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EVALUATION OF MSW PROPERTIES FOR SEISMIC ANALYSIS

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ABSTRACT

In situ measurements and observations of field performance provide a valuable source of information on the properties of municipal solid waste (MSW) for analysis of landfills. "Static" properties of MSW such as unit weight and shear strength are evaluated from observations made during and after waste placement, including records of tonnage of waste received and cover soil used during disposal, observations of stable MSW slopes and in situ load tests. "Dynamic" properties of MSW such as modulus and damping are evaluated from observations of the performance of landfills subject to strong ground motions and by geophysical testing.

INTRODUCTION

Seismic design of MSW landfills is complicated by difficulty in obtaining information on the properties of MSW. Difficulties in evaluating appropriate MSW properties for seismic stability and deformation analyses are not limited to the "dynamic" properties of small strain shear modulus and strain-dependent modulus reduction and damping factors. Appropriate values for the "static" properties of MSW unit weight and shear strength required for seismic stability and deformation analyses are also difficult to establish. The selected value of these static properties

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can have a significant influence of the results of dynamic analyses. Considering the difficulty associated with the evaluation of MSW properties, design engineers often rely on sensitivity studies and conservative assumptions in performing and interpreting the results of seismic analyses for MSW landfills.

The conventional approach to establishing geotechnical properties of field sampling and laboratory testing is of limited value in evaluating the properties of MSW. Limitations of this approach include constraints on sampling of MSW related to health and safety issues and the small size of test specimens relative to the inhomogeneity of waste and the sizes of the waste constituents. Considering these difficulties, in-situ measurements and observations of field performance provide perhaps the best means of evaluating the properties of MSW for seismic analyses.

SEISMIC ANALYSIS OF SOLID WASTE LANDFILLS

Seismic stability and deformation analyses of MSW landfills rely primarily upon methods developed for seismic analysis of earth structures (Seed and Bonaparte, 1992; Repetto et al., 1993). Seismic analyses for MSW landfills typically employ pseudo-static limit equilibrium stability analyses to evaluate the yield acceleration of potential slip surfaces and seismic response analyses to assess the acceleration response of the waste mass. If the peak average acceleration of the failure mass from the seismic response analysis exceeds the yield acceleration from the limit equilibrium analysis, a "Newmark" seismic deformation analysis is performed to evaluate the potential for permanent seismic deformations. The Newmark permanent seismic deformation analysis is based upon the yield acceleration from the stability analysis and the acceleration response of the waste mass from the seismic response analysis.

Pseudo-static limit equilibrium stability analyses are usually performed using standard computer programs for geotechnical slope stability analysis. Seismic response analyses of landfills typically employ standard computer programs for equivalent-linear one-dimensional site response analysis. Permanent seismic deformation analyses typically employ either a computer program developed for the specific purpose of implementation of Newmark's method for calculating seismic displacement or charts developed from Newmark analyses performed by previous investigators.

MATERIAL PROPERTIES FOR SEISMIC ANALYSIS

The waste properties required for the seismic analysis of landfills are the same as the soil properties required for seismic analyses of earth structures. For pseudo-static limit equilibrium stability analyses and one-dimensional equivalent-linear site response analyses, the required properties include unit weight (or mass density), initial shear wave velocity, shear modulus reduction curve, and equivalent viscous damping curve. The initial shear wave velocity together with mass density defines the initial, small strain, shear modulus.

For the "static" waste properties of unit weight and initial shear wave velocity, it is important to provide the distribution versus depth, and not just a single representative, or average, value for these parameters. Kavazanjian and Matasović

(1994) have demonstrated that use of average values for unit weight and initial shear wave velocity in seismic response analyses can lead to discrepancies of over 100 percent for the peak acceleration at the top of the landfill and 40 percent for the peak average acceleration of the landfill compared to analyses in which these properties vary with depth. Typically, no attempt is made to differentiate between dynamic and static shear strength for MSW. However, available data (Siegel et al., 1990) and the authors observations indicate there may be some difference between the shear strength that is mobilized for these different loading conditions.

The "dynamic" properties of shear modulus and equivalent viscous damping are generally provided as a function of a representative cyclic shear strain. The representative cyclic shear strain is generally set equal to some fraction of the maximum shear strain. Therefore, the effective strain factor used to relate the maximum cyclic shear strain from the analysis to the representative cyclic shear strain is also a required parameter for equivalent-linear site response analyses. For a Newmark permanent seismic deformation analysis, no additional material properties are needed. The required input parameters are not material properties, but are derived from the results of the seismic response and limit equilibrium analyses.

