softer (Type A) (see Figure 7).

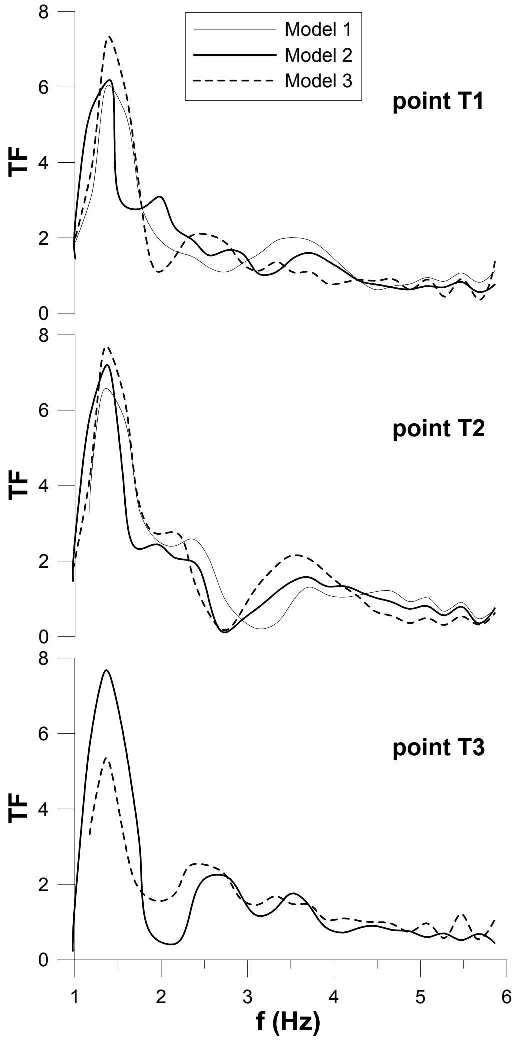

Figure 5. Transfer Functions for the Ricker pulse excitation: the moderately nonlinear case (PGA=0.1g) with material Type A is examined

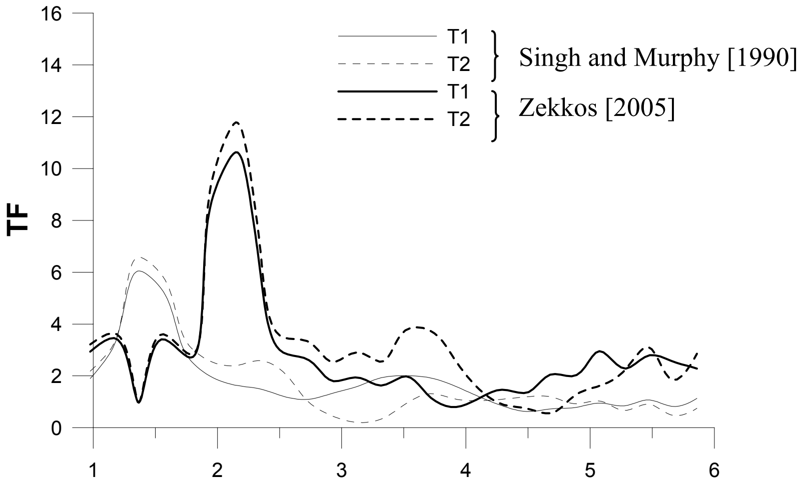

Figure 6. Sensitivity of the nonlinear response to various proposed curves of modulus reduction and damping ratio increase. Transfer Functions at points T1 and T2 for Model 1, Ricker pulse (PGA=0.1g) and Type A material are presented

