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Seismic Design of Mixed and Hazardous Waste Landfills

Edward Kavazanjian Jr.
GeoSyntec Consultants, Huntington Beach, CA

Neven Matasovic
GeoSyntec Consultants, Huntington Beach, CA

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Edward Kavazanjian, Jr.
GeoSyntec Consultants
2100 Main Street, Suite 150
Huntington Beach, California-USA-92648

Neven Matasovic
GeoSyntec Consultants
2100 Main Street, Suite 150
Huntington Beach, California-USA-92648

ABSTRACT

Due to the absence of federal criteria, seismic design and performance criteria for mixed and hazardous waste landfills are generally developed on a project-specific basis, supplemented by state and project-specific standards. In developing project-specific criteria, the federal Subtitle D standards for seismic design of municipal solid waste landfills are often used as a minimum standard for mixed and hazardous waste facilities. Seismic performance standards are also usually developed on a project-specific basis, employing either a "withstand without harmful discharge" or a "withstand without damage" performance standard, depending on the certainty of continuing aftercare. Quantitative criteria established to demonstrate compliance with these performance standards should consider the inherent conservatism in the type of analysis employed to evaluate the selected performance measure. Material properties for seismic design of mixed or hazardous waste landfills are also usually developed on a project-specific basis. Material property values are often subject to considerable uncertainties about waste composition, variability in the waste composition, and waste heterogeneity. Parametric and sensitivity studies are generally used to compensate for the uncertainty in waste properties and the variability and heterogeneity of the waste. Four case histories are presented to illustrate these issues.

INTRODUCTION

Seismic design of mixed and hazardous waste landfills is subject to many of the same challenges as seismic design of municipal solid waste landfills. These challenges include characterization of the mechanical properties of waste materials, consideration of the dynamic interaction between the waste containment system and the waste, and difficulty in establishing rational performance standards. However, seismic design for mixed and hazardous waste landfills is further complicated by the absence of federal standards for establishing the design earthquake loading and both wide variability and, at some landfills, extreme heterogeneity in waste composition. These factors combine to make site-specific investigations and/or sensitivity analyses on key parameters important components in seismic analysis and design for mixed and hazardous waste landfills. Four case histories are presented herein to illustrate the challenges associated with seismic design of mixed and hazardous waste landfills.

BACKGROUND

The Resource Conservation and Recovery Act (RCRA), found in Title 40 of the Code of Federal Regulations (40 CFR), provides nationwide minimum standards for design of both municipal solid waste landfills and hazardous waste landfills. Title 40 of the Code of Federal Regulations provides regulatory mandates for the United States Environmental Protection Agency (EPA). Section 258 of Title 40 (40 CFR 258), also referred to as RCRA Subtitle D (or Subtitle D), provides minimum standards for design of municipal solid waste landfill facilities (MSWLF). Seismic design criteria provided in Subtitle D include restrictions on siting of landfills in areas with Holocene time (Holocene) faults and requirements for design of MSWLF to resist strong shaking from earthquakes. Holocene time is defined as the most recent epoch of the Quaternary period, extending from the end of the Pleistocene epoch to the present (approximately the last 10,000 to 11,000 years). Section 264 of Title 40 (40 CFR 264), also referred to as RCRA Subtitle C (or Subtitle C), also provides siting restrictions for hazardous waste landfills in areas of Holocene faulting. However, Subtitle C is silent on design of landfills to resist strong ground motions generated by earthquakes. In some cases, the federal Subtitle C standards are supplemented or superseded by regulations and/or requirements promulgated by state agencies or by federal agencies other than EPA which include criteria for design of hazardous waste landfills subject to earthquake strong ground shaking. In other cases, seismic design criteria for hazardous waste landfills subject to earthquake strong ground shaking are left to the discretion of the design engineer, sometimes subject to the approval of the regulator.

Mixed and hazardous waste landfills accommodate a wide variety of materials, from construction and demolition debris and drums containing liquid or solid wastes to sludges and bulk liquid wastes. For a new facility, information on the types of waste anticipated at the facility and waste processing and placement procedures are generally used to estimate the anticipated range of waste properties. If the waste is already in place (e.g., design of a final cover for an existing landfill), historic information of waste types and waste placement can be supplemented with site-specific testing for evaluation of waste properties. For both new and existing facilities, sensitivity studies play an essential role in accommodating uncertainty over the mechanical behavior of the waste in design.

Four case histories are used to illustrate how the above issues may be accommodated in seismic design of mixed and hazardous waste landfills. Included in these case histories are two new mixed waste units, at Fernald, Ohio, and Rocky Mountain Arsenal (RMA), Colorado, and two existing hazardous waste units, the Operating Industries, Inc. (OII) and Casmalia Pesticide/Solvent (P/S) landfills in California. At Fernald and RMA, new waste units were designed to contain building debris and soil contaminated with low level radioactivity and hazardous chemical waste. At the OII and Casmalia P/S sites, final covers were designed for closure of existing hazardous waste units. Table 1 provides an overview of these four facilities. A more detailed discussion of geotechnical aspects of seismic design for these four facilities is provided in subsequent sections of this paper.