MSW Unit Weight

Values of MSW unit weight immediately after placement in a landfill are typically reported by landfill operators based upon daily estimates of waste tonnage, cover soil quantities, and waste lift thicknesses. Average in-place unit weights for MSW landfills derived from waste and cover soil quantities and landfill surface elevations over the life of MSW landfills cited by landfill owners and operators for the purposes of evaluating landfill capacity are often used for engineering analyses of stability and seismic response. However, few studies have attempted to evaluate the distribution of unit weight with depth within the landfill or changes in unit weight with overburden pressure and/or time. Kavazanjian and Matasović (1994) have demonstrated that the assumed distribution of unit weight within the landfill can have a significant influence on the results of seismic response analyses.

Average in-place unit weights used by owners and operators for landfill capacity estimates are typically in the range of 8.6 to 10.2 kN/m^3. Values in this range have also been used for seismic analysis by Singh and Murphy (1990), Sharma and Goyal (1991), and Repetto et al. (1993). Fassett et al. (1994) provide a summary of reported values of in-place unit weight for MSW from a variety of sources. Unit weight values summarized by these investigators vary from 2.9 kN/m^3 to 14.4 kN/m^3, with a value of 15.6 kN/m^3 reported for one special case. While few details are provided as to the conditions under which these values apply, the lower values may be assumed to correspond to uncompacted or poorly compacted waste immediately after placement and the higher values may be assumed to correspond to older waste under relatively high overburden pressures.

Initial in-place unit weights of MSW reported by Fassett et al. vary from 2.9 to 7.5 kN/m^3, or 500 to 1300 pounds per cubic yard in the units typically used in practice. The higher end of this range of initial in-place unit weights may be

assumed to correspond to modern landfills using good standards of practice for waste compaction and daily cover application. In fact, some southern California landfills have permit conditions requiring minimum initial waste unit weights of over 7.0 kN/m^3 (1200 pounds per cubic yard). Primary factors influencing the initial in-place unit weight of MSW include waste composition, volume of daily cover soil, and compactive effort employed during placement of the waste.

The initial in-place unit weight will increase with compression immediately following application of overburden pressure due to waste placement. The in-place unit weight may also increase with the additional compression that occurs over time. Earth Technology (1988), in reporting on a field and laboratory studies performed at the Puente Hills landfill near Los Angeles, developed an interpreted profile of unit weight versus depth for that landfill. This interpreted profile was developed from measurements of unit weight on drive samples recovered for laboratory testing and down-hole geophysical gamma-gamma logging. The resulting interpreted unit weight profile, shown in Figure 1, varied from 3.3 kN/m^3 at the surface to 12.8 kN/m^3 at depths greater than 60 m.

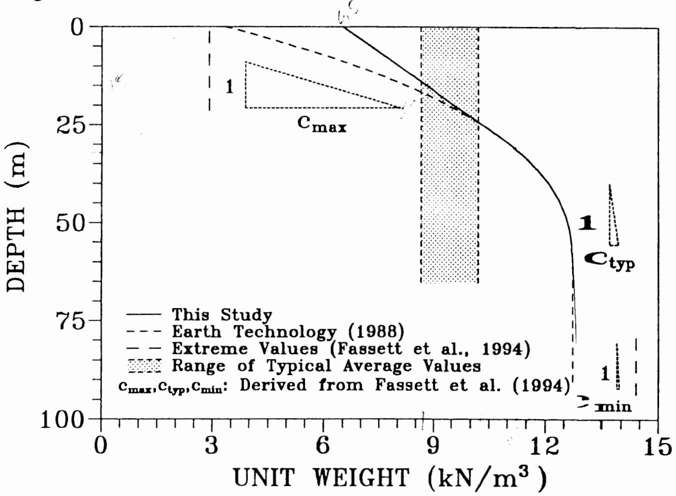

FIG. 1 Unit Weight Profile for MSW

Maximum and minimum MSW unit weights and derived values of maximum, typical, and minimum MSW compressibility, from Fassett et al. (1994), and the range of typical unit weights used for capacity estimates are plotted in Figure 1 for comparison with the profile developed by Earth Technology for the Puente Hills landfill. The Puente Hills profile agrees well with the range of unit weight and waste compressibility values reported by Fassett et al. and with the typical average values used for capacity estimates. However, the initial in-place unit weight used at the surface in the interpreted Puente Hills profile is too low for modern landfills using good waste placement practice. Furthermore, the constant unit weight used at depths in the interpreted Puente Hills profile is not consistent with the assumption that waste will continue to compress with additional confining pressure, even at very large confining pressures. Therefore, based upon reported initial in-place waste densities for modern landfills and the waste compressibility values reported by Fassett et al. (1994), the interpreted Puente Hills profile was modified to develop the authors' profile shown on Figure 1. In the absence of site specific information ,the authors have used this profile in engineering analysis of the seismic response of modern MSW landfills.

