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SEISMIC ANALYSIS OF SOLID WASTE LANDFILLS

Edward Kavazanjian, Jr.[1], Member, ASCE, and
Neven Matasović[2], Associate Member, ASCE

ABSTRACT

Equivalent-linear and truly non-linear seismic site response analyses for solid waste landfills are calibrated with the observed behavior of the OII landfill in recent earthquakes. The calibrated analyses provide insight into the selection of solid waste properties for seismic design, fundamental aspects of the seismic behavior of solid waste landfills, and limitations of the equivalent-linear method. Observations and predictions of seismic response demonstrate that outcrop motions can be amplified by landfills, that the peak average acceleration of the landfill mass is unlikely to exceed the peak outcrop acceleration, and that the unit weight and initial shear wave velocity gradients within the landfill are important factors in seismic response analyses. Non-linear analyses demonstrate the potential benefit of low shear strength geosynthetic interfaces with respect to reduction of the peak acceleration response of the landfill.

INTRODUCTION

Recently promulgated federal regulations have focused increased attention on seismic design of solid waste landfills. This increased attention is related to both the relatively extreme recurrence interval of approximately 2400 years for the design acceleration specified by these regulations and to prescriptive standards contained in the regulations for geosynthetic liner and cover systems which create the potential for continuous low shear strength interfaces within the landfill. Seismic design analyses used in practice to assess compliance with these regulations for municipal solid waste landfills typically employ conventional one-dimensional equivalent-linear

[1]Associate, GeoSyntec Consultants, 16541 Gothard Street, Suite 211, Huntington Beach, CA 92647.

[2]Senior Staff Engineer, GeoSyntec Consultants, 16541 Gothard Street, Suite 211, Huntington Beach, CA 92647.

seismic response analyses in conjunction with limit equilibrium stability analyses and Newmark-type seismic deformation analyses (Repetto et al., 1993). One of the major limitations associated with this approach is uncertainty with respect to the dynamic properties of the solid waste (USC, 1994). Strong motion records obtained during recent earthquakes from the OII landfill (OII) in Monterey Park, California, (Hushmand Associates, 1994) provide for the first time a rational basis for back-calculation of the dynamic properties of solid waste for seismic response analyses.

By combining profiles of the unit weight and initial shear wave velocity of solid waste developed from field observations and measurements (Kavazanjian et al., 1994) with observations of seismic response at OII, a calibrated set of material properties for equivalent-linear and truly non-linear seismic site response analyses of solid waste has been developed. Analyses employing these calibrated solid waste properties are used herein to investigate fundamental aspects of the seismic response of solid waste landfills. The potential for amplification of the peak outcrop acceleration by the waste mass and the relationship of the peak outcrop acceleration to the peak average acceleration of the landfill mass are two key facets of solid waste seismic response which are investigated. Results of equivalent-linear and truly non-linear analyses indicate that response analyses using over-simplified unit weight and initial shear wave velocity profiles and unsubstantiated dynamic properties for the solid waste may lead to erroneous conclusions about the seismic response of solid waste landfills. The non-linear analyses are also used to provide insight into the impact of geosynthetic interfaces in the liner and cover on seismic response.

DYNAMIC MATERIAL PROPERTIES OF SOLID WASTE

Dynamic material properties of solid waste were developed for equivalent-linear and truly non-linear one-dimensional seismic response analyses by back-analysis of the strong motion records obtained at OII during the 17 January 1994 Northridge (M 6.7) and 28 June 1992 Landers (M 7.4) earthquakes. OII is a closed "superfund" landfill currently monitored for static and seismic performance by the United States Environmental Protection Agency. OII may not be a typical solid waste landfill in that it received both municipal and industrial wastes, including some liquid wastes, during its active life. However, to the authors knowledge, it is currently the only solid waste landfill at which strong ground motion data is available. Therefore, in the absence of any other data, solid waste properties back-calculated from the observed seismic response of OII provide the best available information on the dynamic properties of solid waste.

Details of the waste composition, landfill geometry, instrumentation, and the measurements of seismic response at OII are provided by Hushmand et al. (1990) and Hushmand Associates (1994). In the analyses of the seismic response of OII reported herein, a 1.2 m-thick layer of compacted cover soil placed on top of a 75 m- thick solid waste column placed on top of bedrock was used to model field conditions. The solid waste landfill unit weight and initial shear wave velocity profiles developed by Kavazanjian et al. (1994), presented in Figure 1, were used in the back-analysis of the observed response of the OII landfill reported herein.