SEISMIC DESIGN CRITERIA

Seismic Loading Criteria

The only seismic design requirement in Subtitle C concerns siting of hazardous waste landfills near Holocene faults. Section 264.18 of Subtitle C (40 CFR 264.18) prohibits locating portions of new facilities for treatment, storage, or disposal of hazardous waste within 200 ft (61 m) of a Holocene fault. This siting requirement is similar to but more stringent than the corresponding siting requirement in the Subtitle D regulations for MSWLF. The Subtitle D regulations prohibit siting of the waste containment system for a municipal solid waste landfill within 200 ft (61 m) of a Holocene fault *unless* the elements of the waste containment system are designed to withstand the effects of fault displacement. Subtitle C does not include this important caveat that provides the engineer with the option of locating the containment system within 200 ft (61 m) of a Holocene fault if he can design it to withstand the effects of fault displacement.

Subtitle C says nothing about design of hazardous waste landfills subject to strong ground shaking from earthquakes. Subtitle D requires that the waste containment system be designed to withstand the maximum horizontal acceleration in lithified earth (MHA) evaluated either from a map presenting the peak horizontal ground acceleration (PHGA) with a 90 percent probability of not being exceeded in 250 years or from a site-specific analysis. The details of what constitutes an appropriate site-specific analysis are not provided in Subtitle D but are left to the discretion of the governing state or tribal regulatory agency. Due to the absence of any strong ground shaking design criteria in Subtitle C, the Subtitle D standards are sometimes looked upon as a minimum standard for Subtitle C hazardous waste landfill design. Furthermore, there are often other applicable regulations promulgated by state or federal agencies with jurisdiction over hazardous waste landfills that address seismic design criteria. In some situations (e.g., at Superfund sites), the governing regulatory agency (or agencies) may establish a set of project-specific requirements that include seismic design criteria.

California is an example of a state that has established its own regulations for seismic design of hazardous waste landfills. California requires that the waste containment system for hazardous waste landfills, including all structures which control gas, leachate, or surface water, be designed to withstand the Maximum Credible Earthquake (MCE). The MCE is defined as the maximum earthquake considered capable of impacting the site under the currently known tectonic framework. The phrase "maximum" is typically interpreted to mean the earthquake with the largest damage potential, as opposed to the earthquake with the largest peak horizontal ground acceleration. The use of the MCE for design of hazardous waste landfills is in contrast to the California requirement that the less stringent Maximum Probable Earthquake (MPE) be used for seismic design of municipal solid waste landfills. The MPE is defined as the maximum earthquake expected to impact the site in a 100-year period.

Landfills at the United States Department of Energy (DOE) sites designed to contain low level radioactive waste are examples of cases where there is another federal agency with applicable regulations that address seismic design. The DOE standards are contained in DOE-STD-1020-94. These standards call for sites to be designed to resist an earthquake with annual probability of exceedance of 1×10^{-3} (a 1000-year return period). The Superfund program is an example of a program where project-specific regulations for seismic design may be established at the start of a project. At the start of the design phase of a Superfund project, Applicable, Relevant, and Appropriate Regulations (ARARs) are established by the EPA to govern the design of project elements, which may include new waste units for consolidation of on-site wastes and engineered covers for existing waste units. Superfund ARARs invariably include seismic design criteria in areas where seismic loading is of concern. Superfund ARARs may include Subtitle D seismic design requirements, state seismic design requirements (e.g., use of the MCE in California), or other seismic design regulations deemed appropriate by the EPA (e.g., the Uniform Building Code).

Seismic Performance Criteria

Specifying the seismic loading to be used in design of elements of the waste containment system is only part of the necessary criteria for seismic design. The seismic performance requirements, i.e., the performance standard for elements of the waste containment system subject to the design loading, must also be defined. Seismic performance standards provided in regulations generally consist of generic statements requiring the waste containment system be designed to resist or to withstand without damage the design earthquake. In general, there are two approaches to seismic performance standards: design to either "withstand without harmful discharge" or to "withstand without damage." For facilities where there is a reasonable expectation of continuing aftercare, a design standard that calls for the containment system to withstand the design earthquake without a discharge of contaminants harmful to human health or the environment may be employed. When such a "withstand without harmful discharge" standard is employed, an earthquake response and recovery plan is an essential element of seismic design. Furthermore, financial assurance for post-earthquake repairs should also be a project requirement.

For facilities that are designed to maintain their integrity for thousands of years, it may be unreasonable to assume there will be continuing aftercare. If it is not reasonable to assume that there will be continuing aftercare, the facility may have to be designed to withstand the design earthquake without any damage whatsoever to the containment system (unless the damage is self-healing). Designing a waste containment system to withstand the design earthquake without any damage can be a particularly difficult task for a waste unit with a design life in the thousand to tens of thousands of years, as the design earthquake may represent an extreme event with a correspondingly high PHGA. Particularly when geosynthetic barrier layers are employed in the waste containment system, it may not be possible to demonstrate unconditional seismic stability (e.g., zero seismically induced displacement) in an earthquake with a PHGA in excess of 0.5 g. Therefore, the inherent weakness in geosynthetic barrier systems may preclude design of hazardous waste landfills using a "withstand without damage" performance standard in areas of high seismicity (e.g., the west coast of the United States), where the design PHGA may exceed 1.0 g under current standards.