MSW Shear Strength

MSW shear strength values reported in the technical literature vary widely, with friction angles as low as 10 degrees and as high as 53 degrees and cohesion values varying from 0 to 67 kPa. Many of the lower values are directly contradicted by observations of stable landfill slopes in the field. Therefore, a critical re-evaluation of the available shear strength data on MSW was performed by the authors. The authors used selected data from this re-evaluation, supplemented with shear strength back-calculated from observations of stable waste slopes in the field, to develop the assessment of MSW shear strength presented herein.

In performing the assessment of MSW shear strength, the authors recognized that factors such as waste compressibility and strain compatibility should be considered when developing strength parameters for limit equilibrium analysis. The authors assessment of MSW shear strength was based primarily on shear strengths back-calculated from case histories and the results of in-situ testing. With the exception of one set of data from large scale tests, laboratory test data on MSW shear strength was not used. The excluded laboratory data was not considered reliable due to either the use of processed waste in the testing program or the small size of the MSW samples relative to the inhomogeneity of MSW landfills. Field and laboratory test data considered reliable and used in the re-evaluation of MSW shear strength are summarized in Table 1.

TABLE 1 DATA USED IN THE MSW SHEAR STRENGTH RE-EVALUATION

REFERENCE	DATA TYPE	RESULTS	COMMENTS
Pagotto and Rimoldi (1987)	Back calculation from plate bearing tests.	$\phi = 22°$, $c = 29$ kPa	No data on waste types or test procedures are provided.
Landva and Clark (1990)	Laboratory direct shear tests on MSW.	$\phi = 24°$, $c = 22$ kPa to $\phi = 39°$, $c = 19$ kPa	Normal stresses up to 480 kPa. Lower strength not used in Fig. 2, corresponds to shredded waste.
Richardson and Reynolds (1991)	Large direct shear tests performed in situ	$\phi = 18°$ to $43°$ and $c = 10$ kPa	Normal stresses range from 14 to 38 kPa. Unit weight of waste and cover estimated as 15 kN/m^3.

Pagotto and Rimoldi (1987) reported the results of plate-bearing tests performed at an *"urban waste"* landfill in Italy. No details are given on waste properties, test methods, or test interpretation. Considering the limitations of plate-bearing tests, these results must correspond to very low normal stresses in the waste. Landva and Clark (1990) presented the results of direct shear tests on MSW materials conducted in a 434 mm by 287 mm direct shear box at normal stresses up to 480 kPa. Results reported for fresh shredded refuse containing a large amount of plastic were not used in the re-evaluation as they are not considered representative of MSW in situ. Richardson and Reynolds (1991) reported the results of tests performed on MSW using a 1.5 m by 1.5 m direct shear box. The box was loaded with concrete blocks to normal stresses between 14 and 38 kPa.

The data in Table 1 was supplemented by the authors with data from back-analyses of existing MSW landfill slopes known to be stable. Table 2 presents back calculated MSW shear strengths from four existing landfills (GeoSyntec Consultants, 1993).

TABLE 2 BACK-ANALYSIS OF EXISTING LANDFILL SLOPES

LANDFILL	AVERAGE SLOPE		MAXIMUM SLOPE		WASTE STRENGTH, ϕ		
	Height (m)	Slope (H:V)	Height (m)	Slope (H:V)	FS = 1.0	FS = 1.1	FS = 1.2
Lopez Canyon, CA	120	2.5:1	35	1.7:1	25°	27°	29°
OII, CA	75	2:1	20	1.6:1	28°	30°	34°
Babylon, NY	30	1.9:1	10	1.25:1	30°	34°	38°
Private Landfill, OH	40	2:1	10	1.2:1	30°	34°	37°

Note: FS = Factor of safety for back analysis assuming c = 5 kPa.

