CYCLIC CHARACTERIZATION OF OII LANDFILL SOLID WASTE

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ABSTRACT: As part of predesign studies for closure of the Operating Industries, Inc. (OII) landfill Superfund site, field and laboratory studies were combined with back analyses of strong motion data to characterize the behavior of the OII solid waste when subjected to strong earthquake shaking. Small strain shear modulus values for the solid waste material were established on the basis of field measurements of shear wave velocity and unit weight. Large-diameter (457 mm) cyclic direct simple shear (CyDSS) testing was performed on reconstituted solid waste specimens to investigate the modulus reduction and damping characteristics of solid waste at large strains. Results of two-dimensional finite element back analyses of strong motion data recorded at the site were combined with the results of CyDSS testing to establish solid waste modulus reduction and damping curves over the range of cyclic shear strain required for site closure design. One-dimensional deconvolution of motions recorded on fill at the base of the landfill was an essential step in the two-dimensional finite element back analyses of strong motion data. The resulting modulus reduction and damping curves indicate that OII solid waste is a fairly linear material in the small to intermediate strain range, but that a significant reduction of shear modulus occurs when the cyclic shear strain exceeds approximately 0.1%.

INTRODUCTION

Scope of Study

As part of predesign studies for closure of the Operating Industries, Inc. (OII) landfill Superfund site, the behavior of the OII solid waste when subject to earthquake-induced cyclic loading was characterized. This cyclic behavior characterization was needed for use in equivalent-linear seismic response analyses carried out in support of predesign analyses for landfill closure design. The cyclic behavior characterization of the OII solid waste includes shear wave velocity, unit weight, and Poisson's ratio profiles from field testing and modulus reduction and damping curves developed using a combination of back analysis of strong motions recorded at the landfill and large-diameter cyclic direct simple shear (CyDSS) laboratory tests on reconstituted solid waste specimens.

The shear wave velocity profile developed for OII solid waste in situ is based upon statistical analysis of the spectral analysis of surface wave (SASW) surveys at 27 locations on the landfill. The unit weight profile is based upon in-situ density testing conducted in three large-diameter (840 mm) bucket auger borings at depths of up to 45 m and in a test trench 6 m deep. The solid waste Poisson's ratio profile was calculated based upon the assumption of linear elastic behavior from compressional and shear wave velocities measured by two different techniques in one borehole.

Two-dimensional finite element equivalent-linear back analysis of strong motions recorded at the landfill was used to develop modulus reduction and damping curves for the solid waste for cyclic shear strains of up to 0.08%. The back analysis relied on the landfill foundation geometry and small strain material properties developed on the basis of the site investigation program. One-dimensional equivalent-linear deconvolution of earthquake motions recorded on compacted soil at the base of the landfill was an essential step of the back analysis. Large-diameter (457 mm) CyDSS testing on reconstituted samples was used to guide the development of the solid waste modulus reduction and damping characteristics at cyclic shear strains larger than 0.08%, the maximum cyclic shear strain calculated in the solid waste by back analysis.

Site Conditions

The OII landfill is located in southern California, approximately 16 km east of downtown Los Angeles (Fig. 1). The site is divided by California State Road 60 (the Pomona Freeway) into a relatively small and level north parcel and the steep-slope 58-ha south parcel where most of the landfilling occurred. The south parcel, the subject of the present study, has been moving toward final closure under the United States Environmental Protection Agency (EPA) Superfund program since 1985. The landfill site was formerly a sand and gravel quarry pit. The approximately 60-m deep pit was filled with solid waste over a 40-year period. There is no evidence that any subgrade preparation or liner installation took place prior to the disposal of solid waste. The top of the landfill ranges from 21 to 76 m above the adjacent ground surface. The maximum thickness of solid waste on the south parcel is approximately 100 m.

Native ground that underlies the landfill is primarily the Tertiary age Pico unit of the Fernando formation, consisting primarily of poorly indurated interbedded sands and gravels with occasional silt and clay lenses. Local pockets of ancient landslide and artificial fill materials are also found at the site. The site accepted residential, commercial, and industrial solid wastes. In addition, liquid wastes were accepted at the landfill at times, primarily at the west end of the south parcel. Waste was disposed of at the site without any separation or compaction. Soil cover was placed on the side slopes of the landfill and on the decks and waste faces as the landfill rose above grade. The landfill last received waste in 1984, after which an interim soil cover was placed on top of the landfill. The cover soils appear to have been derived primarily from local borrow sources and typically vary in classification from silty clay to silty sand. The thickness of the existing soil cover typically varies from 1 m to 5 m.

Seismic Stability Concerns

In September 1988, after the 1987 moment magnitude (M_W) 6.0 Whittier-Narrows earthquake, concerns were voiced about the seismic stability of the landfill mass (Siegel et al. 1990). These concerns were given special attention by EPA due to the proximity of the landfill to the Pomona Freeway and adjacent residences (Fig. 1). As part of the response to these concerns, EPA installed three-component strong motion instruments at the base and top deck of the landfill. Inclinometers

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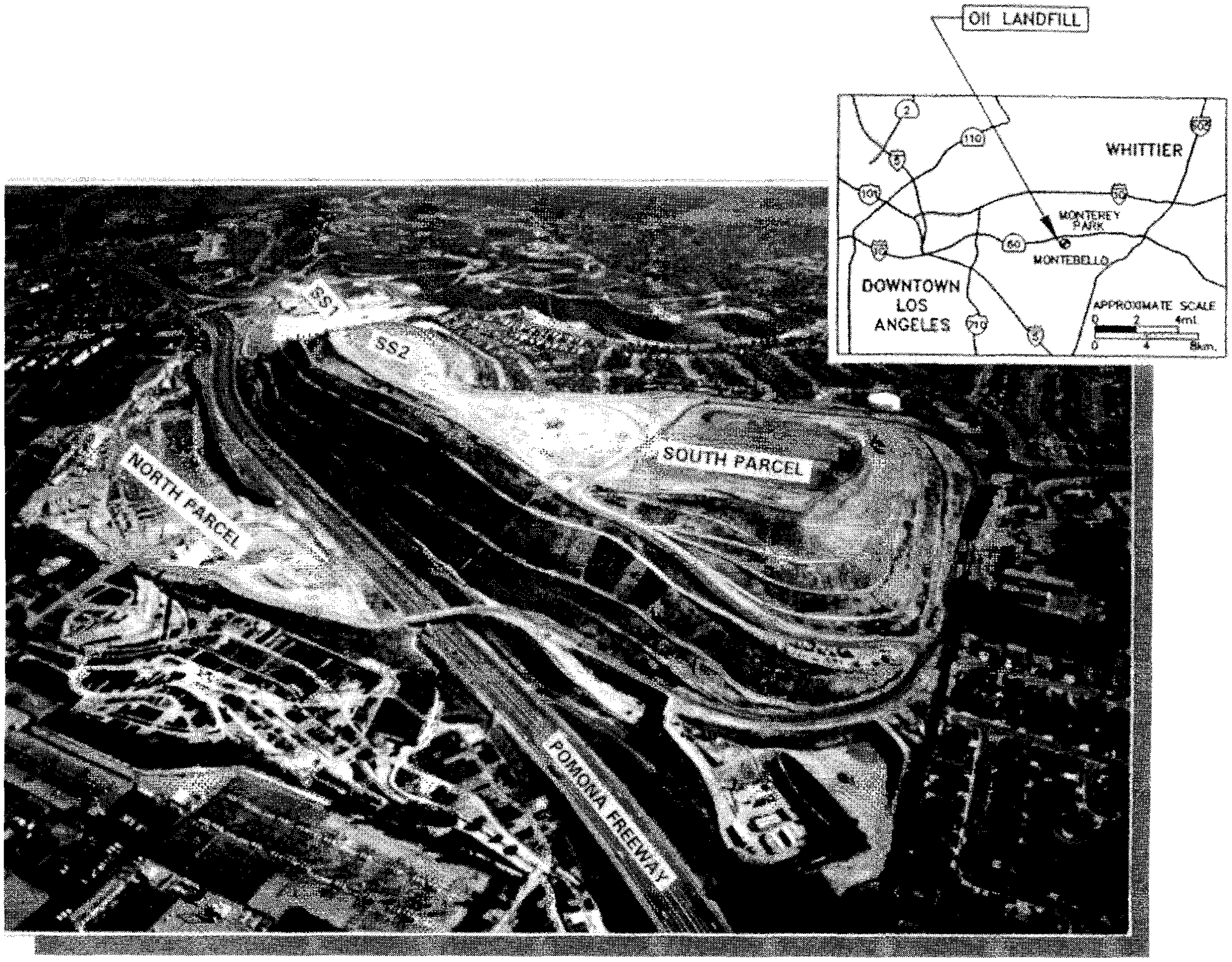


FIG. 1. Aerial View of OII Landfill

and survey monuments were also installed to monitor landfill deformations.

Along with instrumentation and monitoring of the landfill, a variety of site characterization and predesign analytical studies were conducted at the OII site after 1985. These studies were initially conducted by EPA contractors and later continued under EPA oversight by representatives of the potentially responsible parties (PRPs) who assumed responsibility for closure of the south parcel under the Superfund program. Due to continuing concern over seismic response and stability of the landfill, the studies included a comprehensive program of field and laboratory testing specifically focused on providing input for numerical analyses of landfill behavior under static and cyclic loading (GeoSyntec 1996b, 1996c). Results of the field and laboratory testing program and the numerical analyses carried out to characterize the behavior of the OII solid waste subjected to earthquake-induced cyclic loading (GeoSyntec 1996a) are presented herein.