Even when a quantitative seismic performance standard has been defined, there are practical problems that complicate evaluation of landfill seismic performance. Besides uncertainty about waste composition and waste behavior (discussed in the next section of this paper), waste / waste containment system interaction is a major hindrance to evaluation of the seismic performance of the waste containment system. Most seismic performance analyses used in practice today employ a "decoupled" approach to seismic deformation analysis of waste containment systems. In a "decoupled" analysis, the seismic response of the liner (if a liner is present), waste mass, and cover system is calculated assuming that there is no slip (relative displacement) between adjacent layers in the system. However, comparison of the shear stresses calculated using this assumption to the interface shear strength of the layered soil-geosynthetics-waste system may indicate that slip (yield) will occur. If the analysis indicates that slip will occur, the results of the seismic response analysis are used in conjunction with a yield acceleration calculated using limit equilibrium analysis in a Newmark-type seismic deformation analysis to calculate cumulative slip, or permanent seismic displacement. This type of "decoupled" approach to seismic deformation analysis has been shown to be from conservative to extremely conservative for essentially all practical situations (Rathje and Bray, 1999).

Significant additional conservatism may be added to the decoupled analysis by the common practice of using of residual shear strength parameters in calculating the yield acceleration (Matasovic et al., 1998a). The net result is often a calculated seismic permanent displacement that is simply an index of seismic performance and not truly an estimate of the seismic deformation expected in the design earthquake. Due to the excessive conservatism built in to such conventional seismic deformation analyses, seismic performance standards must distinguish between calculated and expected deformations. Considering that the level of conservatism depends on the type of analysis, if the calculated seismic deformation is the basis of the performance standard, it may be necessary to specify what type of analysis is to be used to calculate the seismic deformation for comparison to the established performance standard.

MATERIAL PROPERTIES

Evaluation of the mechanical behavior (material properties) of hazardous waste subject to seismic loading is characterized by uncertainty, variability, and heterogeneity. Sources of uncertainty with respect to hazardous waste properties required to evaluate seismic response include:

- uncertainty as to the composition of the waste that was or will be put into the landfill;
- uncertainty as to the mechanical properties of the hazardous waste and/or waste/soil mixtures, even if the waste composition is known;
- uncertainty as to the effect of processing (e.g., crushing and grinding of building demolition debris) and/or chemical or biological transformation (e.g., dissolution by solvents, corrosion, organic decomposition) of the waste on waste properties; and
- uncertainty in mechanical properties due to the difficulty in sampling and testing hazardous wastes.

Sources of variability with respect to hazardous waste seismic response include:

- changes over time in the composition of waste coming into the landfill;
- changes over time in the method of waste placement;
- changes over time in the composition and state of waste within the landfill; and
- segregation of different types of waste into different areas of the landfill.

Sources of heterogeneity of the waste contained in hazardous waste landfills include:

- containerization of waste (e.g., placement of waste in drums);
- placement of waste in the landfill without processing (e.g., placement of large blocks of concrete in building debris in the landfill); and

- changes in time in the composition of waste coming into the landfill.

Due to the uncertainty, variability, and heterogeneity of hazardous waste properties at both new and existing facilities, parametric sensitivity studies on the impact of key parameters on the seismic response of the facility are often an essential element in the seismic design of hazardous waste landfills. For new facilities, the anticipated range of waste properties may be established based upon an understanding of the types of waste that will be placed in the landfill and of the waste processing and placement procedures that will be employed. This information is complemented with generic information on the mechanical behavior of waste materials (soil, crushed concrete, municipal solid waste). For existing hazardous waste landfills, historic information on the waste receipts and landfilling practices is usually essential to understanding waste composition. Some properties (e.g., small strain dynamic properties) can be measured in situ non-intrusively at existing facilities. While other properties can sometimes be evaluated using intrusive sampling and testing (e.g., unit weight, shear strength, large strain stiffness), at other times these properties cannot be measured directly at all due to difficulties associated with sampling and testing of hazardous waste. When direct measurement is not possible, the same indirect methods used to evaluate hazardous waste properties for new facilities (i.e., generic information on soil and waste properties combined with knowledge of waste receipts and waste placement and processing) must be used.

CASE HISTORIES

General

The challenges associated with seismic design of hazardous and mixed waste landfills are illustrated by four case histories. These case histories include design of the liner and cover systems for the mixed waste landfills at the Fernald site, near Cincinnati, Ohio, and at the Rocky Mountain Arsenal in Commerce City, near Denver, Colorado, and design of the final cover systems for closure of the Operating Industries, Incorporated (OII) landfill in Monterey Park, California (near Los Angeles) and the Pesticides and Solvents (P/S) Landfill at the Casmalia Resources Hazardous Waste Management Facility near Santa Maria, California (in Santa Barbara County). Table 1 summarizes the characteristics of these four facilities, including the type of waste and regulatory considerations. Table 2 summarizes the seismic design criteria employed at each of the four facilities. Table 3 provides details of the seismic analysis performed at each site. (Tables are provided at the end of the paper.)