The back-calculated friction angles for MSW presented in Table 2 were obtained assuming a cohesion of 5 kPa using the modified Bishop method of slices. As the slopes at these landfills have been standing for up to 1[illegible] years without excessive deformation or other signs of impending instability, the factors of safety against slope failure within the waste are certainly larger than 1[illegible] and probably greater than or equal to 1.3. To be conservative, the authors used results for a factor of safety of 1.2 in the MSW shear strength assessment.

The authors assessment of the available shear strength data was performed in a manner similar to Howland and Landva (1992). These investigators presented available data from the technical literature on MSW strength on a plot of shear stress at failure versus normal stress. From the plot, they derived strength parameters that represented the *"lower bound"* for the entire body of data. The lower-bound strength parameters are strongly influenced by the back-calculated waste strengths from the failure of a New Jersey landfill where the slip surface passed through a very soft tidal marsh deposit. Failure of the marsh foundation soil occurred at relatively small displacements, resulting in only a portion of the waste strength being mobilized at failure. Thus, if a factor of safety of 1.0 is assumed, back-analyses of this failure will underestimate the waste strength. In addition, the results the back-analysis for this case is highly dependent on the assumed shear strength of the foundation soil. Uncertainty associated with the foundation shear strength significantly impacts the degree of confidence with which the waste strengths back calculated from this study can be relied upon. Therefore, data from the failure of the landfill founded on a soft tidal marsh deposit was not considered in the MSW shear strength assessment.

The lower-bound parameters from Howland and Landva are also strongly influenced by the landfill load test performed at the Operating Industries, Inc. (OII) landfill in Monterey Park, California. This is perhaps the most widely cited source of field data on MSW shear strength. The load test at OII was terminated due to excessive deformation. As the landfill slope did not actually fail during the load test, the actual MSW strength is larger than the strength back-calculated using limit equilibrium analysis and an assumed factor of safety of 1.0 (i.e., incipient failure).

The shear strengths from Tables 1 and 2 are plotted versus normal stress in Figure 2. The data plotted on Figure 2, combined with the observation from landfill operations that excavated in trenches in waste will remain stable with vertical faces in excess of 6 m in height, appear to support a bi-linear representation of MSW shear strength. Based upon this observation and the data plotted on Figure 2, a Mohr-Coulomb strength envelope consisting of $\phi = 0$ with c = 24 kPa at normal stresses below 30 kPa and $\phi = 33°$ with c = 0 at higher normal stresses was developed for use in stability analyses of MSW landfills.

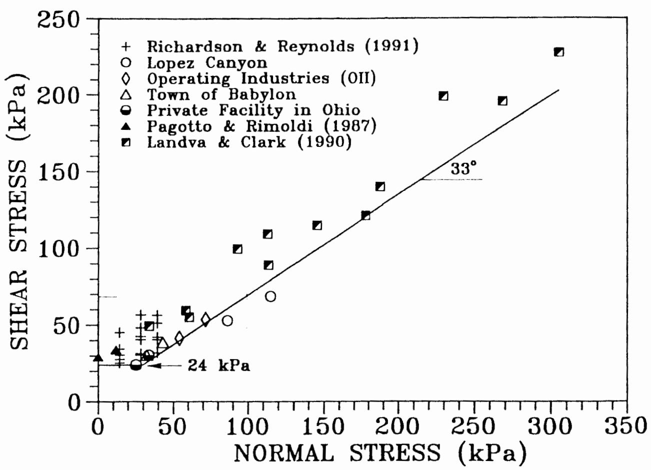

FIG. 2 Shear Strength of MSW

It should be noted that the two data points that fall below the bi-linear strength envelope on Figure 2, from the Lopez Canyon landfill, are back calculated using a static factor of safety of 1.2 for a slope recently subjected to an estimated peak ground acceleration of 0.44 g in the magnitude 6.7 Northridge earthquake of 17 January 1994 without any apparent slope instability. No attempt was made in the strength assessment to distinguish between the static and dynamic shear strength of MSW. A number of other MSW landfills besides the Lopez Canyon landfill were subjected to strong ground motions from the Northridge earthquake. Several landfills were in the epicentral region where peak ground accelerations were estimated to be in excess of 0.4 g. Slopes at these landfills were typically on the order of 3H:1V. There were no reported waste slope stability problems at these landfills. Back analysis of the performance of these landfills may demonstrate that the dynamic shear strength of MSW is even higher than the MSW shear strength envelope plotted in Figure 2. Such back analysis is beyond the scope of this paper.