Recorded Ground Motions

The strong motion instrument array at the OII landfill consists of two three-component strong motion instruments. The locations of the strong motion instruments are shown in Figs. 1 and 2. The first instrument, labeled SS1, is located adjacent to the base of the landfill, while the other instrument, labeled SS2, is on the top deck of the landfill. Through April 1994, 34 earthquakes and aftershocks were recorded by these instruments at the OII site. Seismological characterization of these events and the recovered data are presented in Hushmand Assoc. (1994) and PEA (1995).

The 34 events recorded at the OII site included both nearby small magnitude events and distant large magnitude events. Exclusive of the January 17, 1994 M_W 6.7 Northridge earthquake, the largest peak horizontal ground acceleration (PHGA) recorded at the top deck of the landfill was 0.10g in the M_W 7.3 Landers earthquake of June 28, 1992, and the largest PHGA recorded at the base of the landfill was 0.22g in the M_W 5.0 Pasadena earthquake of December 3, 1988. The M_W 7.3 Landers earthquake was the largest magnitude event captured by the instrumentation. The Northridge earthquake was the largest intensity earthquake recorded at the site. A PHGA of 0.25g was recorded at the top deck and a PHGA of 0.26g was recorded at the base of the landfill in the M_W 6.7 Northridge event.

PREVIOUS STUDIES

Previous studies that provide data on cyclic characterization of OII landfill solid waste include Hushmand et al. (1990), Anderson et al. (1992), Kavazanjian and Matasović (1995), Idriss et al. (1995), and Matasović et al. (1995).

Hushmand et al. (1990) studied ambient vibrations and strong motions recorded at the site in a number of small earthquakes, including two M_W 5 events. Based on comparison of base and top deck Fourier Amplitude Spectra, these investigators concluded that spectral energy at frequencies above 3 Hz is attenuated through the landfill, while spectral energy below a frequency of 3 Hz is amplified. Anderson et al. (1992)

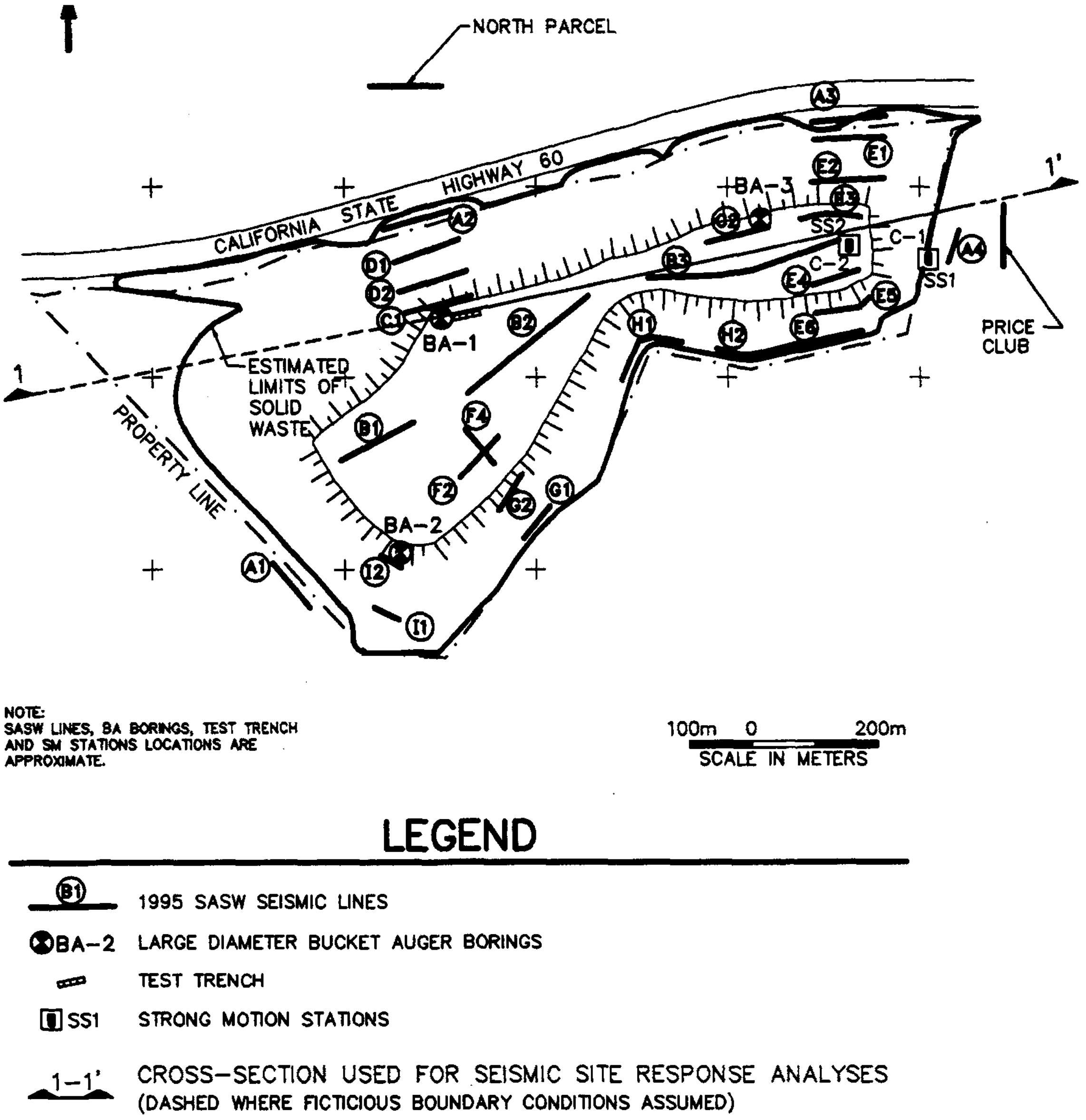


FIG. 2. Location of SASW Lines, Test Trench, and Borings

used the same techniques as Hushmand et al. (1990) to analyze another set of small ($M_W \approx 4$), relatively close earthquakes. They reported up to twelve-fold amplification of spectral amplitudes for frequencies below 1–2 Hz and attenuation in other frequency ranges for these small amplitude events.

Kavazanjian and Matasović (1995) performed equivalent-linear seismic site response analyses of the OII landfill using strong motion records from the January 17, 1994 M_W 6.7 Northridge earthquake. In this study, the authors assumed that the base station motion was a free-field weak rock motion, and they used "typical" solid waste properties from Kavazanjian et al. (1995) to develop modulus reduction and damping curves for solid waste. However, as Matasović et al. (1995) and Idriss et al. (1995) subsequently reported, the base station was later found to be located on compacted fill, not weak rock. In these Matasović et al. (1995) and Idriss et al. (1995) studies, seismic site response back analyses of the OII strong motion records were performed to develop solid waste modulus reduction and damping curves. Both of these studies included deconvolution of the base station records and used field-measured shear wave velocity profiles at the base and top deck stations. Matasović et al. (1995) used one-dimensional equivalent-linear and one-dimensional nonlinear models in their back analyses. Idriss et al. (1995) used a two-dimensional equivalent-linear finite element model for their back analysis.

SITE CHARACTERIZATION STUDIES

Site-Specific Exploration and Testing Program

As part of the OII landfill site characterization studies, extensive site-specific exploration and testing were performed at the site. Initial predesign field exploration studies included air-rotary borings with downhole seismic velocity surveys at the two strong motion stations (ESI 1995). Subsequent predesign field studies included SASW surveys at 27 locations on top of the waste and four locations on native material adjacent to the landfill, three 840 mm-diameter bucket auger borings with in-situ unit weight measurements to depths of up to 45 m, and an approximately 6-m long by 6-m deep test trench with in-situ unit weight measurements (GeoSyntec 1996b). Fig. 2 shows the exploration locations from these two field studies. Laboratory testing conducted on 457 mm-diameter reconstituted solid waste specimens in conjunction with the field work

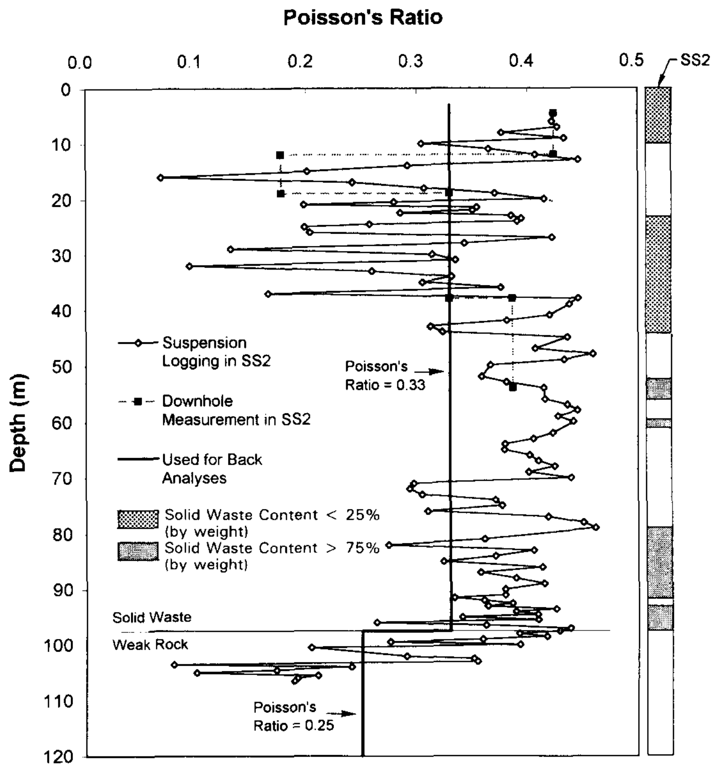


FIG. 3. Poisson's Ratio of OII Landfill Solid Waste

included one-dimensional consolidation, direct shear, and CyDSS testing (GeoSyntec 1996c).