Fernald

The Fernald site, near Cincinnati, Ohio, represents a case where a federal agency other than EPA had jurisdiction over the landfill and where that agency had applicable design criteria. Because the Fernald site was a former nuclear weapons production facility, the United States Department of Energy (DOE) was the lead agency for design and construction of the on-site mixed waste landfill. At Fernald, a new, geosynthetic-lined and covered facility was designed to contain low level radioactive waste consisting primarily of soil but also containing fly ash, sludge, and building demolition debris (GeoSyntec, 1997a). Under DOE guidelines, the Fernald landfill was considered a "Performance Category 2" facility. DOE design standard DOE-STD-1020-94 requires design of Performance Category 2 facilities to resist an earthquake with a PHGA with an annual probability of occurrence of less than or equal to 1×10^{-3} (a return period of at least 1000 years). However, as the Fernald facility also qualified as a RCRA Subtitle C waste unit, the designers decided that the RCRA Subtitle D seismic design criteria should also be applied as a minimum design standard. The Subtitle D design ground motion criterion of a PHGA with a probability of not being exceeded of 90 percent in 250 years corresponds to an annual probability of occurrence of 4.2×10^{-4} (a return period of 2372 years). Therefore, the Subtitle D criterion is more stringent than the DOE criteria and governed design. Using the USGS national seismic hazard map, the design PHGA for Fernald was established as 0.16 g. Using information on local and regional seismic sources, this PHGA was assigned a moment magnitude (M_W) of 6.1 and a site-to-source distance of 32 km.

Available geotechnical data indicated that the soil at the site that would be going into the waste fill was primarily low plasticity silty clay and clayey silt. Operational procedures called for the waste to be broken up into pieces no greater than 0.3 m in dimension and embedded within a soil matrix within the landfill. The waste was to be placed in lifts not exceeding 0.9 m in thickness and compacted with tamping foot compactors. Based upon this information, the waste was assigned a unit weight of 19.6 kN/m^3, a shear wave velocity of 235 m/s, and modulus reduction and damping curves from Vucetic and Dobry (1991) for soil with a plasticity index (PI) of 15.

The Fernald facility liner system was designed to withstand the design earthquake without damage. The Fernald facility cover system was design to withstand the design earthquake with no more than minor cracking in the soil cover (damage no more serious than soil erosion). The quantitative performance criteria established to meet these requirements were a permanent seismic displacement of 0.15 m for the liner system and a permanent seismic displacement of 0.3 m for the cover system, calculated using the results of one-dimensional equivalent linear site response analysis as implemented in SHAKE91 (Idriss and Sun, 1992) and a Newmark-type analysis based upon residual shear strength parameters. These criteria were established based upon comparison of the results of this type of analysis to the observed performance of landfills in earthquakes (Anderson and Kavazanjian, 1995, Augello, et al., 1995, Matasovic et al., 1998b).

Rocky Mountain Arsenal

At the Rocky Mountain Arsenal (RMA) site in Commerce City, near Denver, Colorado, a new geosynthetic-lined and covered mixed waste unit was designed for contaminated soil removed during clean up of this former pesticides manufacturing and chemical weapons production facility (GeoSyntec, 1997b). Similar to Fernald, the RCRA Subtitle D design ground motion criterion was considered as the minimum standard for this RCRA Subtitle C facility. However, the RMA site is in an area of recent seismic activity (some of which has been attributed to deep injection of liquid wastes). As recently as 1981, a moderate (M_W 4.3) earthquake occurred on a shallow fault directly beneath the site. Therefore, the 0.27 g PHGA from the USGS national seismic hazard map for 90 percent probability of not being exceeded in 250 years (the Subtitle D design criterion) was supplemented with a site-specific analysis for the Maximum Credible Earthquake (MCE). The MCE was defined in accordance with California regulations as the most damaging earthquake expected to occur within the current understanding of the tectonic framework for the area. Results of the site-specific hazard analysis indicated the MCE was a M_W 6.0 event within 3 km of the site, generating a bedrock PHGA of 0.45 g at the site. This event was estimated to have a return period of approximately 10,000 years (an annual probability of occurrence of 1×10^{-4}) and was used for design.

The seismic performance criteria for the RMA waste unit was the same as established for the Fernald waste unit. Based upon site-specific geotechnical data and operational criteria for waste placement, the waste was assigned a unit weight of 18.1 kN/m^3 and modulus reduction and damping curves from Vucetic and Dobry (1991) for PI = 15. The seismic response of the waste mass was analyzed using upper and lower bound shear wave velocity profiles developed based upon previous shear wave velocity measurements made at industrial waste landfills.