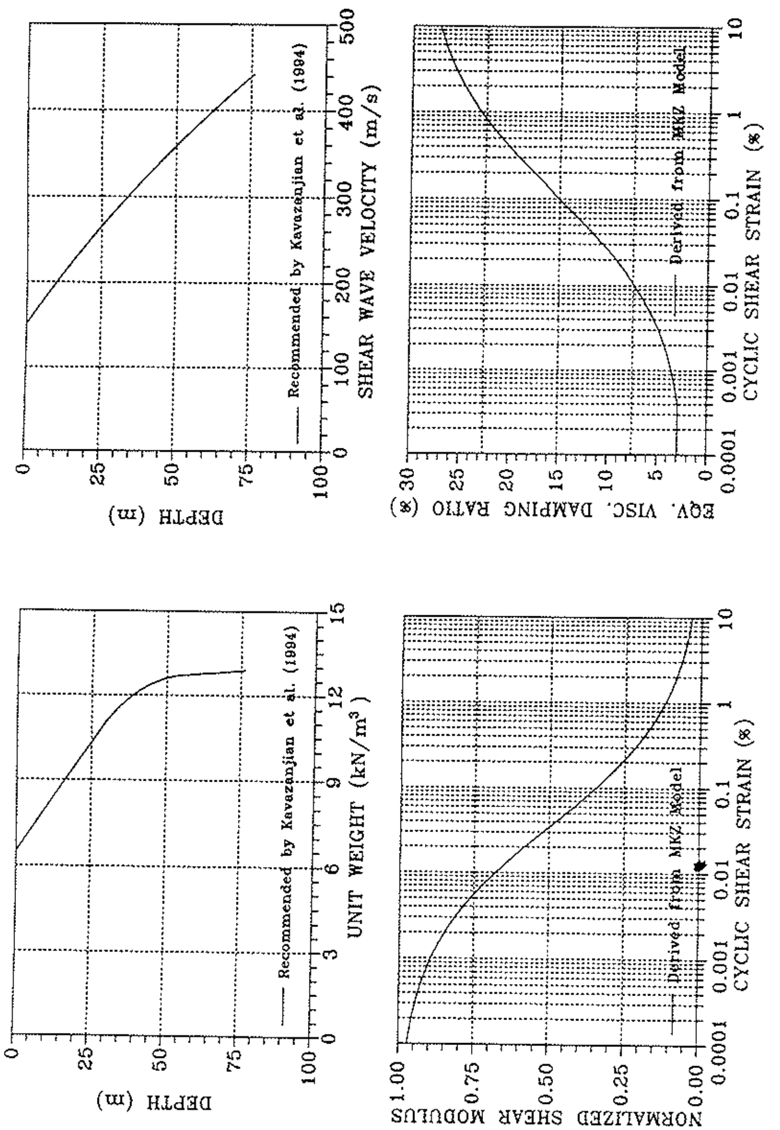

FIG. 1. Material Properties of Solid Waste used in Dynamic Response Analyses

Non-linear analyses of the seismic response of OII were performed using the computer program D-MOD (Matasović, 1993). D-MOD uses the same dynamic response model used in the computer program DESRA-2 (Lee and Finn, 1978). However, DMOD employs different constitutive equations than DESRA-2. The stress-strain behavior of solid waste was modelled in the D-MOD analyses using the MKZ model (Matasović and Vucetic, 1993). The MKZ parameters for solid waste were back-calculated from the observed response of OII in the Northridge and Landers events. The equivalent-linear modulus reduction and damping curves for solid waste shown in Figure 1 were then calculated from the back-calculated MKZ parameters using the explicit equations presented in Matasović and Vucetic (1993). One-dimensional equivalent-linear analyses of the response of OII in the Northridge and Landers events were performed using the computer program SHAKE (Schnabel et al., 1972; Idriss and Sun, 1992), the equivalent-linear modulus and reduction curves calculated from the MKZ parameters, and the unit weight and shear wave velocity profiles shown in Figure 1. Trial and error analyses were performed to determine the best fit value for the "effective strain factor" that relates the peak shear strain calculated in the response analysis to the shear strain at which the equivalent-linear modulus and damping are evaluated. Results of these analyses indicated that an effective strain factor of 0.8 gave the best fit with the measured acceleration response over the range of spectral periods from 0 to 4 seconds.