SHEAR WAVE VELOCITY OF MSW

A number of investigators have reported in situ measurements of MSW shear wave velocity from geophysical surveys, including seismic refraction, down-hole, cross-hole, and surface wave velocity surveys. Field measurements of ambient vibrations and of ground motions from small earthquakes also provide a basis for evaluation of MSW shear wave velocity.

Cross-hole shear wave velocity surveys have been reported at the Puente Hills landfill in Los Angeles (Earth Technology, 1988) and the Brookhaven landfill on Long Island, New York (Carey et al., 1993). Shear wave velocities varying from 240 m/s at a depth of 6 m to 270 m/s at a depth of 14 m were reported at Puente Hills for waste buried below 6 m of soil fill. At the Brookhaven landfill, the measured shear wave velocity is reported to have ranged from 185 to 478 m/s, though the depth at which these measurements were made is not reported. The maximum depth of the landfill was reported along with a plot of Young's modulus versus depth derived from the shear wave velocity . Based upon the maximum waste depth and the maximum depth for which modulus data were reported, the maximum depth at which the shear wave velocity was measured is inferred to be between 24 and 37 m. The higher shear wave velocity is assumed to correspond to the deeper depths.

Kavazanjian et al. (1994) report on shear wave velocity profiles derived from Rayleigh wave (surface wave) measurements made at eight MSW landfills in southern California using both Spectral Analysis of Surface Waves and Controlled Source Surface Wave profiling techniques. Shear wave velocities measured in these surveys varied from as low as 80 m/s near the surface to over 300 m/s at a depth of 30 m.

Sharma et al. (1990) reported on down-hole shear wave velocity measurements at a MSW landfill in Richmond, California. These investigators reported an average shear wave velocity of 198 m/s over the top 15 m of the landfill. In a down-hole survey performed as part of the Puente Hills investigation by Earth Technology (1988), an average velocity of 287 m/s was reported for MSW over a depth interval of 6 to 23 m. Woodward Clyde Consultants (WCC, 1987) reported an average shear wave velocity of between 206 and 244 m/s from seismic refraction surveys for the OII landfill. For the same landfill, Hushmand Associates (1994) reports that ambient vibration measurements and measurements of ground motions from small magnitude earthquakes yield a predominant period of between 0.8 and 1.2 seconds for the landfill. Using the maximum reported waste thickness of about 76 m, these periods correspond to average shear wave velocities of between 244 and 366 m/s as back calculated by the authors.

The field measurements of MSW shear wave velocity cited above, plotted on Figure 3, were interpreted by the authors to develop a typical profile for use in seismic analysis. In developing this profile, the relatively high velocities from the cross-hole results from Brookhaven were discounted due to uncertainty about the depths of the measurements. Cross hole data is also suspect because of the potential for "short circuiting" of the travel path between boreholes by the daily cover layers. The down-hole results and the ambient vibration and earthquake motion-derived values were considered as average values to which the typical profile should conform. Based upon these considerations, the shear wave velocity profile shown on Figure 3 was developed for use in seismic analysis of MSW landfills in the absence of site-specific data.

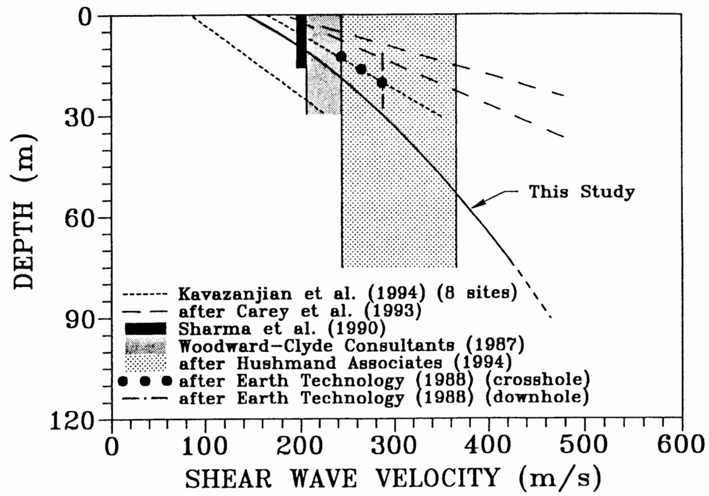

FIG. 3 Shear Wave Velocity of MSW

Equivalent-Linear Parameters for MSW

Due to a lack of documented case histories, current practice for seismic response analysis of MSW landfills relies primarily on engineering judgement in choosing equivalent-linear response parameters for MSW. Modulus reduction and damping curves are typically assumed to correspond to previously established curves for clay or peat (Earth Technology, 1988; Singh and Murphy, 1990; Sharma and Goyal, 1991; Seed and Bonaparte, 1992; Repetto et al., 1993). The same effective strain factor used in the analysis of earth structures is usually assumed for analysis of landfills. Until recently, neither cyclic testing data nor field observations of the response of landfills to dynamic loading have been available for evaluation of the equivalent-linear properties of MSW.