<u>Operating Industries, Inc.</u>

The Operating Industries, Inc. (OII) landfill is a Superfund site located in Monterey Park, California, approximately 16 km east of downtown Los Angeles. The landfill is located immediately adjacent to a major freeway and residential development (Figure 1) and directly on top of a blind thrust fault considered capable of generating a M_W 7 earthquake. Landfill slopes were up to 90 m above grade and were in places steeper than 1.5H:1V (1.5 horizontal to 1 vertical), averaging 1.5H:1V over large portions of the slope adjacent to the freeway. Due to the above factors, EPA considered the landfill to pose a unique urban seismic hazard and constituted a blue-ribbon Technical Review Panel to oversee seismic analysis and design. In establishing the ARARs for the site, the EPA adopted the California seismic design requirements for hazardous waste landfills, calling for use of the MCE as the design event. Seismic hazard analysis identified two MCE events that had to be considered in design: a M_W 7.0 event at a depth of 11 km directly beneath the site generating a PHGA of 0.61 g and a M_W 8.0 event at a distance of 52 km, generating a PHGA of 0.15 g at the site.

Seismic performance criteria were developed for the OII landfill on a component-specific basis. Due to the intensity of the peak acceleration, the magnitude of the design earthquake, and the steepness of the landfill slopes, design to withstand the MCE without damage was not considered feasible. Therefore, the final cover system was designed to withstand the design earthquake without a release of contaminants harmful to human health and the environment, including consideration of post-earthquake response and recovery measures. Table 4 (Kavazanjian, et al., 1998) presents the component-specific seismic performance criteria developed for the final cover at the OII site, including response and recovery considerations. The performance criteria also included allowing up to 0.9 m of deformation in the waste mass, as the waste was determined to be a ductile material with no post-peak strength decrease and negligible potential for flow sliding subsequent to failure. The results of two-dimensional equivalent-linear finite element seismic response analysis were used along with residual shear strengths to evaluate landfill performance in the MCE for comparison to the criteria in Table 4.

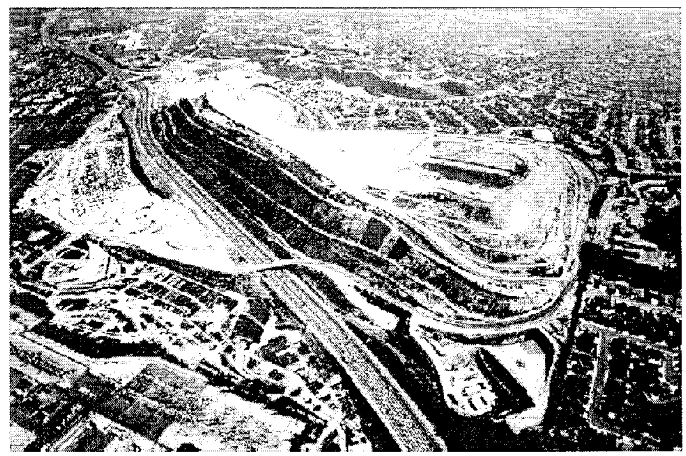

Figure 1: OII Landfill, Monterey Park, California (View from the Northwest)

The waste at OII was primarily industrial and municipal solid waste. However, large quantities of liquid wastes, including organic solvents, were disposed of in the southwest corner of the site. Geotechnical exploration at the site frequently encountered zones of perched liquid, though the liquid zones appeared to be discontinuous both vertically and laterally. The seismic response analysis conducted for final cover design consisted of a two-dimensional equivalent-linear finite element seismic response analysis using the computer program QUAD 4M (Hudson et al., 1994). A site-specific unit weight profile was established for use in seismic analysis based upon in-situ testing in three large-diameter (750-mm diameter) bucket auger borings and one large (20 m long by 20 m deep) test trench. The small-strain dynamic modulus of the waste was established from site-specific shear wave velocity profiles developed using the non-intrusive Spectral Analysis of Surface Waves (SASW) method. Intermediate-strain dynamic properties were established by back analysis of strong motion records obtained at the site during a series of nearby small and distant large earthquakes. Large-strain properties were established based upon large-diameter (450-mm diameter) direct simple shear laboratory tests on reconstituted samples of waste recovered from the bucket auger borings. Details of the field investigation and seismic analysis for the OII landfill are presented in Matasovic and Kavazanjian (1998).

The waste mass characterization at OII indicated considerable uncertainty with respect to both the strength of the waste mass and liquid levels at the site. Due to these uncertainties, the limit equilibrium analysis used to calculate the yield acceleration for use in the Newmark deformation analyses included parametric analyses on waste shear strength and liquid levels within the waste mass (GeoSyntec, 1996). The parametric analyses on waste strength included consideration of weak horizontal planes within the waste mass due to the method of waste placement. Therefore, as illustrated in Figure 2, both circular failure surfaces using the shear strength assigned to the refuse and wedge analysis using the "weak layer" shear strength on horizontal planes through the waste mass were conducted to calculate the factor of safety and yield acceleration. Parametric analyses on liquid levels included consideration of a static liquid level at the base of the fill and perched liquid levels with 2.4 m of hydraulic head throughout the fill. For the governing case, a "weak layer" wedge analysis with 2.4 m of hydraulic head on the weak plane, calculated seismic deformations were within the 0.9 m limiting value, indicating acceptable stability for the waste mass. While calculated deformations for the cover system were also within acceptable limits, final design included a debris barrier at the toe of the slope adjacent to the freeway as an added safety measure.