Figure 2 compares the measured longitudinal acceleration response at the top of OII for the Northridge and Landers earthquakes to the response calculated using the material properties presented in Figure 1. Both the equivalent-linear SHAKE analyses (with an effective strain factor of 0.8) and the non-linear D-MOD analyses show reasonably good agreement with the measured response. For the more intense motion (larger peak ground acceleration) of the Northridge event, the equivalent-linear analysis shows relatively poor agreement around the 0.5-second period associated with the measured peak spectral acceleration. When the equivalent-linear parameters (e.g., effective strain factor) were adjusted to achieve a better fit with the measured response in the 0.5-second period range, the SHAKE analyses significantly under-predicted both the peak acceleration and the long period spectral response that is the most important contribution to the seismic deformation potential of earthquake ground motions. For the Landers event, where most of the energy of the motion is associated with relatively long periods (i.e., 1 to 2 seconds) and where non-linear effects are small due to the low intensity, both SHAKE and D-MOD results agree well with the measured response for spectral periods from 0 to 4 seconds.

Kavazanjian et al. (1994) compared the measured longitudinal acceleration response at the top of OII in the Northridge Earthquake to results from SHAKE analyses using an effective strain factor of 0.8 and the modulus reduction and damping curves in Figure 1 and to results from SHAKE analyses using dynamic properties for municipal solid waste recommended by other investigators (Earth Technology, 1988; Singh and Murphy, 1990; Sharma and Goyal, 1991; Repetto et al., 1993). Based upon these analyses, Kavazanjian et al. concluded that the MKZ-derived equivalent-linear parameters shown in Figure 1 combined with an effective strain factor of 0.8 gave the best agreement with the observed response of

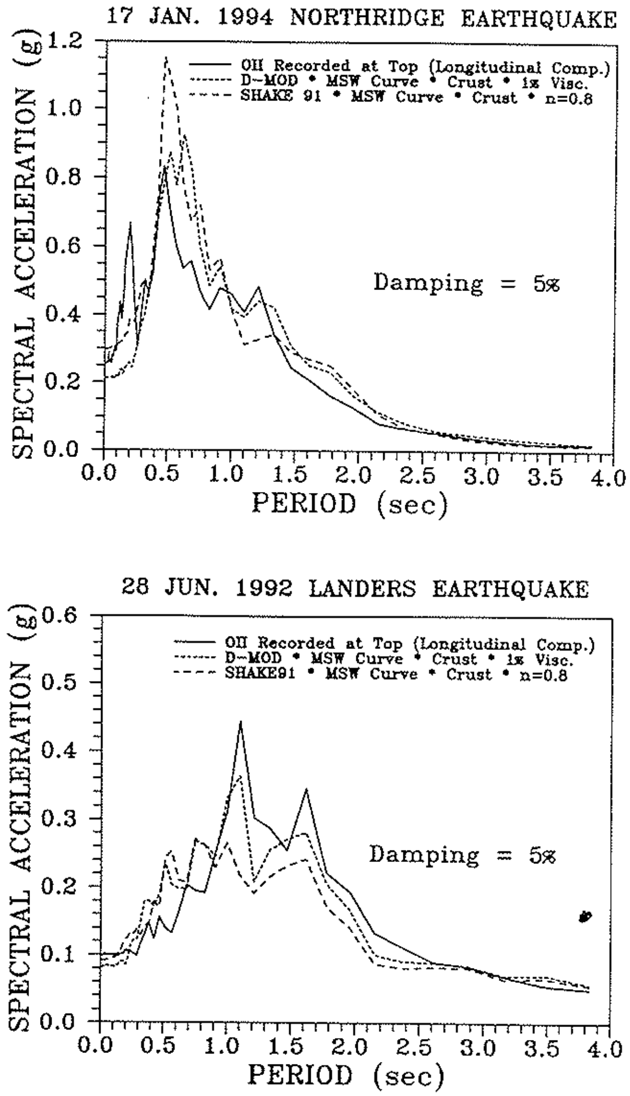

FIG. 2. Recorded and Calculated Response, OII Landfill, Longitudinal Direction

the OII landfill based upon the fit between measured and calculated spectral acceleration over the range of spectral periods from 0 to 4 seconds.

Effect of Refuse Unit Weight and Initial Shear Wave Velocity Profile

Constant values for the unit weight and initial shear wave velocity of solid waste have been assumed in most previously published seismic response analyses of landfills and in many of the landfill analyses used in engineering practice that have been reviewed by the authors. Representative, or average, values commonly used in seismic response analyses of municipal solid waste landfills are between 8.8 and 10 kN/m^3 for unit weight and between 175 and 225 m/s for initial shear wave velocity (Singh and Murphy, 1990; Sharma and Goyal, 1991). Based on the profiles from Kavazanjian et al. (1994) shown in Figure 1, these average values appear to be reasonable averages for approximately 30 to 70 m of waste.