Field Investigation

Shear and compressional wave velocity profiles were developed at both strong motion station locations using in-hole suspension logging and conventional downhole logging (ESI 1995). The shear wave velocity profiles at these locations have been reported previously by Matasović et al. (1995) and Idriss et al. (1995). The shear and compressional wave velocities measured in the borehole at strong motion station SS2 were used to calculate Poisson's ratio, ν, for the solid waste based upon basic equations from linear elasticity. Fig. 3 shows the Poisson's ratio values calculated in this manner. Zones of solid waste content lower than 25% and higher than 75% are indicated in the margin of Fig. 3 by shading. Given the large excursions of ν along the profile, a value of $\nu = 0.33$ was adopted as an appropriate approximation for OII solid waste.

SASW testing was performed at the landfill under the direction of Dr. Kenneth Stokoe of the University of Texas. A vibroseis, a truck-mounted servohydraulic actuator capable of applying a dynamic force of up to 133 kN at frequencies from 1 Hz to 200 Hz was used for the testing. Fig. 4 shows a composite shear wave velocity profile for OII landfill solid waste developed by statistical analysis of the SASW surveys at the 27 locations where testing was performed on waste. The "recommended" solid waste shear wave velocity profiles developed by Kavazanjian et al. (1995) and Kavazanjian et al.

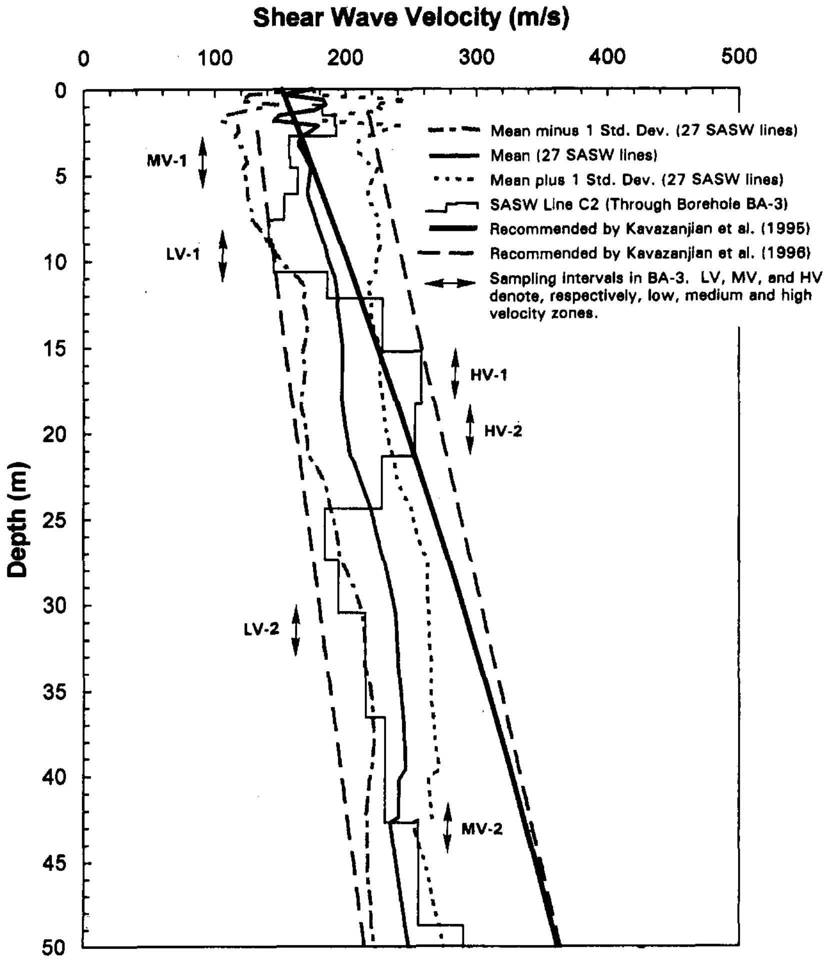


FIG. 4. Shear Wave Velocity of OII Landfill Solid Waste

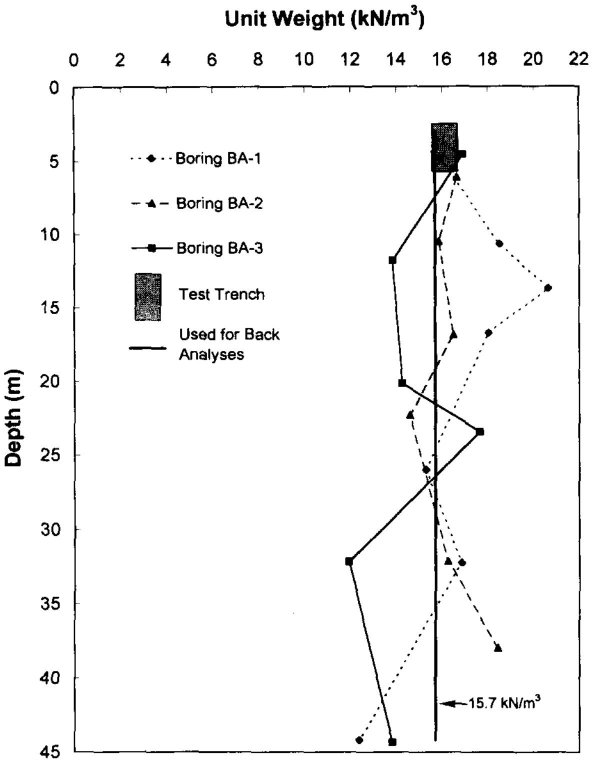


FIG. 5. Unit Weight of OII Landfill Solid Waste

(1996) for southern California municipal solid waste landfills are also shown in Fig. 4 for the purpose of comparison.

In-situ unit weight measurements were made at six locations in each of the three large-diameter bucket auger borings. Bulk samples recovered from these six locations were used subsequently in waste characterization and laboratory testing studies. The measurement and sampling locations were chosen such that unit weight measurements were made at both deep and shallow locations where the in-situ shear wave velocity from the SASW sounding closest to the boring was approximately one standard deviation below the mean velocity (LV locations), approximately one standard deviation above the mean velocity (HV locations), and approximately equal to the mean velocity (MV locations) calculated from all 27 SASW soundings. The measurement and sampling locations for boring BA-3 are shown in Fig. 4.

In-situ unit weight was initially evaluated using an adaptation of the conventional sand cone procedure (*ASTM D 1556*). In the adapted procedure, the weight of solid waste removed from a 2 – 3 m length of borehole was carefully measured, and the volume of the boring over this interval was evaluated by backfilling the 2 – 3 m interval with a "calibrated" gravel. However, this procedure gave anomalous results at several locations, most notably at intervals where liquids were seeping into the boring at a relatively rapid rate. Therefore, based upon evaluation of the OII data and data from another landfill where the adapted sand cone procedure was used successfully, the volume of the 2 – 3 m interval of the boring from which the solid waste was removed and weighed was calculated assuming a constant 16% overbore. Results of the calculations based upon a 16% overbore, shown in Fig. 5, indicated the in-situ unit weight of the solid waste varied in a nonsystematic manner between approximately 12 kN/m^3 and 21 kN/m^3, with most values between 14 kN/m^3 and 18 kN/m^3.

The in-situ unit weight of the solid waste was also evaluated in a large test trench excavated near the location of bucket auger boring BA-1. A trench approximately 6 m long, 6 m deep, and 1 m wide was excavated with a backhoe through approximately 1.5 – 2 m of soil cover. The solid waste excavated from a depth of 2.2 m to the bottom of the trench was carefully weighed. The volume of the trench interval from which the solid waste was excavated was determined by backfilling the trench with the calibrated gravel and was based upon measured trench dimensions. Results of both calculations indicated an average unit weight of approximately 16 kN/m^3 for the solid waste in the test trench. The results from the test trench are also plotted in Fig. 5.

Laboratory Testing

Bulk samples of solid waste were recovered for waste characterization and for laboratory testing from each of the 18 intervals in boreholes BA-1, BA-2, and BA-3, in which an in-situ unit weight evaluation was conducted. Testing was conducted in a laboratory established at the landfill site using large-diameter (457 mm) testing equipment designed and fabricated for the project (GeoSyntec 1996c). Reconstituted samples were used in the testing program because of the difficulties in obtaining undisturbed specimens of solid waste of any size, let alone of the large diameter required for a representative sample. CyDSS testing was used for the cyclic characterization of the solid waste. The CyDSS apparatus developed for the OII landfill project is shown in Fig. 6.