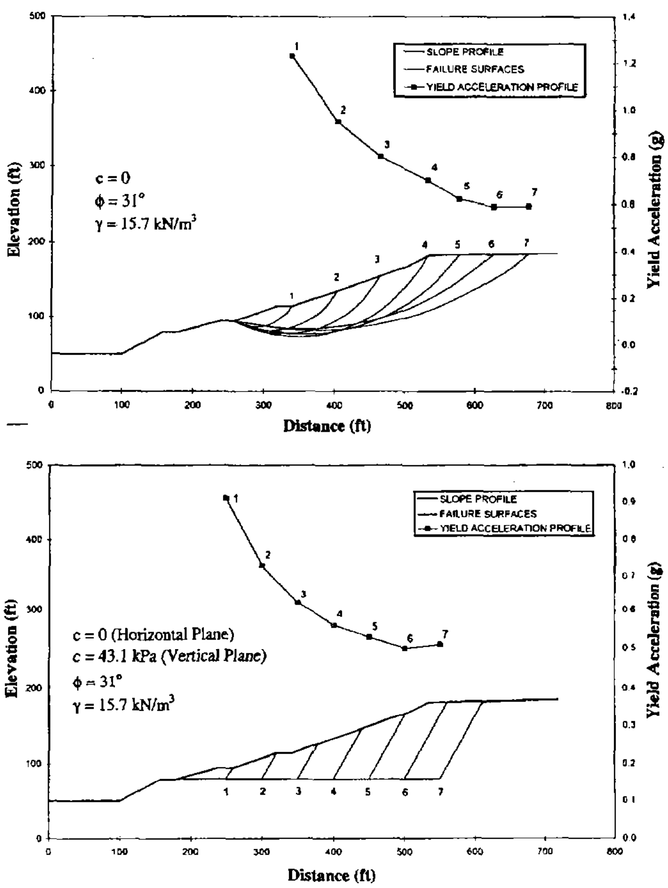

Figure 2: OII Southwest Corner Failure Mechanisms

<u>Casmalia Pesticides and Solvents Landfill</u>

Design of the final cover for the Pesticides and Solvents (P/S) landfill at the Casmalia Resources Hazardous Waste Management facility in Santa Maria, California, was also governed by the MCE, as specified in California regulations for seismic design of hazardous waste facilities. The MCE for the Casmalia site was established as a M_W 6.6 event with a site-to-source distance of 2.6 km, generating a PHGA of 0.86 g at the site (GeoSyntec, 1998). Due to the high PHGA at Casmalia, equivalent-linear site response analysis was not considered appropriate and a non-linear one-dimensional site response analysis was performed using the computer program D-MOD (Matasovic, 1993: Matasovic and Vucetic, 1995). Due to the difficulty in withstanding an earthquake of such intensity and magnitude without any damage, the seismic performance criteria for Casmalia was based on a "withstand without discharge" criteria and included a maximum calculated seismic deformation of 0.3 m for both the cover system and the waste mass. Waste mass deformation was limited to less than 0.3 m compared to the 0.9 m limit employed at OII because the non-linear seismic response analysis used at Casmalia was considered less conservative than the equivalent-linear method employed at OII. A cover deformation of 0.3 m was considered acceptable at Casmalia because the cover is repairable and cover failure would not immediately impact either human health or the environment.

Evaluation of waste mass properties at Casmalia site was complicated by the heterogeneous nature of the waste. Much of the waste placed in the P/S landfill was contained in steel drums that were stacked in horizontal layers and backfilled with native soils, as shown in Figure 3. However, given the nature of the waste in the drums and the environment in which they were placed and based upon previous geotechnical exploration activities at the site (borings and cone penetration test (CPT) soundings), it was suspected that many of the drums had corroded and lost their integrity.