Presumably, constant values have been used for solid waste unit weight and initial shear wave velocity in previous analyses because of uncertainty with respect to the variation of these properties with depth. Another possible justification is that the use a constant value of unit weight may in some situations give reasonable results for seismic response analyses of soil profiles and earth structures. However, due to the relatively compressible nature of solid waste, typical velocity and unit weight gradients in solid waste landfills are significantly greater than the corresponding gradients for typical soil deposits. The larger unit weight and velocity gradients in solid waste compared to soil lead to an even greater discrepancy between solid waste and soil with respect to the impedance gradient (impedance is the product of the mass density and the initial shear wave velocity). As impedance contrast is a major factor in the transmission, reflection, and amplification of seismic motions, discrepancies in the impedance profile can lead to significant errors in calculated seismic response, particularly at the top of the landfill.

To demonstrate the impact of unit weight and initial shear wave velocity profiles on the results of site response analyses, analyses using constant values of 10 kN/m^3 for unit weight and 213 m/s for initial shear wave velocity were compared to analyses using the material property profiles shown in Figure 1 for a 61 m-thick landfill. Both equivalent-linear and non-linear analyses were performed using the OII Landers base motion scaled to 0.1 g and 0.4 g as the base input motion. The peak acceleration response from these analyses is summarized in Tables 1 and 2.

Table 1 Effects of Unit Weight and Shear Wave Velocity Distribution - 61 m Refuse Profile, Landers Base Motion Scaled to 0.1 g

DENSITY AND SHEAR WAVE VELOCITY DISTRIBUTION	PEAK ACCELERATION RESPONSE			
	SHAKE		D-MOD	
	Surface	Average	Surface	Average
Constant	0.11 g	0.08 g	0.11 g	0.07 g
Variable	0.28 g	0.11 g	0.17 g	0.09 g

Table 2 Effects of Unit Weight and Shear Wave Velocity Distribution - 61 m Refuse Profile, Landers Base Motion Scaled to 0.4 g

DENSITY AND SHEAR WAVE VELOCITY DISTRIBUTION	PEAK ACCELERATION RESPONSE			
	SHAKE		D-MOD	
	Surface	Average	Surface	Average
Constant	0.40 g	0.24 g	0.27 g	0.16 g
Variable	0.81 g	0.29 g	0.49 g	0.29 g

For equivalent-linear analyses, use of the constant values for unit weight and initial shear wave velocity introduces a discrepancy of approximately 150 percent for the peak acceleration at the landfill crest and almost 40 percent for the peak average acceleration of the waste mass for the 0.1 g input motion. A discrepancy of 100 percent in the peak acceleration at the crest of the landfill and 20 percent for the peak average acceleration of the waste mass is introduced by the use of constant unit weight and initial shear wave velocity in equivalent-linear analyses using the 0.4 g input motion. For non-linear analyses, the discrepancy is approximately 50 percent for the peak acceleration at the crest of the landfill and 30 percent for the peak average acceleration of the waste mass for the 0.1 g input motion and 80 percent for both the peak acceleration at the crest of the landfill and the peak average acceleration of the waste mass for the 0.4 g input motion.

Landfill Amplification of Seismic Motions

Despite published acceleration response spectra from low intensity strong motions recorded at OII showing amplification of spectral accelerations in the 1 to 2 second period range by a factor of up to 12 (Hushmand et al., 1990), the myth that landfills unconditionally attenuate earthquake motions persists. Factors contributing to perpetuation of this myth may include the use of constant values for the unit weight and initial shear wave velocity of the refuse, resulting in the underestimation of peak acceleration illustrated in Tables 1 and 2, and the use of relatively large values of damping for solid waste. Inaccuracies imposed by these factors can be compounded by use in the response analysis of a single input motion with little energy at the predominant frequency of the waste mass. The result of this combination of factors has been postulation by some investigators of unconditional attenuation of earthquake ground motions by solid waste landfills.