The CyDSS testing program included staged testing at uniform cyclic shear strains of 0.1%, 0.3%, 1%, 3%, and 5% at a frequency of approximately 0.1 Hz on waste recovered from six of the bulk sampling intervals. Tables 1 and 2 provide information on the boring and depth from which each bulk sample used in the CyDSS testing program was recovered, the relative in-situ shear wave velocity (low, mean, high) of the sampling interval, the relative moisture content of the specimen (dry, moist), testing stress and strain levels, and the age of the waste as determined from information on the history of landfill development and from pieces of newspaper and other dated materials recovered during sampling. Tables 1 and 2 also provide information on the visual classification of the waste and of the soil or soil-like constituents of the bulk samples.

One set of unprocessed CyDSS testing results are presented in Fig. 7 in terms of cyclic stress-strain loops. These results indicate that solid waste materials follow Masing's (1926) rules for cyclic stress-strain behavior of soils.

Processed CyDSS testing results, expressed in terms of shear modulus reduction and equivalent viscous damping ratio,

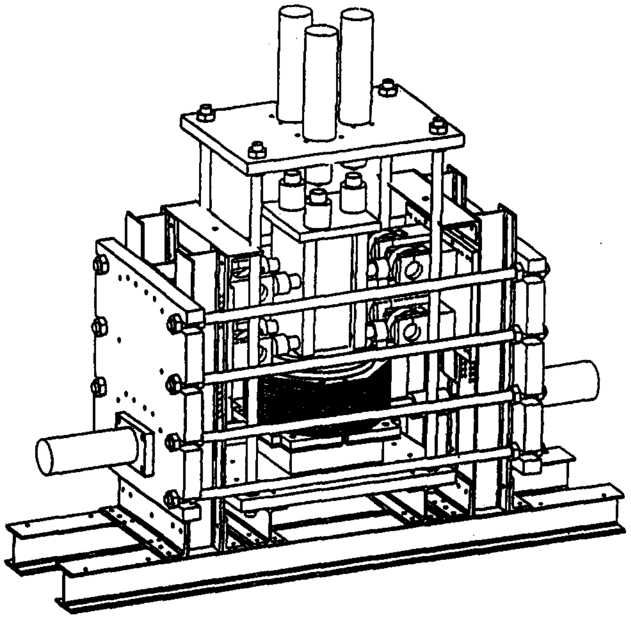


FIG. 6. Large-Diameter Cyclic Direct Simple Shear Device

TABLE 1. CyDSS Testing Program

Test number (1)	Boring/sampling interval[a] (2)	Depth (3)	Age of sample[b] (4)	Applied normal stress (5)	Moisture content[c] (6)	Shear wave velocity[d] (7)	Unit weight[e] (8)	Number of stages (9)
1, 2, 3	BA-1/LV-1	3.4–6.1 m	—[f]	100.3; 95.8; 94.1 kPa	15.3%	122 m/s	16.0 kN/m^3	6
4	BA-3/MV-1	3.4–6.1 m	1980	97.4 kPa	16.6%	162 m/s	16.9 kN/m^3	2
5, 6	BA-1/HV-1	9.2–12.2 m	—[f]	176.2; 176.4 kPa	33.5%	231 m/s	18.5 kN/m^3	6
7	BA-1/LV-2	15.2–18.3 m	1984	315.1 kPa	25.5%	148 m/s	18.1 kN/m^3	4
8	BA-3/LV-2	30.5–33.5 m	1964	511.4 kPa	24.7%	195 m/s	12.0 kN/m^3	4
9, 10	BA-2/HV-1	15.2–18.3 m	1983	292.1; 292.3 kPa	41.2%	231 m/s	16.5 kN/m^3	6

[a] BA = bucket auger borehole indicated in Fig. 2; LV, MV, HV = low, mean, and high in-situ shear wave velocity zone, respectively, as indicated in Fig. 4.

[b] Age of the solid waste part of the sample estimated from partially decomposed newspapers.

[c] Moisture content of soil and soil-like materials measured prior to the test.

[d] Shear wave velocity measured in the 457-mm consolidation device for the same initial density and overburden pressure.

[e] In-situ unit weight. The unit weight achieved in CyDSS was ±2% of this value.

[f] Age of waste undetermined.

TABLE 2. CyDSS Testing Program

Test number (1)	Paper and cardboard (2)	Plastics and rubber (3)	Wood (4)	Metals (5)	Glass (6)	Textiles and miscellaneous (7)	Soil and soil-like materials composition[a] (8)
1, 2, 3	1.6%	7.0%	2.3%	0.6%	2.5%	1.2%	84.8% (SM; 10% gravel; 50–60% sand; 30–40% fines)
4	1.7%	1.1%	0.4%	0.8%	0.4%	0.9%	94.6% (CH; 10% gravel; 15% sand; 75% fines)
5, 6	6.9%	11.8%	4.0%	0.8%	5.6%	5.3%	64.6% (CH; 5% gravel; 5% sand; 90% fines)
7	9.5%	3.2%	3.7%	2.4%	1.6%	2.2%	77.5% (CL; 10–15% gravel; 30–40% sand; 50–55% fines)
8	10.3%	0.4%	2.9%	0.9%	0.1%	0.1%	85.4% (Fine-grained)
9, 10	1.2%	3.7%	3.4%	4.9%	0.4%	1.5%	84.8% (ML; 10% gravel; 30–40% sand; 50–60% fines)
[Average]	5.2%	4.5%	2.8%	1.7%	1.8%	2.0%	82.0%

[a] Unified Soil Classification System by visual classification.

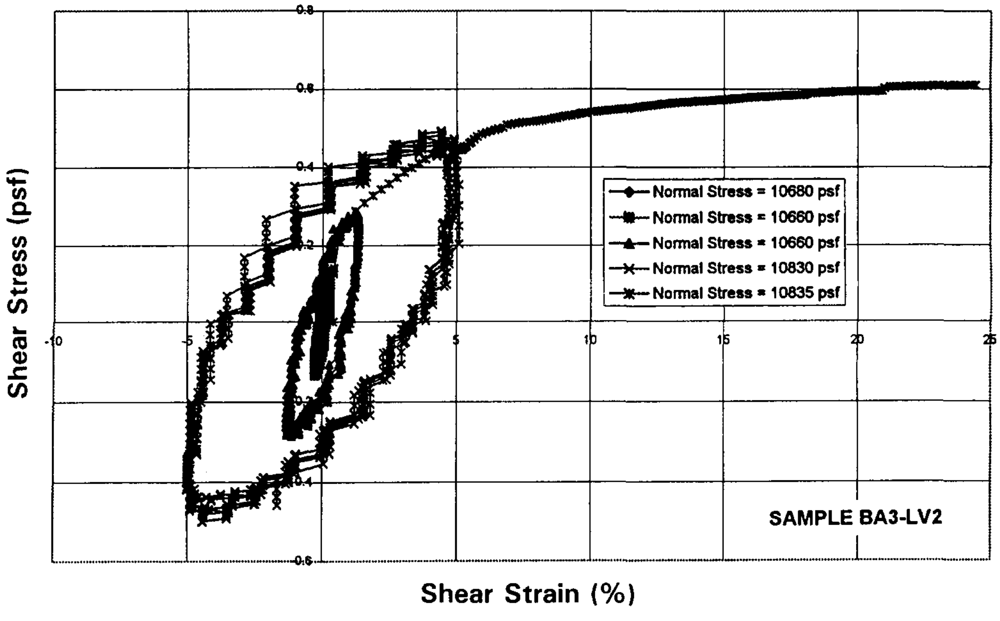


FIG. 7. Unprocessed Solid Waste Cyclic Direct Simple Shear Test Results

are shown in Fig. 8. The modulus reduction data were normalized by small strain moduli calculated from the mass density of the compacted specimen and the estimated shear wave velocity. Shear wave velocity was estimated on the basis of shear wave velocity measured in the laboratory in 457 mm diameter consolidometers on specimens from the same bulk sample compacted to the same density and subject to the same consolidation pressure as the CyDSS specimens (Geosyntec 1996c). Damping values were calculated from the cyclic loops based upon the assumption that material damping can be characterized with the strain-dependent equivalent viscous damping ratio, defined as a ratio of damping energy to the equivalent strain energy [see, e.g., Ishihara (1996)]. Damping calculated from the experimental cyclic hysteresis loops was corrected for system friction by subtracting 4% from the experimental damping ratio values. The value of 4% was based on the comparison of damping measured in tests run on a "standard" sand in the large-diameter CyDSS device to damping reported in the literature for the same sand when tested in a Norwegian Geotechnical Institute-type CyDSS apparatus (Matasović and Vucetic 1993) and on CyDSS test performed in the large-diameter apparatus on "dummy" neoprene specimens (GeoSyntec 1996c).