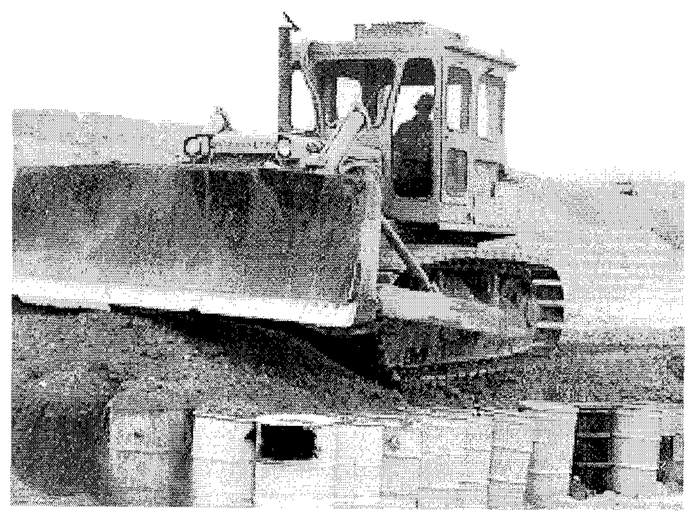

Figure 3: Containerized Liquid Waste Disposal Practice

Small strain dynamic properties were based upon the shear wave velocity profiles shown in Figure 4, developed from SASW test results. The shear wave velocity profiles at Casmalia compared favorable to the range of shear wave velocity established by Kavazanjian et al. (1996) for southern California municipal solid waste landfills. Large strain properties for the waste at Casmalia were based upon geotechnical testing of on-site soils from the same borrow area used to supply soil for waste filling operations. This testing indicated the on-site borrow soil was a plastic clay. Thus, the Vucetic and Dobry (1991) curves for PI=30 were used in the dynamic response analysis. Waste shear strength was based upon the results of the CPT soundings. A site-specific value for the CPT shear strength factor N_k was developed from correlation between the CPT results, the shear wave velocity profiles, and shear strength of plastic clay soils. The site-specific N_k profile for the Casmalia P/S landfill is shown in Figure 5, where N_k relates CPT tip resistance, q_c, to undrained shear strength, S_u, and in situ total vertical stress, σ_{vo}, by the equation:

$$S_u = (q_c - \sigma_{vo}) / N_k \qquad (1)$$

As the CPT profiles indicated the possible existence of two weak layers within the Casmalia P/S landfill, both the seismic response analysis and the limit equilibrium analysis included consideration of these weak layers.

CONCLUSIONS

Due to the absence of seismic design criteria in the federal Subtitle C standards for hazardous waste landfills, seismic design and performance criteria for mixed and hazardous waste landfills are generally developed on a project-specific basis, supplemented by state and project-specific standards. In developing project-specific criteria, the federal Subtitle D seismic design standards for municipal solid waste landfills are often used as a minimum design standard for Subtitle C facilities. Seismic performance standards are also usually developed on a project specific basis. If there is a reasonable expectation of continuing aftercare, the landfill may be designed to withstand the design earthquake without a discharge of contaminants harmful to human health or the environment (the "withstand without harmful discharge" standard) may be employed. Alternatively, the landfill may be designed to withstand the design earthquake without damage (the "withstand without damage" standard). However, the "withstand without damage" standard may not be feasible for closure design of existing waste units in areas of high seismicity. The quantitative performance criteria established to meet either of the above performance standards should depend on the type of analysis, as different types of analyses contain different inherent levels of conservatism.

Material properties for seismic design of mixed or hazardous waste landfills are also usually developed on a project specific basis using information on waste composition and project-specific testing (on existing waste units) where possible. However, material property values are often subject to considerable uncertainty due to uncertainties about waste composition, variability in the waste composition, and waste heterogeneity. Parametric and sensitivity studies are generally used to compensate for the uncertainty with respect to material properties. Generic material parameters for waste and soil materials provide a rational basis for these parametric studies.