Observations of the response of the OII landfill in recent earthquakes and both equivalent-linear and non-linear response analyses indicate that the amplification potential of landfills may be similar to that of soft soil deposits. Figure 3 shows the relationship between the peak ground acceleration at a bedrock outcrop and the peak acceleration at the surface of soft soil deposits proposed by Idriss (1990). Also plotted on this figure are observed peak accelerations at OII from four recent earthquakes and results of D-MOD analyses. The D-MOD analyses were performed using the Landers outcrop record from the OII site (0.03 g peak acceleration), the

Yerba Buena outcrop record from the 1989 M 7.1 Loma Prieta earthquake (0.07 g peak acceleration), the Pacoima Dam outcrop record from the Northridge earthquake (0.44 g peak acceleration), and 15, 45, and 91 m-thick waste columns. The three accelerograms were scaled to peak accelerations of 0.1 g, 0.3 g, and 0.5 g for the analyses. The observed and predicted landfill motions presented in Figure 3 clearly demonstrate that ground motion amplification can occur in solid waste landfills.

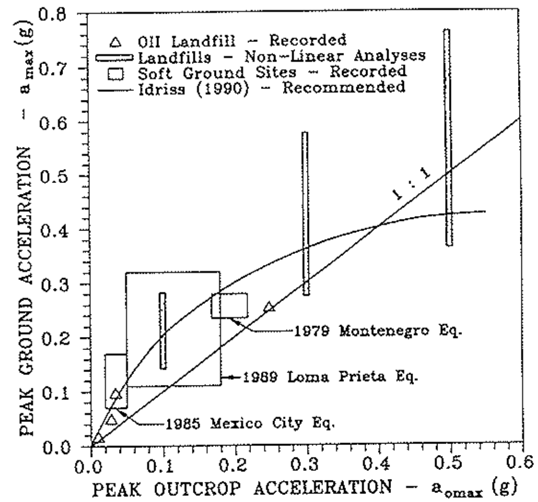

FIG. 3. Amplification of Peak Horizontal Acceleration

The large amplification values shown on Figure 3 for 0.3 g and 0.5 g peak outcrop accelerations correspond to cases wherein a low intensity motion (e.g. Yerba Buena-Loma Prieta or OII-Landers) was scaled to a high intensity. This scaling creates a motion with a relatively enhanced long period energy content with respect to the intensity level that may not be representative of real earthquake motions. Therefore, the large amplification values from the scaled-up low intensity outcrop motions may not be realistic. If the large amplification values from the scaled-up motions are discounted, Figure 3 indicates that the Idriss (1990) soft soil curve may also provide a good description of the amplification potential of solid waste landfills.

Limitations of Equivalent-Linear Response Analyses

The non-linear analyses used to generate Figure 3 can be used to illustrate the potential limitations of equivalent-linear analyses. Figure 4 compares the acceleration response at the landfill surface from SHAKE and D-MOD analyses for base input motions with peak accelerations of 0.1 g and 0.5 g using the Yerba Buena-Loma Prieta record and a 45 m column of refuse. Along with the results presented in Figure 2 and Table 2, Figure 4 demonstrates that, while non-linear and equivalent-linear response analyses may give similar results for low intensity motions (where non-linear effects are relatively insignificant), results from equivalent-linear analyses calibrated on the basis of ground motions of intensity less than 0.4 g may diverge significantly from results of non-linear analyses when the intensity of the bedrock motion exceeds 0.4 g (where the authors' experience indicates that the non-linear behavior of soils becomes an important factor in seismic response).

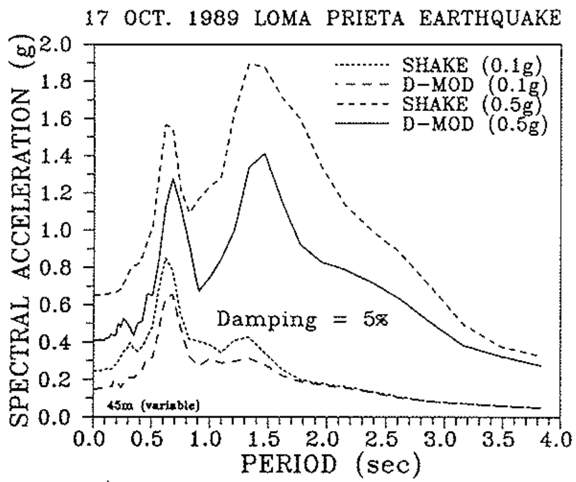

FIG 4. Comparison Between Equivalent-Linear and Non-Linear Models

Shear Stress on the Failure Plane

For a Newmark-type seismic deformation analyses of a landfill, the shear stress time history along the failure plane identified in a limit equilibrium analysis is the essential result from the seismic response analysis. The shear stress time history along the failure plane is directly related to the acceleration time history of the failure mass by Newton's first law of motion (Force = mass *x* acceleration). For a one dimensional site response analysis, the shear stress time history at a given depth is related to the acceleration time history of the overlying layers as follows:

$$\tau(t) = \frac{\sum_{i=1}^{n} h_i \, \rho_i \, g \, a_i(t)}{\sum_{i=1}^{n} h_i \, \rho_i \, g} \qquad (1)$$

where h_i is the thickness of the i^{th} layer above the failure surface, ρ_i is the mass

density of the i^{th} layer, a_i is the acceleration of the i^{th} layer at time t, expressed as a percent of gravity, and τ (t) is the shear stress on the failure plane at time t. Note that in a one-dimensional analysis the denominator of Equation 1 represents the total vertical overburden stress on the plane on which the shear stress is calculated.

Equation 1 shows that the peak shear stress on the failure plane is directly proportional to the peak average acceleration of the mass above the plane. Makdisi and Seed (1978) showed that the peak average acceleration within an earthen embankment was less than the peak acceleration at the crest and decreased systematically with depth. One of the primary reasons for the systematic decrease of peak average acceleration with depth is that the peak acceleration of the various layers are not in phase. Therefore, the peak acceleration of the crest is averaged with an acceleration less than peak in the layer below the crest to determine the average acceleration of the entire mass.

Figure 5 presents the peak acceleration and peak average acceleration versus depth from nine of the D-MOD analyses used to develop Figure 3. Also shown with the peak average acceleration profiles is the representative peak average acceleration profile for earth embankments developed by Makdisi and Seed (1978). The results presented in Figure 5 illustrate the difference between peak acceleration versus depth and peak average acceleration versus depth and indicate that the peak average acceleration at the base of a solid waste landfill is unlikely to exceed 40 percent of the peak crest acceleration. The Idriss amplification curve if Figure 3 indicates that the peak crest acceleration of the landfill is unlikely to be more than 2.5 times the peak outcrop acceleration for peak outcrop accelerations in excess of 0.05 g. Therefore, it may be concluded that, for peak outcrop accelerations in excess of 0.05 g, the peak average acceleration of the waste mass between the base and crest of the landfill is unlikely to exceed the peak outcrop acceleration, except possibly for thin veneers (less than 15 m) of waste.

Influence of Geosynthetic Interfaces

The use of geosynthetic cover and liner systems can introduce continuous interfaces with potentially low shear strengths into the landfill. It has been suggested that these low shear strength interfaces may have a beneficial effect on the seismic response of the landfill similar to that of frictional base isolation systems for buildings (USC, 1994). Kavazanjian et al. (1991) have demonstrated the potential application of geosynthetic materials as frictional base isolation systems in shaking table and centrifuge model tests. The potential impact of low shear strength geosynthetic interfaces on the seismic response of a landfill was evaluated by introducing thin layers with shear strengths typical of soil-geosynthetic material interfaces into a non-linear D-MOD analyses. The elasto-plastic behavior of these thin interface elements was assumed to represent the slip that may occur at the geosynthetic interfaces.

To illustrate the influence of slip at low shear strength geosynthetic interfaces on landfill response, two D-MOD analyses for a 45 m solid waste column subject to the Pacoima-Northridge record scaled to a 0.5 g peak acceleration were