Fig. 8(a) also includes modulus reduction data points cal-

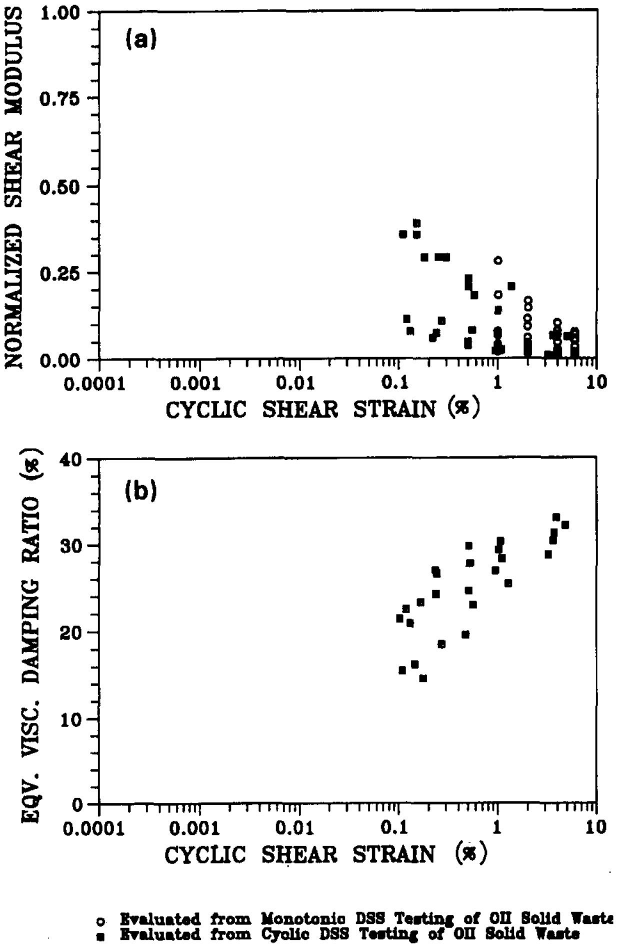


FIG. 8. Processed Solid Waste Cyclic Direct Simple Shear Test Results

culated using the secant modulus from monotonic loading (i.e., static) direct simple shear (DSS) tests on reconstituted specimens. These modulus values were calculated assuming the static stress strain curve represented the backbone curve for cyclic loading.

One goal of the testing program was to identify the influence of the waste characteristics identified in Tables 1 and 2 on the mechanical behavior of the waste. Evaluation of the data from both cyclic and static tests (including direct shear and consolidation tests) showed no discernable trends with respect to waste composition. Therefore, there was no distinguishing among data points on the basis of compositional factors when plotting or evaluating the data.

Waste Profile Idealization

Back analyses of the seismic response of the landfill were conducted on cross section 1-1′ of Fig. 2. Cross section 1-1′, shown in Fig. 9, was developed using a topographic map prepared approximately two months prior to the Northridge earthquake, a base-of-the-landfill contour map developed from historical data (ESI 1996b), and SASW results (GeoSyntec 1996a), as well as the results of other characterization and field investigation studies. The cross section was extended to elevation 55 m msl, approximately 130 m below the top deck of the landfill. Elevation 55 m mean sea level represented the lowest elevation reached by the SASW measurements.

Cross section 1-1′ was idealized for modeling purposes into zones of four materials: cover soil, compacted fill, weak rock, and solid waste. The dynamic characteristics of these materials and of the elastic half-space assumed to underlie the cross section are summarized in Table 3. The dashed lines with question marks on cross section 1-1′ in Fig. 9 indicate a relatively high degree of uncertainty relative to the geometry of the compacted fill and cover soils. The native subsurface material was characterized as a uniform material because, based on the available information, it is difficult, if not impossible, to make a distinction in geometry and material properties between discrete components of the Pico unit, which is present below the cross section. The modulus reduction and damping curves for the cover soil, compacted fill, and weak rock materials were selected on the basis of the classification of these materials. The Vucetic and Dobry (1991) curves for a plasticity index of 15 were selected to represent the cover soils and compacted fill, as these materials were classified primarily as low-plasticity silty clay and clayey silt. The Shibuya et al. (1990) curves for gravel were selected for the Pico unit because the poorly indurated sand and gravel weak rock materials that make up most of this unit appeared to be, in a mechanical sense, similar to a loose or poorly cemented gravel.

The shear wave velocity profile for the solid waste is summarized in Fig. 9. This profile was based upon actual shear wave velocity profiles measured in the SASW and borehole velocity surveys, and not on the average shear wave velocity profile from SASW measurements shown in Fig. 4. Shear wave velocity variations between the points illustrated in Fig. 9 were established by linear interpolation in order to avoid large impedance ratios in the horizontal direction. The shear wave velocity for the compacted fill was based upon the shear wave velocity profile from the in-hole suspension logging at the location of monitoring station SS1. The shear wave velocity profile for the Pico unit foundation soils was based upon the suspension logging at station SS1 and SASW profiles developed on native ground adjacent to the landfill.

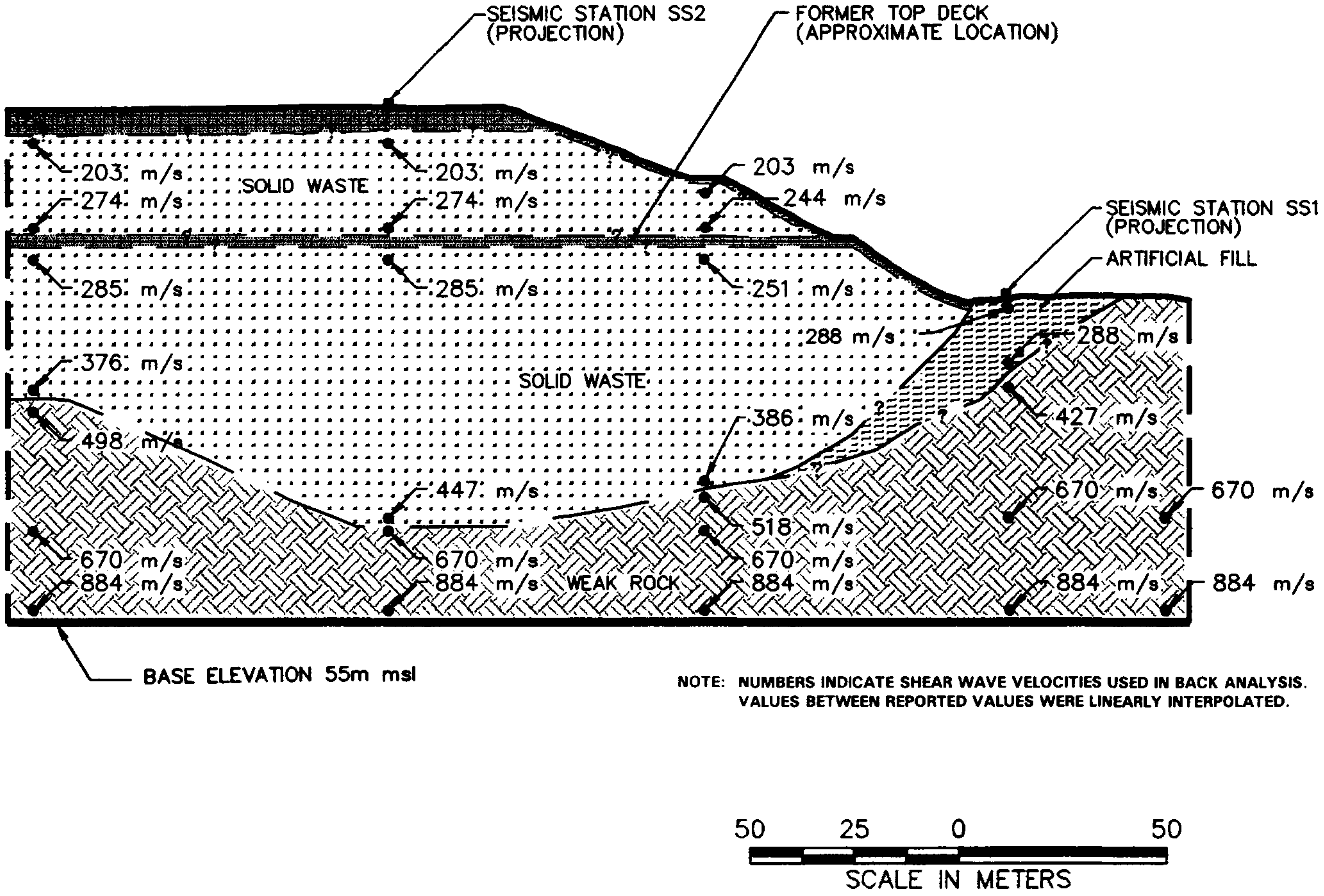
Based upon the data shown in Fig. 5 from the field unit weight evaluations, the solid waste was characterized by a constant unit weight of 15.7 kN/m^3. Based upon unit weight measurements on Shelby Tube samples (ESI 1996a), the cover soils were characterized by a constant unit weight of 17.3 kN/m^3. Based upon typical values for compacted soils, the fill was characterized by a unit weight of 18.8 kN/m^3 to a depth of 22 m and 19.6 kN/m^3 at greater depths. Based upon available geotechnical data, the weak rock Pico formation materials were characterized by a unit weight of 18.8 kN/m^3.

The elastic half-space was characterize by a shear wave velocity of 1,220 m/s and a unit weight of 20.4 kN/m^3. Based upon the data in Fig. 3, the half-space and weak rock were characterized by Poisson's ratio equal to 0.25, and the solid waste was characterized by Poisson's ratio equal to 0.33. A Poisson's ratio of 0.30 was used to characterize the cover soils based upon typical values for similar soils.