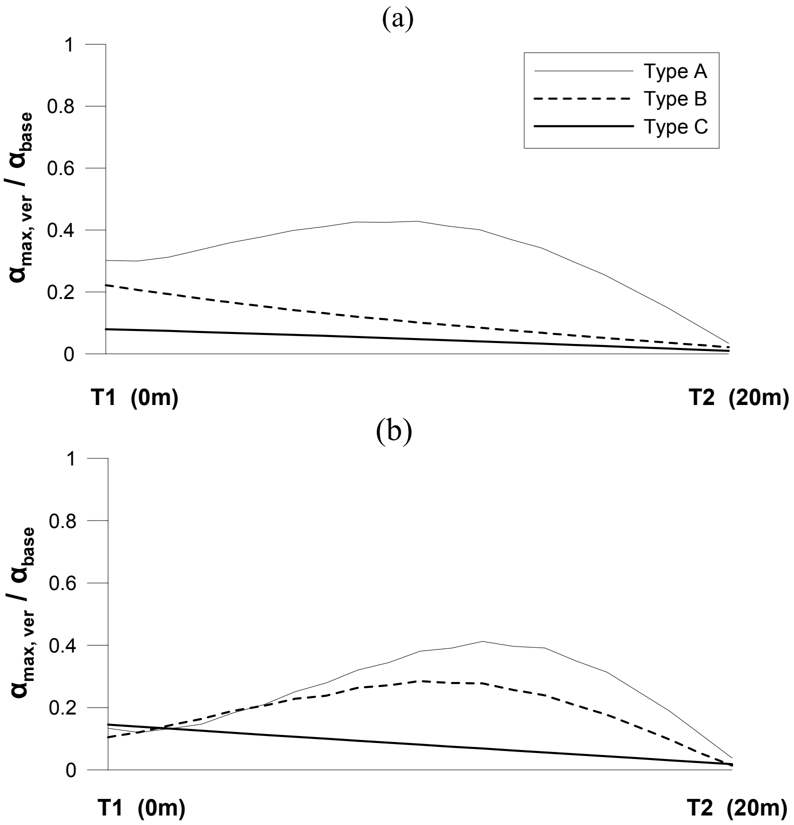

Figure 7. Effect of material properties on the deck response of Model 1 for Ricker pulse; maximum normalized "parasitic" vertical acceleration: a) PGA=0.01g and b) PGA=0.1g

Effect of excitation characteristics

The effect of the excitation on linear response is relevant, since it is strongly related to the transfer function of the examined case. The effect of excitation characteristics on nonlinear dynamic response is examined with respect to the PGA level and the mean period of excitation. The results of the frequency analyses, which were conducted with the updated elastic properties of the equivalent-linear analyses, are presented in Figure 8 in terms of normalized nonlinear eigenperiod (ratio between the linear fundamental eigenperiod, T_{lin}, and the nonlinear fundamental eigenperiod, T_{nonlin}) versus the PGA applied. Referring to the same excitation, the normalized eigenperiod is decreasing as the level of the applied acceleration increases. The maximum acceleration is obviously not the only parameter affecting the stiffness degradation during nonlinear response. Thus, as the mean period of earthquake (see Table 1) increases the normalized eigenperiod decreases. This combined effect results to cases where same nonlinear eigenperiod is observed for higher acceleration level with lower mean period, and lower acceleration level with higher mean period.

SEISMIC SLOPE INSTABILITY

The seismic stability evaluation of the examined models included pseudostatic analyses to define the critical slip surfaces for the level of maximum base acceleration. Note that due to the same material properties and slope inclination, pseudostatic analyses result to the same critical surface for all the three geometries analyzed. The equivalent acceleration time-histories for the critical slip surfaces (both vertical and horizontal) were calculated utilizing the finite–element code QUAD4M, which estimates the seismic coefficient as the force induced by the earthquake over the weight of the sliding surface. Forces acting on the surface are computed by multiplying shear and normal stresses applied on an element with the width of that element. Average stress is calculated between elements on either