Strong motion records recorded at the OII landfill in recent earthquakes have, for the first time, provided data for evaluation of the equivalent linear parameters of MSW. Two strong motion recording stations, one at the crest of the landfill and one at an outcrop adjacent to the landfill, have been operated at the landfill site since 1989. These stations have captured ground motion records from five earthquakes of magnitude greater than 5.0 with peak horizontal ground accelerations (PHGA) from 0.03 g to 0.25 g at the outcrop and from 0.05 g to 0.26 g at the crest (Hushmand Associates, 1994). Among the most significant of these records are those from the 17 January 1994 M 6.7 Northridge earthquake, where recorded PHGA were 0.25 g at the outcrop and 0.26 g at the landfill crest, and the 28 June 1992 M 7.4 Landers earthquake where the PHGA at the outcrop of 0.03 g was amplified by a factor of three to yield a PHGA of 0.09 g at the landfill crest.

Back analysis of the OII strong motion records provides a rational basis for the evaluation of the equivalent-linear response parameters of solid waste. While OII is not a "typical" MSW landfill in that it received both industrial and liquid wastes while in operation, it is primarily composed of MSW. Therefore, in the absence of any other data, modulus reduction and damping curves and an effective strain factor back calculated from the observed response at OII provide the best available information for evaluation of the equivalent-liner properties of MSW. A plan view and cross section showing the location of the two strong motion recording stations at the OII landfill is presented in Figure 4. Figure 5 shows the acceleration time histories in the longitudinal direction (parallel to Section B-B in Figure 4) from the Northridge and Landers events at the outcrop and at the crest of the landfill.

Best-fit equivalent-linear parameters for MSW were visually identified through trial and error using the computer program SHAKE91 (Idriss and Sun, 1992) and the strong motion records shown in Figure 5. The analyses used damping and modulus reduction curves for peat from Seed and Idriss (1970a), clay from Seed and Idriss (1970b), plasticity index of 15 from Vucetic and Dobry (1991), and MSW from Kavazanjian and Matasović (1994).

The clay and peat curves were used based upon the recommendations of previous investigators (Earth Technology, 1988; Singh and Murphy, 1990; Sharma and Goyal, 1991; Repetto et al., 1993). Kavazanjian and Matasović developed their MSW curves from results of non-linear time-domain analyses using the Modified Kondner-Zelasko (MKZ) constitutive model (Matasović and Vucetic, 1993) back-fit to the OII strong motion records. The Kavazanjian and Matasović modulus reduction and damping curves for MSW, shown in Figure 6, were then developed using the best-fit MKZ parameters to model the hysteretic behavior of MSW in uniform cyclic loading.

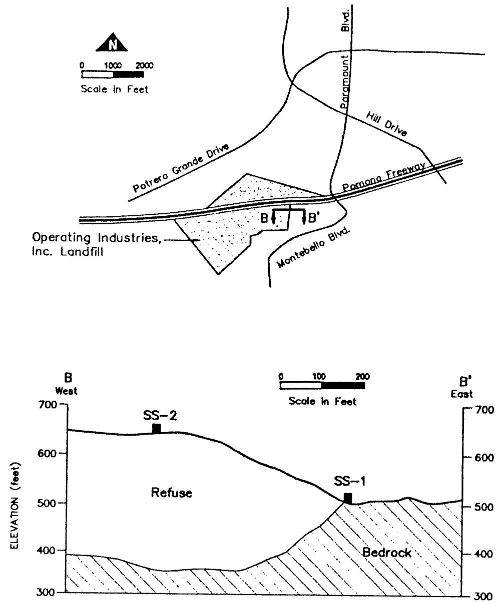

FIG. 4 OII Plan and Longitudinal Section (Hushmand Associates, 1994)