BACK ANALYSIS OF STRONG MOTION RECORDS

Landfill Response Analyses

Back analyses of landfill response were conducted to assess the modulus reduction and damping characteristics of the waste mass in the small to intermediate strain range. The back analyses were conducted in the time domain using equivalent-linear finite element analysis. Because the base station (station SS1) was located on fill and not on a bedrock outcrop, ground motions recorded at SS1 had to be deconvolved to determine the bedrock outcrop motion for input to each finite element back analysis. Therefore, each back analysis was carried out in two steps: (1) Deconvolution of the strong ground motion recorded at SS1 using one-dimensional analysis; and (2) two-dimensional back analysis of site response using the deconvolved motion.



NOTE: NUMBERS INDICATE SHEAR WAVE VELOCITIES USED IN BACK ANALYSIS. VALUES BETWEEN REPORTED VALUES WERE LINEARLY INTERPOLATED.

FIG. 9. OII Landfill Cross Section 1-1′

TABLE 3. Dynamic Material Properties

Zone[a] (1)	Unit weight (2)	Poisson's ratio (3)	Shear wave velocity (4)	Modulus reduction and damping curves (5)
Solid waste	15.7 kN/m^3	0.33	Varies[a]	Evaluated in this study
Cover soils	17.3 kN/m^3	0.30	274 m/s	Vucetic and Dobry (1991) (PI = 15)
Artificial fill	18.8–19.6 kN/m^3	0.30	288 m/s	Vucetic and Dobry (1991) (PI = 15)
Weak rock	18.8 kN/m^3	0.25	Varies[a]	Shibuya et al. (1990)
Elastic half-space	20.4 kN/m^3	0.25	1,220 m/s	—

[a] See Fig. 9.

TABLE 4. Characteristics of Selected Accelerograms

Event (1)	Record[a] (2)	PHGA[b] (3)	Significant duration[c] (4)	RMSA[d] (5)
Jan. 17, 1994 Northridge earthquake $M_W = 6.7$	Base (SS1)	0.258g	10.54 s	0.083g
Jan. 17, 1994 Northridge earthquake $M_W = 6.7$	Top deck (SS2)	0.254g	16.34 s	0.057g
June 28, 1992 Landers earthquake $M_W = 7.3$	Base (SS1)	0.042g	37.57 s	0.012g
June 28, 1992 Landers earthquake $M_W = 7.3$	Top deck (SS2)	0.100g	39.25 s	0.027g
Dec. 3, 1988 Pasadena earthquake $M_W = 5.0$	Base (SS1)	0.218g	3.29 s	0.067g
Dec. 3, 1988 Pasadena earthquake $M_W = 5.0$	Top deck (SS2)	0.091g	3.32 s	0.033g
Jan. 19, 1994 Northridge aftershock number 5 $M_W = 4.5$	Base (SS1)	0.043g	5.49 s	0.012g
Jan. 19, 1994 Northridge aftershock number 5 $M_W = 4.5$	Top deck (SS2)	0.031g	4.96 s	0.007g
Jan. 19, 1989 Malibu earthquake $M_W = 5.0$	Base (SS1)	0.012g	20.49 s	0.003g
Jan. 19, 1989 Malibu earthquake $M_W = 5.0$	Top deck (SS2)	0.010g	26.75 s	0.002g

[a] Baseline correction and conversion to east-west alignment from PEA (1995).
[b] PHGA = (uncorrected) recorded peak horizontal ground acceleration as reported by PEA (1995).
[c] Significant duration of strong shaking defined in accordance with Trifunac and Brady (1975).
[d] RMSA = root-mean-square acceleration over the significant duration of the record.

Out of the 34 events reported by Hushmand Assoc. (1994) and PEA (1995), a set of five ground motion records (accelerograms) were selected for use in the back analyses of the seismic response of the landfill. The criteria used to select these accelerograms were the intensity of the PHGA recorded at the top deck of the landfill in the east-west direction and the energy content and duration of strong shaking of the east-west component. Table 4 provides the characteristics of the

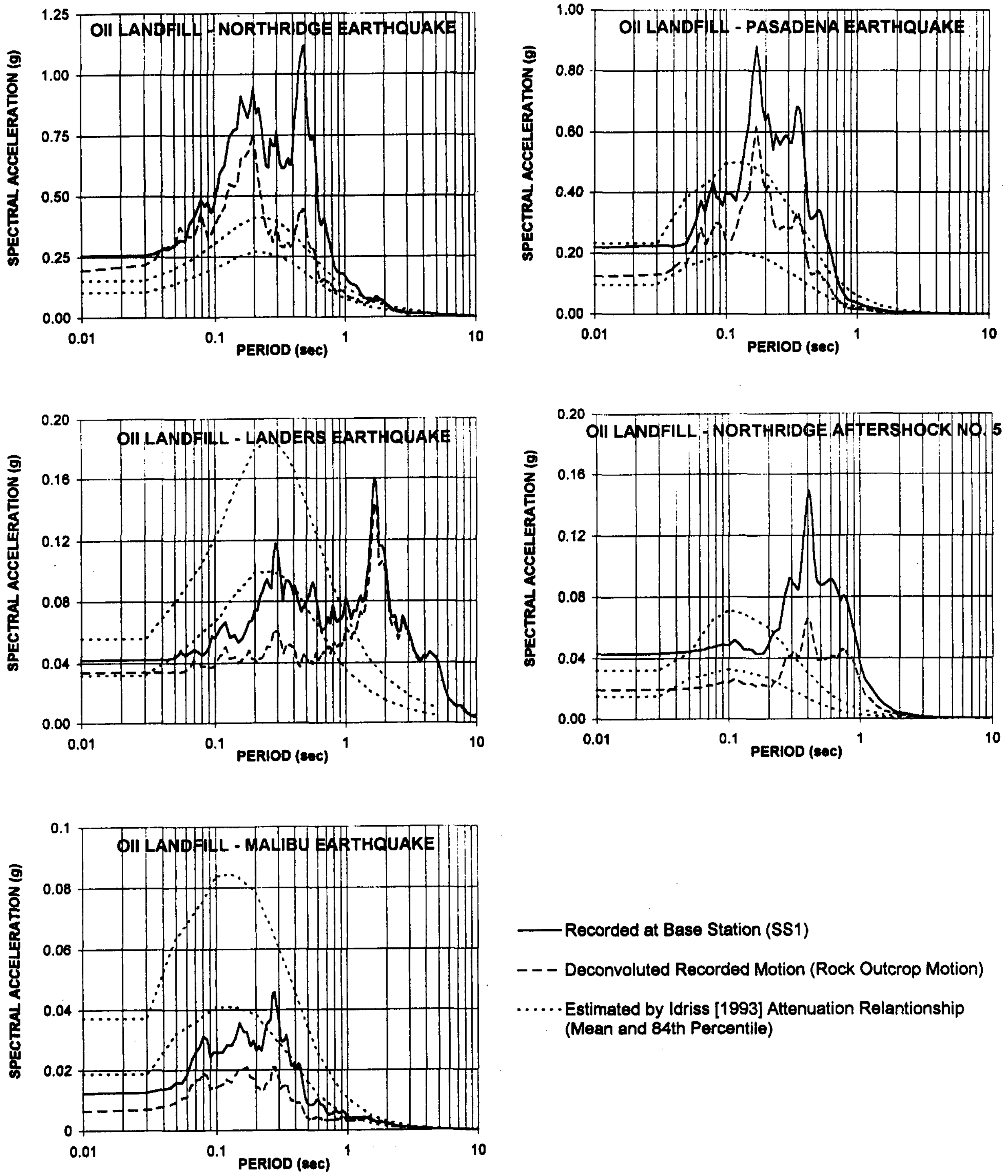


FIG. 10. One-Dimensional Deconvolution of Base Motions

selected accelerograms, with the energy content expressed in terms of the root-mean-square acceleration (RMSA) and with the duration of strong shaking expressed in terms of the significant duration (D_s) defined by Trifunac and Brady (1975). With the exception of the Landers earthquake, the top deck station recorded motions of lesser PHGA than the base station in all five of the selected events (though in the Northridge event, the PHGAs at top deck and base were almost equal).

To avoid circular arguments (i.e., to minimize the interdependence of assumptions and parameters), it was assumed that the data, parameters, and geometry given in Tables 1–3 and Fig. 9 represented best estimates, and thus these values were not varied in the back analyses.

One-Dimensional Deconvolution of Recorded Motions

The location of base station SS1 on compacted fill and the topography surrounding the base station, including its proximity to the edge of the landfill, suggest that the base station records are not representative of free-field outcrop ground motions suitable for direct input to the back analyses of landfill response. Therefore, the effect of the compacted fill on the ground motions at SS1 was evaluated using one-dimensional equivalent-linear deconvolution analyses. The effect of topography was not explicitly considered in the analyses but was qualitatively evaluated in two ways: initially by comparison

TABLE 5. Earthquake Parameters for Selected Records

Event (1)	Moment magnitude (2)	Style of faulting (3)	Site-to-source distance (4)	PHGA recorded at base[a] (5)	PHGA Estimated at Base Attenuation relationship[b] (6)	PHGA Estimated at Base Deconvolution[c] (7)
Jan. 17, 1994—Northridge	6.7	Thrust	43 km	0.258*g*	0.104*g*	0.160*g*
June 28, 1992—Landers	7.3	Strike-slip	140 km	0.042*g*	0.032*g*	0.035*g*
Dec. 3, 1988—Pasadena	5.0	Strike-slip	13 km	0.218*g*	0.096*g*	0.118*g*
Jan. 19, 1994—Northridge aftershock number 5	4.5	Thrust	43 km	0.043*g*	0.015*g*	0.017*g*
Jan. 19, 1989—Malibu	5.0	Thrust	50 km	0.012*g*	0.019*g*	0.007*g*

[a] Larger of two horizontal acceleration components.