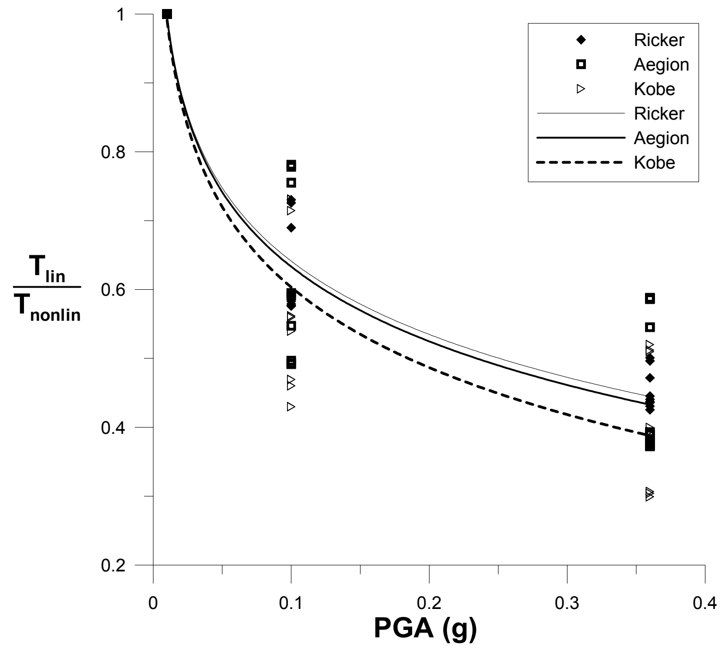

Figure 8. Decrease of the eigenperiod of the three examined landfills as a variation to PGA. Symbols are used to represent calculated values, while the best-fit curves are also given

side of the interface. The summation of forces acting on the surface is computed as a function of time, and the equivalent acceleration time history is provided.

In the current study the permanent displacements were calculated utilizing the decoupled procedure, according to which the dynamic analysis and sliding analysis are performed separately. Therefore, the response is independent of the developed deformation. Based on limit–equilibrium principles the critical acceleration, K_y, is defined as the pseudostatic acceleration that leads to a safety factor equal to one. The yield acceleration utilized for the displacement calculation of the circular slip surface was evaluated also by taking into account the "parasitic" vertical acceleration. Note that in this case the yield acceleration is not constant throughout the displacement analysis, resulting to either higher or lower values of yield acceleration in comparison to the aforementioned ones. Shear-strength properties were selected according to the values reported in the literature for direct shear tests. Due to the wide range of proposed parameters two failure envelopes were selected:

- $c = 18KPa$, and $\varphi = 34^o$
- $c = 0KPa$, and $\varphi = 34^o$

The dynamic frictional properties of the geosynthetic interfaces for the case of sliding along the bottom liner were selected to be characterized by angle of friction equal to 17 degrees. This is consistent with the range of dynamic friction angle values proposed by De and Zimmie (1998), which were obtained from cyclic direct-shear tests and shaking-table tests of eight different geosynthetic interfaces. The corresponding yield acceleration to each one of the selected failure envelopes for the circular slip surfaces were equal to 0.63g for the first and 0.38g for the second, while for the base sliding case the yield acceleration of Model 1 and 2 was equal to 0.30g and of Model 3 was equal to 0.22g.

In Figure 9a the numerical results of this investigation are presented in comparison to the curve proposed for base sliding for rock sites by Bray and Rathje (1998). It is noteworthy that the proposed curve was derived from 1D analyses and refers to elastic normalized eigenperiod. Besides the resonant effects (at ratio of eigenperiod, T_{str}, to mean period of excitation, T_m, equal to one), the values of maximum horizontal equivalent acceleration (MHEA) obtained for the circular slip surface are generally greater than the corresponding ones for base sliding. The results are close to the ones proposed by Bray and Rathje (1998) for base sliding only for ratio of eigenperiod to mean period of excitation greater than 2.5, indicating that base sliding is more critical than slope stability. Thus, when the eigenperiod is less than 2.5 times the mean period of the applied excitation, the equivalent acceleration on circular slip surfaces receives high values and the critical mode of failure is questionable. The aforementioned result is also evident by observing Figure 9b, where the normalized MHEA in variation to normalized eigenperiod for the base sliding case are presented. The corresponding values (MHEA/PGA) are generally reduced for the base sliding case (see Figure 9b) compared to the case of circular slip surface (see Figure 9a) though referring to the same values of normalized eigenperiod.