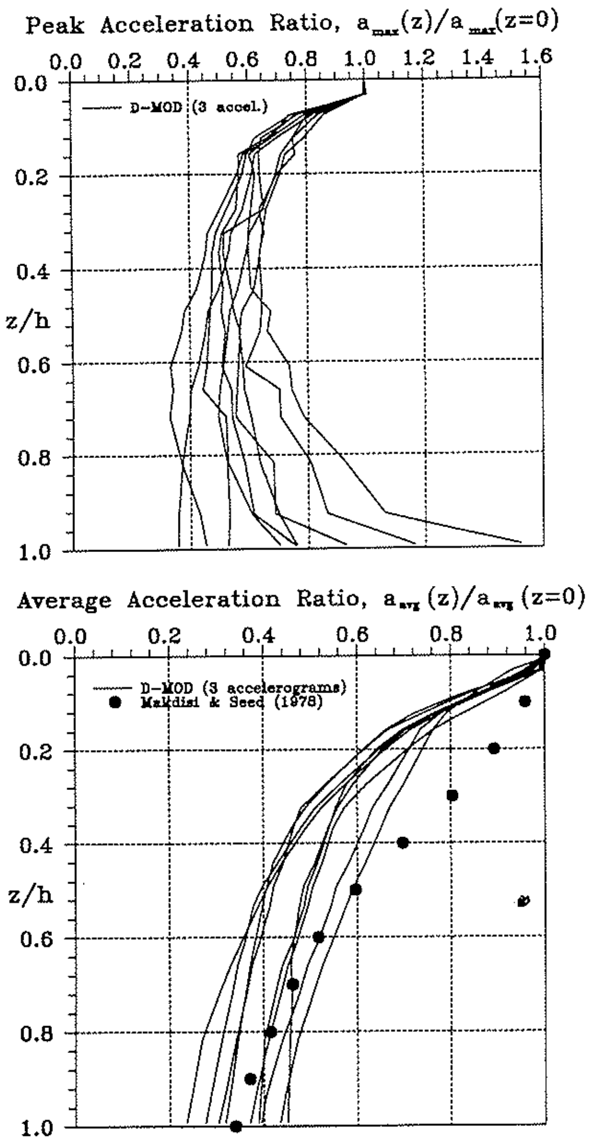

FIG. 5. Maximum Peak Acceleration and Average Acceleration versus Depth

performed. One analysis was performed without interface elements and one analysis was performed using two interface elements: one at the base of the waste mass and one 0.9 m below the top of the landfill, beneath a cover soil layer. An interface shear resistance corresponding to a friction coefficient of 0.20 (friction angle equal to 11 degrees) was used for the interface elements. The average acceleration of the waste mass from these analyses is presented in Figure 6 along with the base input motion. These results indicate that the low shear strength interfaces associated with geosynthetic liners and covers may have a beneficial effect with respect to reducing the peak intensity of seismic motions. However, this benefit must be weighed against the detrimental effects of a low shear strength interface on the overall stability of the liner and cover system and the ability of the interface materials to sustain displacement without impairment to the integrity of the containment system.

Summary and Conclusion

Strong motion records obtained in recent southern California earthquakes at the OII landfill provide a basis for calibration of one-dimensional seismic response analyses of landfills with the observed behavior of a solid waste landfill. Comparison of equivalent-linear SHAKE and non-linear D-MOD analyses to the observed response of OII provide a set of calibrated dynamic material properties for seismic response analysis of solid waste. The observed and predicted response at OII combined with parametric studies of the seismic response of solid waste using the calibrated properties yields insight into fundamental aspects of the seismic behavior of solid waste landfills.

Use of constant values for the unit weight and initial shear wave velocity of the solid waste is shown to introduce significant errors into seismic response analyses, particularly at the top of the landfill. Observations of the response of the OII landfill and the results of non-linear analysis using D-MOD demonstrate that, contrary to a belief widely-held in practice, outcrop seismic motions clearly can be amplified at the crest of landfills. Observations at OII have yielded a peak acceleration amplification factor of 3 and spectral amplification factors of over 10 for outcrop motions of low intensity (peak outcrop accelerations less than 0.04 g). These observations and the non-linear analyses indicate that the amplification curve for soft soil sites developed by Idriss (1990) may also be appropriate for evaluating the amplification potential of solid waste landfills. The analyses also indicate that, with the exception of relatively thin veneers of refuse, the peak average acceleration at the base of a landfill is not likely to exceed either the peak outcrop acceleration or 40 percent of the peak acceleration at the top of the landfill.

Comparison of results from equivalent-linear response analyses to observations of seismic response at OII and to results from truly non-linear analyses illustrates potential limitations of the equivalent-linear response method. For low amplitude outcrop motions (e.g., the 0.1 g bedrock motion at OII from the Landers earthquake), results from the equivalent-linear response analyses agree reasonably well with the observed response at OII and results of non-linear analyses. As the