[b] Estimates from Idriss (1993) attenuation relationship (rock sites).

[c] Results of deconvolution by *SHAKE91* (Idriss and Sun 1992) (monitored as rock outcrop motion).

of the acceleration response spectra for the deconvolved motions to statistically based response spectra for free-field conditions, and subsequently by comparison of the response spectra for the motions predicted at SS1 in the two-dimensional finite element back analysis to the response spectra of the recorded motions.

Deconvolution through the compacted fill of the recorded base motions was performed using the computer program *SHAKE91* (Idriss and Sun 1992). *SHAKE91* is a one-dimensional equivalent-linear computer program that operates in the frequency domain. The idealized shear wave velocity profile used for the deconvolution analysis was based upon the results of the borehole velocity surveys at the location of SS1. These data are reported in Idriss et al. (1995). The material properties used in the deconvolution analyses for the fill, weak rock, and elastic half-space are given in Table 3. The acceleration response spectra from the deconvolution analyses (monitored in *SHAKE91* as a rock outcrop motion) are plotted in Fig. 10 versus the acceleration response spectral shapes derived from the Idriss (1993) acceleration attenuation relationship. Outcrop PHGA values from the deconvolution analyses are compared to mean PHGA values predicted by the Idriss (1993) attenuation relationship in Table 5.

Fig. 10 indicates that, with the exception of the Malibu earthquake, the deconvolved motions fall within (or close to) the range of anticipated values for free-field motions (i.e., between the estimated 16th and 84th percentile spectral values from the Idriss attenuation relationship). The deviation from the expected statistical shape is smallest for the two strongest records — the January 17, 1994 Northridge and December 3, 1988 Pasadena earthquakes. The motions from these two earthquakes govern the back calculation of solid waste modulus reduction and damping curves, since they induce the largest shear strains in the waste. Table 5 indicates that relatively good agreement was also achieved between the peak acceleration values of the deconvolved motions and the peak acceleration values estimated using the Idriss (1993) attenuation relationship. The deconvolved free-field PHGA values presented in Table 5 indicate amplification of the PHGA at the top of the fill at the location of SS1 in all five events considered in the back analysis (when compared to the hypothetic free-field bedrock PHGA). This, in turn, implies that the amplification of PHGA values by the OII waste fill, as represented by the motions recorded at SS2, is even greater than reported previously by Kavazanjian and Matasović (1995).

Two-Dimensional Back Analyses

The finite element mesh developed to back analyze the seismic response of cross section 1-1′ had more than 7,000 elements. Following recommendations by Lysmer et al. (1975), lateral boundaries of the mesh were extended more than 10 times the mesh thickness beyond the boundaries of the waste fill to minimize the influence of the lateral boundaries on the computed response. The material parameters used in the back analysis are summarized in Table 3 and are shown in Fig. 9.

The back analyses were carried out using the computer program *QUAD4M* (Idriss et al. 1973; Hudson et al. 1994). *QUAD4M* performs time domain seismic response analyses using the equivalent-linear constitutive model with frequency-dependent damping. The back analyses were performed using the deconvolved ground motions characterized in Table 5 and shown in Fig. 10 in the form of acceleration response spectra. Following an iterative procedure, the "best-fit" OII solid waste modulus reduction and damping curves were determined on the basis of qualitative examination of the observed and predicted acceleration response spectra at SS2. Results of the back analyses using the "best-fit" parameters are shown in Fig. 11. The "best fit" modulus reduction and damping curves, shown in Fig. 12, are truncated at a strain of 0.08% as this was the maximum cyclic shear strain in the solid waste calculated in the back analyses (induced by the deconvolved record from the January 17, 1994 Northridge earthquake).

MODULUS REDUCTION AND DAMPING DATA INTEGRATION AND INTERPRETATION

The modulus reduction and damping data from the back analysis were integrated with the data from the CyDSS testing program to create a family of "internally consistent" modulus reduction and damping curves that were considered to represent the range of likely values for the solid waste at OII. A set of modulus reduction and damping curves were considered internally consistent if the damping curve in the intermediate strain range could be derived from the modulus reduction curve using the Masing (1926) rules. The family of internally consistent modulus reduction and damping curves developed based upon the back analysis and laboratory data are shown in Fig. 12. The "upper bound" modulus reduction curve shown in this figure is internally consistent with the "lower bound" damping curve, and the "lower bound" modulus reduction curve is internally consistent with the "upper bound" damping curve.

From the family of internally consistent curves, a "best-estimate" set of modulus reduction and damping curves were identified to represent the cyclic characteristics of the OII solid waste for subsequent analytical studies of the seismic response of the landfill. The "upper bound" modulus reduction curve and corresponding "lower bound" damping curve were chosen as the "best-estimate" curves for the following reasons: (1) The "upper bound" modulus curve was more consistent with the back analysis results than were the other curves; (2) due to disturbance associated with sampling and sample preparation, the reconstituted specimens used in the laboratory testing were likely to be less "structured" and thus show increased modulus reduction and damping compared to the waste in situ; and (3) the lower rate of energy dissipation and the reduced modulus reduction associated with the "upper