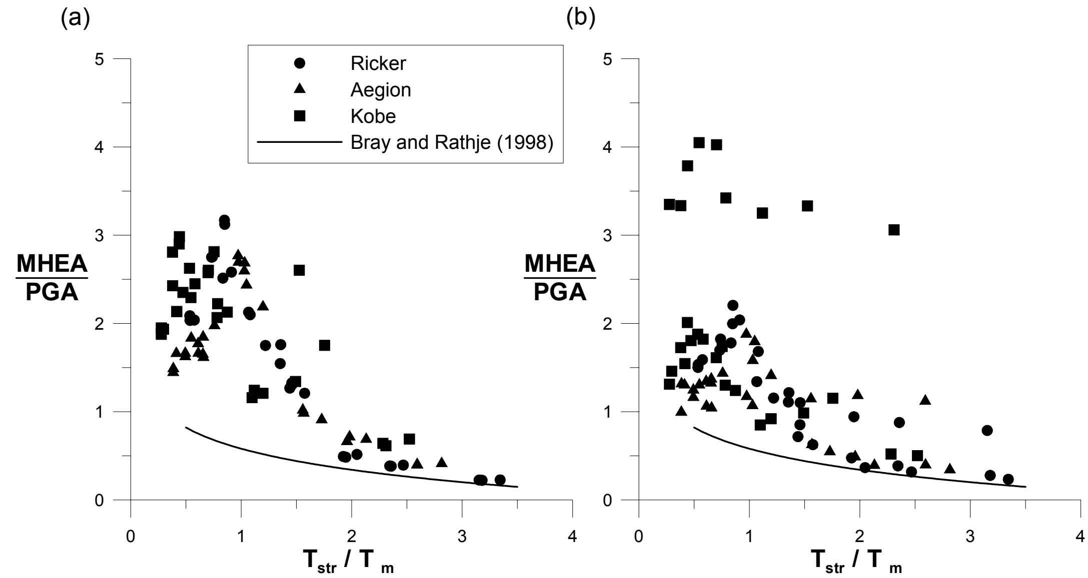

Figure 9. Ratio of maximum horizontal equivalent acceleration (MHEA) to PGA is presented in variation to the ratio of the eigenperiod of the landfills (T_{str}) to the mean period of the excitation (T_m) for: a) circular slip surface and b) base sliding case

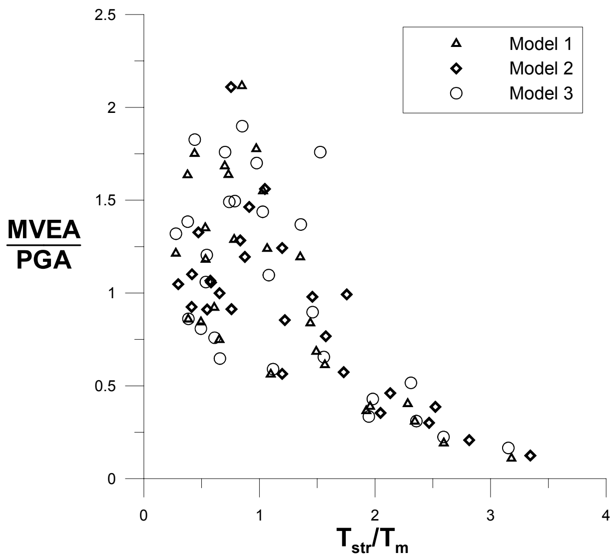

Figure 10. Effect of geometry on response characteristics of slip surface in terms of normalized maximum vertical equivalent acceleration (MVEA) as a variation to the ratio of the eigenperiod of the landfills to the mean period of the excitation.