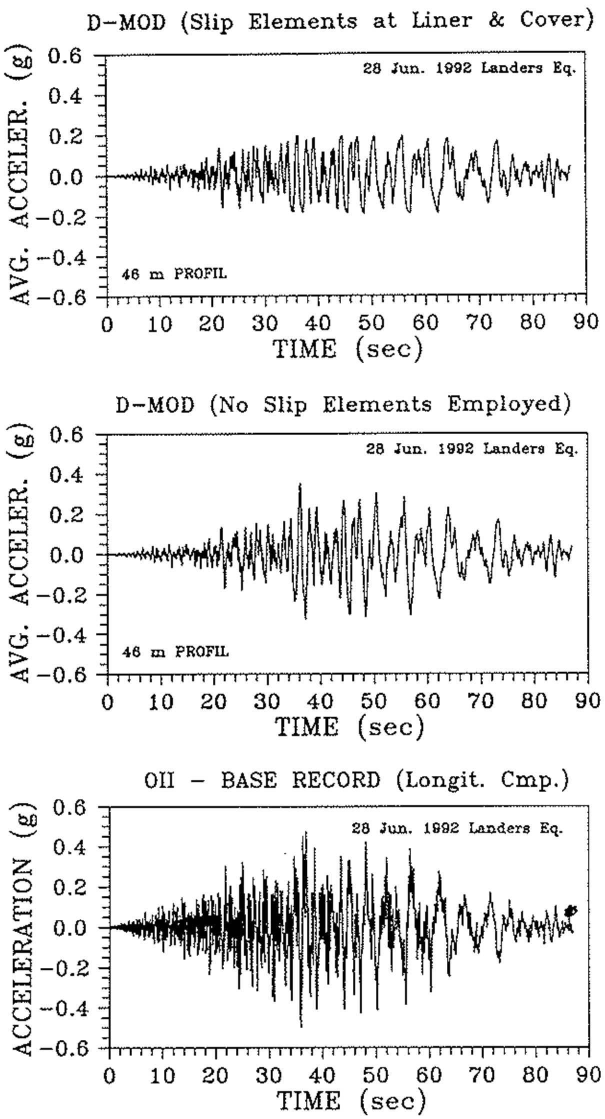

FIG. 6. Influence of Interface Slip on Seismic Response

intensity of the bedrock outcrop motion increases,the discrepancy between results from equivalent-linear analyses and the observed response at OII and results from truly non-linear analyses increase. For the 0.25 g bedrock motion at OII from the Northridge earthquake, equivalent-linear analyses using parameters that gave the best fit between observed and predicted acceleration response at spectral periods greater than 1 second significantly over-predicted the peak spectral acceleration response of the landfill, which occurred at a period of around 0.5 seconds. Use of equivalent-linear parameters that yield good agreement in the 0.5-second period range significantly under-predicts both the peak acceleration at the top of the landfill and the acceleration response at the longer periods that govern seismic deformation potential. At peak outcrop accelerations exceeding 0.4 g, where non-linear stress-strain behavior becomes an even more important factor in seismic response, the best fit equivalent-linear analyses significantly over-predict the acceleration response at the top of the landfill over the range of spectral periods from 0 to 4 seconds.

Non-linear analyses using low shear strength interface elements indicate a potential benefit from low shear strength interfaces with respect to reducing peak seismic response. However, caution is advisable in relying on the predicted benefit in design pending more detailed one- and two-dimensional response analyses of the influence of the low shear strength interfaces on static and seismic behavior of solid waste landfills and evaluation of the impact of displacement along liner and cover interfaces on the integrity of the landfill containment system.

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Seismic Evaluation of Municipal Solid Waste Landfills

Sukhmander Singh[1], M. ASCE, and Joseph I. Sun[2], M. ASCE

ABSTRACT: This paper discusses the seismic response of Municipal Solid Waste Landfills (MSWL), summarizes current practice, presents case histories of MSWL performance during recent earthquakes and develops simplified procedures to estimate amplification of seismic ground motions by MSWL and estimate shear strains likely to develop within the clay liners during earthquakes. Results of seismic response analyses (for different levels of base motion) performed by the authors and other investigators are examined to evaluate the impact of stiffness and height of the refuse fill on the overall response. The authors noted a strong influence of refuse shear wave velocity on the landfill response and prepared charts for preliminary assessment. The importance and effects of low and high frequency contents of the base motions are also addressed. An attempt is made to relate earthquake induced displacements along the interface of the geomembrane/clay liner to strains developed in the clay liner. It is shown that the development of shear distortions leading to cracking in the clay liner is governed by the interface friction angle, the maximum shear stresses developed at the interface, and the material characteristics (PI) of the clay liner. After the sliding begins, it is shown, shear strains are independent of the permanent displacements estimated using Newmark or Makdisi-Seed approach.

INTRODUCTION

There have been extensive studies on slope stability of Municipal Solid Waste Landfills (MSWL) over the past decade. Nowadays, slope stability studies for MSWL are routinely performed by design engineers and consultants. Although these studies

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[1]Professor and Chairman, Dept. of Civil Engineering, Santa Clara University, Santa Clara, California 95053

[2]Project Engineer, Woodward Clyde Consultants, Oakland, California