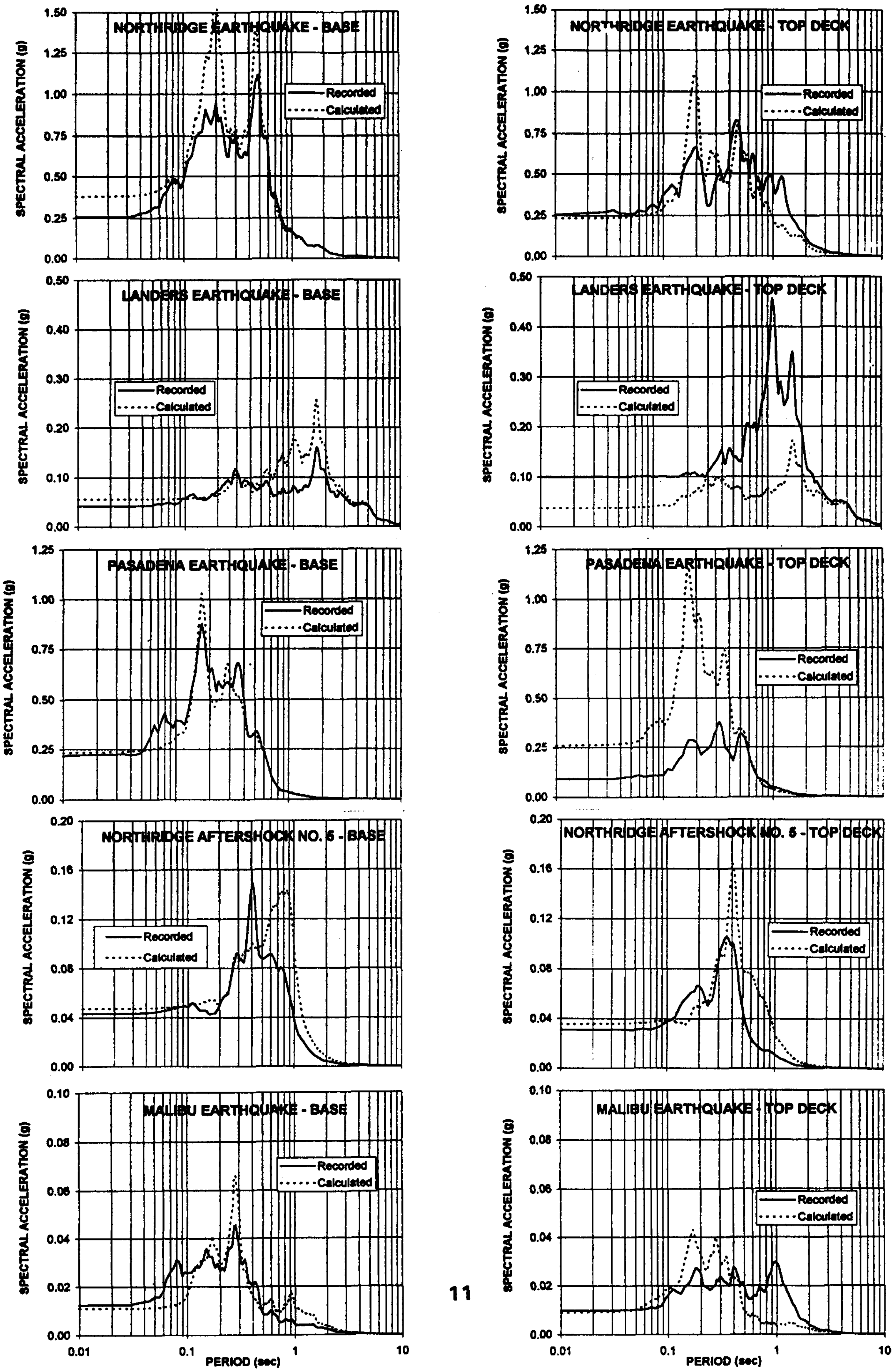


FIG. 11. Back Analysis of Strong Motion Data

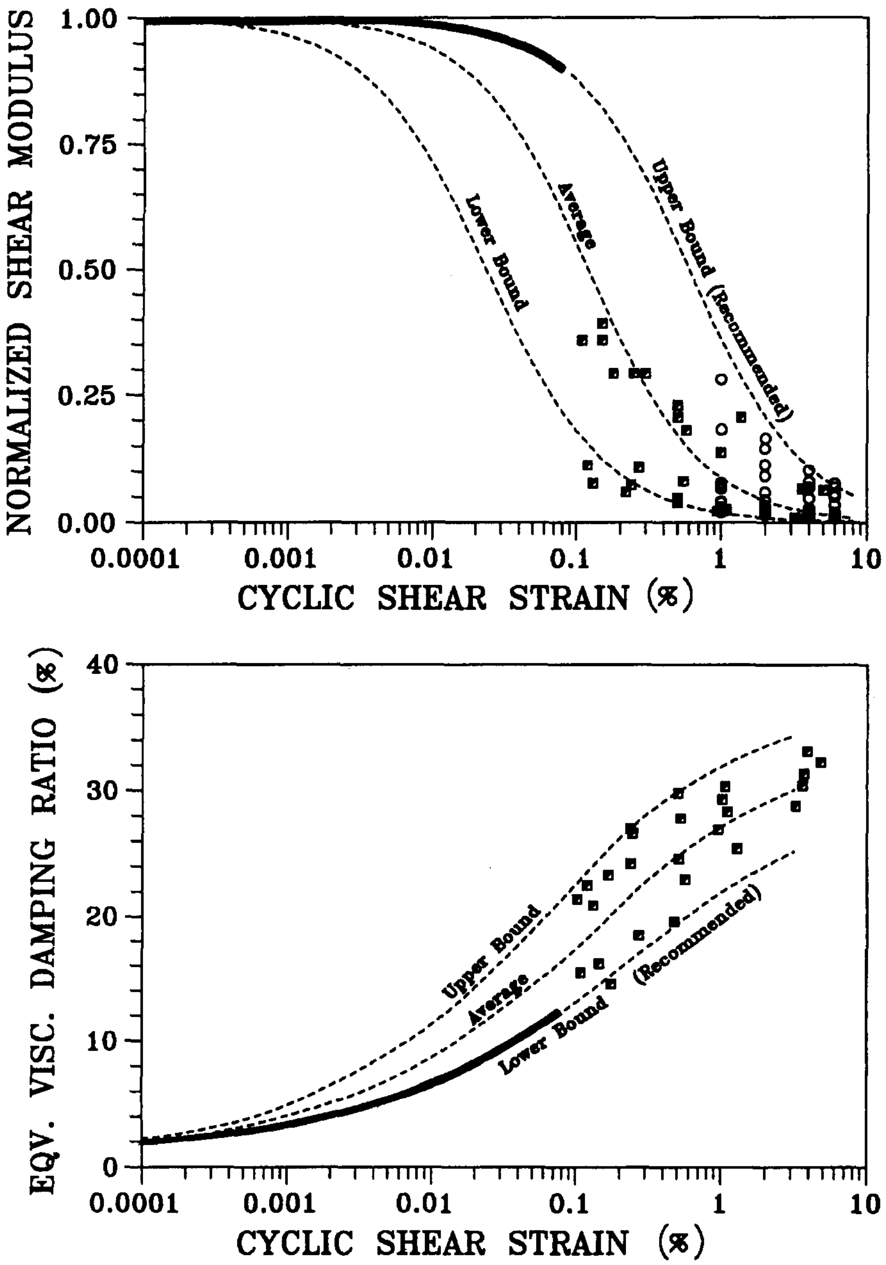


FIG. 12. Internally Consistent Modulus Reduction and Damping Curves

bound" modulus reduction and "lower bound" damping curves was considered to be conservative with respect to the acceleration response at the landfill surface (i.e., they generated larger peak accelerations at the landfill surface than did the other curves).

Fig. 13 compares the "best estimate" modulus reduction and damping curves developed in the present study to characterize the OII solid waste to modulus reduction and damping curves for solid waste derived by previous investigators from the OII data. While the damping curves from this and previous studies are all reasonably consistent, there are significant differences among the modulus reduction curves. The modulus reduction curve developed for the present study was used in subsequent analytical studies of landfill response in lieu of the curves developed by previous investigators because it is consistent with back analyses using geometry, shear wave velocity, and unit weight values based upon field and laboratory data; it is extrapolated to large strain values on the basis of site-specific laboratory testing; and it is internally consistent with the damping curve.

SUMMARY AND CONCLUSIONS

The cyclic characteristics of the OII landfill solid waste were established for use in subsequent analytical studies based upon field and laboratory testing and back analyses of strong motion data recorded at the base and top deck of the landfill. The shear wave velocity profile for the solid waste was developed on the basis of downhole and in-hole seismic velocity surveys and SASW testing. Poisson's ratio for the solid waste was evaluated based upon a comparison of compressional and shear wave velocities measured in the downhole and in-hole surveys. The unit weight of the solid waste was evaluated on the basis of the field investigation.

The modulus reduction and damping curves for the OII solid waste were based on a combination of laboratory test data and back analysis. The laboratory test data were based upon CyDSS tests performed on 457 mm diameter specimens reconstituted in the laboratory from bulk samples recovered from the landfill. The laboratory testing program provided information on the hysteretic damping and modulus reduction

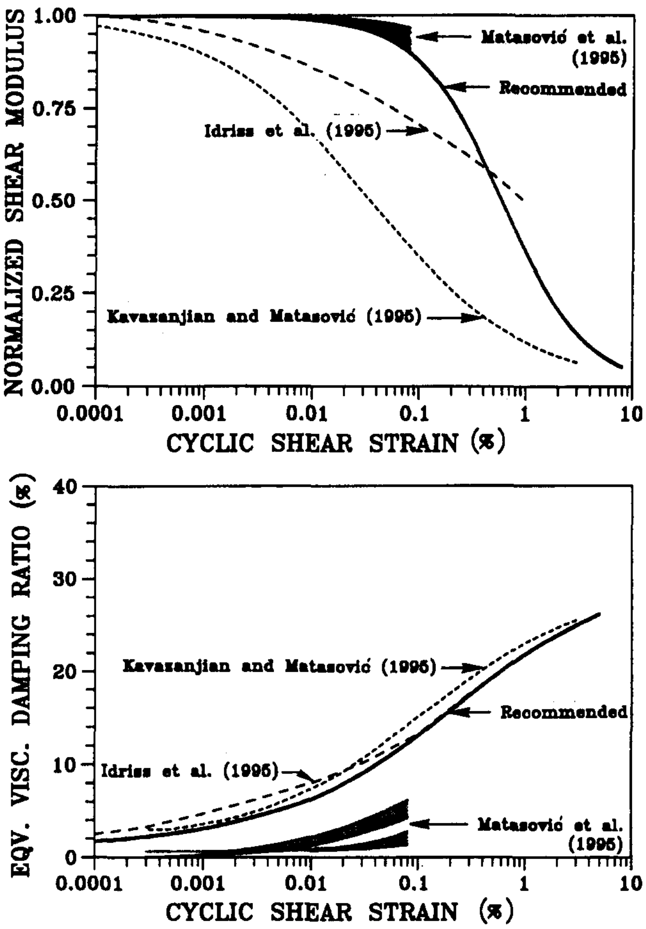


FIG. 13. Best Estimate OII Solid Waste Modulus Reduction and Damping Curves

of reconstituted samples at cyclic shear strains between 0.1% and 5%. The back analysis provided data on modulus reduction and damping at cyclic shear strains of up to 0.08% based upon recorded motions at the top deck and base of the landfill from five earthquakes, including the M_W 7.3 Landers event and the M_W 6.7 Northridge event. The geometry of the waste, soil, and weak rock materials used in the back analysis was based upon borings, topographic maps, and other information on the history of landfill development. The properties of the soil and weak rock materials were based upon the results of the field investigation and typical properties.

The back analysis was performed using two-dimensional equivalent-linear time domain response analyses with the computer program *QUAD4M*. However, as the base strong motion station was located on fill, the "outcrop" input motions for the two-dimensional back analyses were determined by deconvolution of the recorded base station motions. The deconvolution analyses were performed using the one-dimensional equivalent-linear frequency domain computer program *SHAKE91*. The deconvolution analyses indicated that the fill amplified the bedrock motions recorded at the base station and that amplification of bedrock motions by the OII waste fill was even greater than reported previously. Results of the back analysis using the deconvolved motions indicated little modulus reduction within the waste for cyclic shear strains up to 0.08%.

The modulus reduction and damping data from the laboratory testing program and back analyses were integrated to develop a family of internally consistent modulus reduction and damping curves. From this family of curves, a "best-estimate" set of modulus reduction and damping curves were selected to characterize the OII solid waste for use in subsequent analytical studies. These "best-estimate" curves were used for subsequent studies in lieu of previous modulus reduction and damping curves derived from the OII strong motion records because they are based upon field data on landfill geometry, shear wave velocity, and unit weight; they are internally consistent in the intermediate strain range; they are consistent with the strong motion data recorded at the top and base of the landfill; and they use laboratory data to extrapolate back calculated modulus reduction and damping curves into the large strain domain.

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