The results obtained for the base sliding of Model 3 is an exception to this observation, especially for the Kobe excitation case. It is also noteworthy that for base sliding case of Model 3 the parasitic vertical acceleration is significant, dissimilar to Model 1 and 2 where it diminishes. Most probably the critical overall instability of Model 3 may be attributed to the two non-parallel boundaries from which the seismic excitation is introduced. The curve proposed for base sliding by Bray and Rathje (1998) for rock sites appear to be a rough lower estimate of the values obtained from the 2D dynamic analyses. This discrepancy can be explained by the fact that the curve proposed by Bray and Rathje (1998) is derived from 1D analyses. Furthermore, as depicted in Figure 10, the developed vertical equivalent acceleration, MVEA, is strongly influenced by geometry effects and by the frequency characteristics of excitation. It is noteworthy that for mean period of excitation greater than half of the eigenperiod of the landfill the maximum equivalent vertical acceleration receives values higher than the applied PGA.

Permanent horizontal displacements, for circular slip surfaces, were calculated for both directions of motion by taking into account the stability of the symmetrical slope for Model 1 and Model 2. Figure 11 shows the variation of the developed horizontal displacement, d, with respect to the normalized eigenperiod of the landfill, T_{str} / T_m. The values refer to ratios of yield acceleration to maximum horizontal equivalent acceleration greater than 0.4, for which according to Rathje and Bray (2000) the decoupled procedure provides potentially over-conservative estimates of the developed displacements. Nevertheless, the detrimental effect of "parasitic" vertical acceleration on the developed horizontal displacements is obvious. As depicted in Figure 11 the increase of sliding attributed to the effect of vertical acceleration is at least of the order of 100% of the value calculated without considering the "parasitic" vertical acceleration.

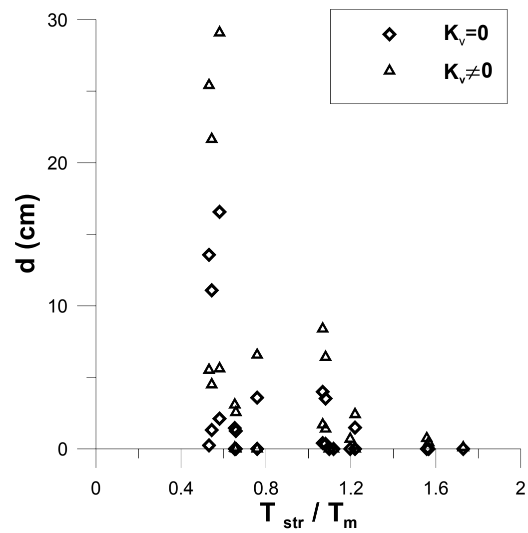

Figure 11. Displacement obtained from decoupled procedure for circular slip surface in variation to the ratio of eigenperiod to mean excitation's period.

CONCLUSIONS

The aim of the present study was twofold: a) to examine the factors that influence the seismic distress of MSW landfills in terms of developed inertia accelerations, and b) to evaluate their potential instabilities under dynamic loading. The numerical evaluation of the seismic response of three typical geometries of MSW landfills (two above–ground trapezoids and one side–fill) has shown the significant role of the involved parameters. Initially, the effect of the adopted geometry was highlighted, showing clearly its impact not only on the eigenperiod of the landfill but on the amplification levels as well. For the excitations examined the nonlinear eigenperiod of the landfill increases, as the mean period of the earthquake and the peak ground acceleration increase. The developed "parasitic" vertical acceleration (due to the wave reflections and the generation of surface waves) may be a contributing factor on stability of the landfills. Another important issue related to the stability of landfills is the fact that maximum horizontal equivalent acceleration is strongly dependent on the normalized eigenperiod of the landfill. The aforementioned parameter may receive values of the order of three times the peak ground acceleration. It is noteworthy to mention at this point that for the slope stability calculations seismic code provisions (e.g. Eurocode 8, 2002), propose a value of horizontal seismic coefficient not greater than the peak ground acceleration when the structure is founded on a rigid rock formation. The results presented in the current study indicate that the aforementioned parameter may receive values as high as three times the PGA (in the resonance case) a phenomenon that should not be disregarded.

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