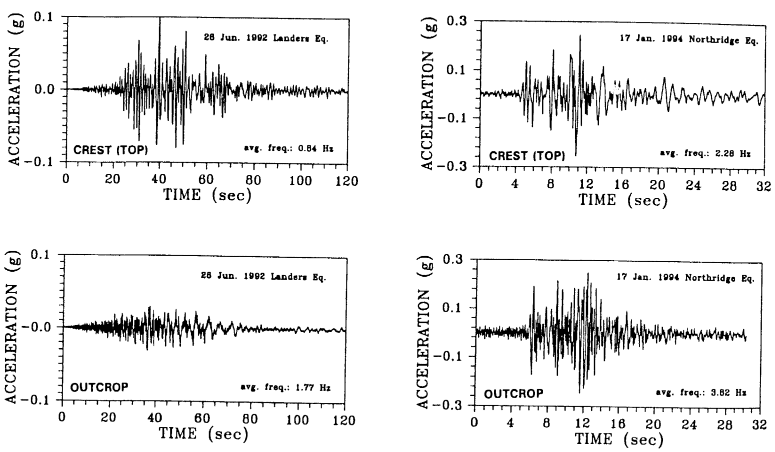

FIG. 5 OII Strong Motion Records, Northridge and Landers Earthquakes

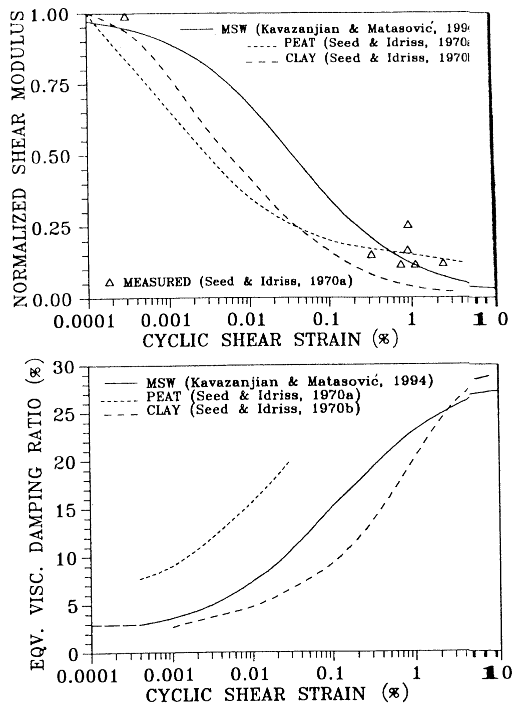

FIG 6. Modulus Reduction and Damping Curves for MSW

The MSW unit weight and shear wave velocity profiles presented in Figures 1 and 3 were used in the trial and error analysis to obtain the best-fit equivalent-linear soil parameters. The upper 1.5 m of the MSW unit weight and shear wave velocity profiles were deleted and replaced with values representative of compacted cover soil to simulate field conditions. The effective strain factor used to compute the representative shear strain from the calculated peak cyclic shear strain for evaluation of modulus reduction and damping factors was varied to achieve the best fit with the observed acceleration response. Both the Northridge and Landers records for OII were used in the analysis.

When comparing the equivalent-linear analysis results to the observed behavior in the Northridge earthquake, it was observed that when the parameters were adjusted to match the peak acceleration, a poor fit was obtained with the rest of the response spectra. Therefore, matching the peak acceleration was discarded as a basis of comparison and the analyses focused on achieving a good fit with the observed response spectra over the broadest possible range of periods, with emphasis placed on the longer periods which contribute the most to seismic deformation potential. In matching computed results to the observed spectra from the Landers event, where most of the motions were in the small strain range, the computed results were relatively insensitive to the choice of modulus reduction and damping curves and effective strain factor. However, significant differences developed in analyses of the landfill response in the Northridge earthquake when the effective strain factor was varied.

In general, the best results for each particular set of damping and modulus reduction curves were obtained using an effective strain factor greater than 0.7. Figure 7 presents a comparison of response spectra for the longitudinal motion at the crest of the landfill calculated using the four sets modulus reduction and damping curves and an effective strain factor of 0.8. The closest fit for the four sets of curves as a group was observed for an effective strain factor of 0.8. Of all the combinations of equivalent linear parameters evaluated, the MSW curves developed by Kavazanjian and Matasović combined with an effective strain factor of 0.8 gave the best agreement between the observed and predicted response of the OII landfill in the Northridge earthquake.

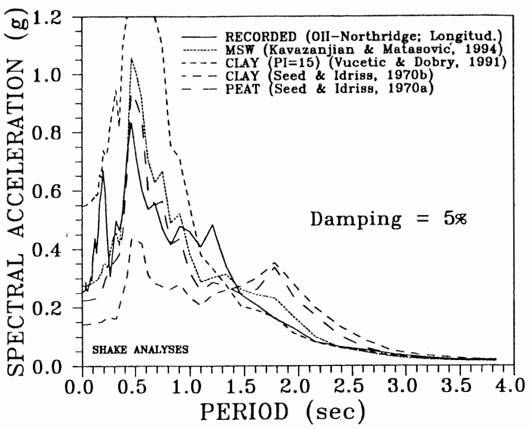

FIG. 7 Observed at Predicted Response at OII, Northridge Earthquake

The Kavazanjian and Matasović MSW modulus reduction and damping curves are plotted in Figure 6 along with the Seed and Idriss (1970b) clay curves, the Seed and Idriss (1970a) peat curves, and the data used by Seed and Idriss to develop their peat modulus curve. The Kavazanjian and Matasović MSW curves provide as close a fit to the peat modulus data as the curves proposed by Seed and Idriss. Seed and Idriss recommended use of an effective strain factor of 0.8 for equivalent-linear analysis of peat, the same value recommended from this study for the Kavazanjian and Matasović MSW curves. This comparison supports intuitive suggestions from earlier investigators that the dynamic behavior of MSW be represented using modulus reduction curves for peat and damping curves for clay.

CONCLUSION

MSW properties required for seismic analyses typically employed in engineering practice include unit weight, shear wave velocity, shear strength, and equivalent-linear modulus, damping, and effective strain factor. Field observations and in situ measurements provide valuable information on these MSW properties.

For unit weight and shear wave velocity, the distribution of these parameters with depth, and not just an average value, should be used in evaluation of seismic response. Figure 1 presents a profile of MSW unit weight versus depth developed by the authors based upon reports of initial in-place unit weight from landfill operators, the range of published values of unit weight and compressibility, and a field investigation at the Puente Hills landfill in southern California. The unit weight profile shown on Figure 1 is consistent with average values of MSW unit weight typically cited in practice for landfill capacity estimates.

A bi-linear shear strength envelope for MSW developed by the authors for use in seismic stability and deformation analyses is presented in Figure 2. This strength envelope is based upon back-analysis of a load test at an MSW landfill, observations of steep but stable slopes at four landfills, and direct shear tests performed in the laboratory and in the field. Observations of landfill performance in the Northridge earthquake suggest that the dynamic shear strength of MSW may be even larger than the shear strength corresponding to the bi-linear envelope shown on Figure 2.

Figure 3 presents a profile of MSW shear wave velocity versus depth developed by the authors. This profile is based on several different types of geophysical velocity surveys at MSW landfills, including down-hole, cross-hole, and surface wave surveys. The shear wave velocity profile shown in Figure 3 is consistent with average shear wave velocities for the OII landfill derived from seismic refraction surveys, ambient vibrations, and ground motions from small magnitude earthquakes.

Figure 6 presents modulus reduction and damping curves for MSW developed from back-analysis of strong ground motions recorded at the OII landfill in the Northridge and Landers earthquakes. These curves were developed from non-linear time-domain response analyses of the OII landfill. The recorded motions at OII were compared with results of equivalent-linear analysis using these MSW curves and using the peat and clay soil curves recommended by previous investigators. The analyses using the Kavazanjian and Matasović curves combined with an effective strain factor of 0.8 gave the best fit with the observed response at OII in the Northridge earthquake over a broad range of periods.

The MSW properties described in this paper provide consistent set of properties for conventional equivalent-linear seismic response and pseudo-static limit equilibrium stability analysis of solid waste landfills. These properties are calibrated based upon available field observations of the behavior of solid waste. In the authors' opinion, such equivalent-linear analyses are appropriate for ground motions of intensity less than or equal to 0.4 g. In the authors experience, when ground motion intensity exceeds 0.4 g non-linear cyclic stress-strain effects start to become important in site response analyses. In such cases, equivalent-linear site response analyses may become unreliable and the design engineer should consider the use of truly non-linear time domain site response analyses (Kavazanjian and Matasović, 1994) for seismic analysis of MSW landfills.

APPENDIX - REFERENCES

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