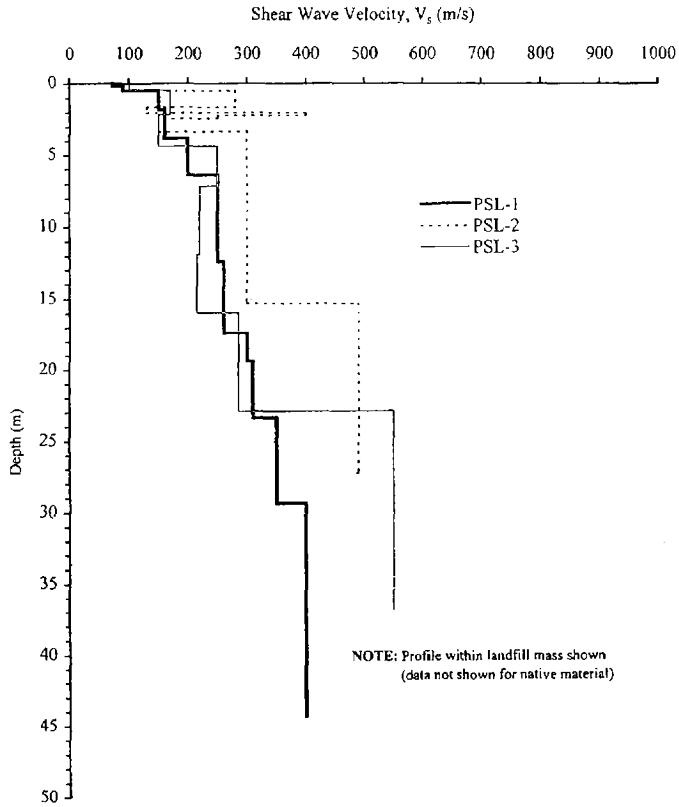

Figure 4: Measured Shear Wave Velocity Profiles, Casmalia P/S Landfill

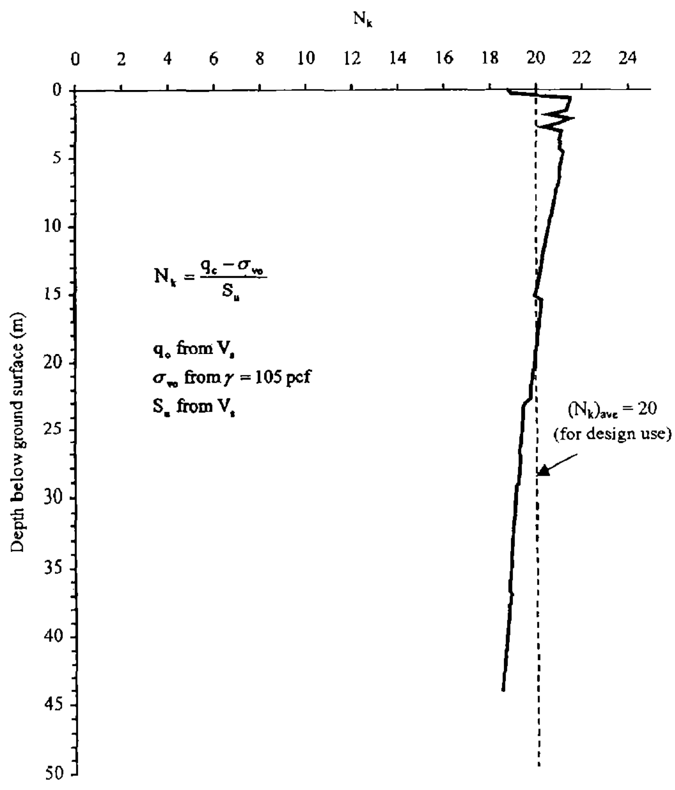

Figure 5: N_k Profile Estimated from the Results of SASW Measurements at Casmalia P/S Landfill

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TABLE 1. LANDFILL CASE HISTORIES

Site	Landfill Type[1]	Task	Waste Type	Regulatory Agency Oversight	Governing Regulations
Fernald (Ohio)	Area Fill (Lined)	New Cell Design	Low level radioactive waste (primarily soil, but also fly ash, sludge and building debris)	DOE and USAEC	Subtitle D DOE-STD-1020-94
RMA (Colorado)	Pit Fill (Lined)	New Cell Design	Mixed waste from pesticide and chemical weapons production (78% CL soil, 21% building debris, 1% organic waste)	EPA and CDPH&E	Subtitle D
OII (Southern California)	Sand/Gravel Pit Fill (Unlined)	Closure Design	Industrial and municipal solid waste locally mixed w/ liquid waste (approx. 80% soil and soil like materials)	EPA	CCR Title 23
Casmalia P/S Landfill (Central California)	Canyon Fill (Unlined)	Closure Design	57% containerized liquid waste, 43% railroad ballast, sludges, construction debris, and miscellaneous	California EPA (Under EPA Supervision)	Subtitle D CCR Title 23

Notes: (1) According to the landfill type classification presented in Matasovic et al. (1995).
EPA = Environmental Protection Agency.
CDPH&E = Colorado Department of Public Health and Environment.
CCR = California Code of Regulations.
DOE = United States Department of Energy.
USAEC = United States Atomic Energy Commission.

TABLE 2. SEISMIC DESIGN CRITERIA

Site	Ground Motion Criteria	Design Earthquake (PHGA)	Stability Criteria
Fernald (Ohio)	More stringent of: DOE-STD 1020-94 (1000-yr. RP) and EPA/600/R-95/051 (2500-yr. RP)	M_W 6.1 @ 32 km (0.16 g)	$u_{max} < 0.15$ m (liner) $u_{max} < 0.30$ m (cover)
RMA (Colorado)	10% PE in 250 Years MCE	M_W 5.4 @ 3 km (0.27 g) M_W 6.0 @ 3 km (0.45 g)	$u_{max} < 0.15$ m (liner) $u_{max} < 0.30$ m (cover)
OII (Southern California)	MCE	M_W 7 @ 11 km (0.61 g) M_W 8 @ 52 km (0.15 g)	Component-Specific (see Table 4)
Casmalia P/S Landfill (Central California)	MCE	M_W 6.6 @ 2.6 km (0.86 g)	$u_{max} < 0.30$ m (waste mass) $u_{max} < 0.30$ m (cover)

Notes: PE = Probability of Exceedance.
M_w = Moment Magnitude.
MCE = Maximum Credible Earthquake, as defined in CCR Title 27.
PHGA = peak horizontal ground acceleration in hypothetical bedrock outcrop at the site.
RP = Return Period.
u_{max} = Maximum Calculated Permanent Displacement.

TABLE 3. SEISMIC RESPONSE ANALYSES DETAILS

Site	Site Response Analysis Type	Site-Specific Investigations (Waste Only)	Total Unit Weight Profile	Shear Wave Velocity Profile	Poisson Ratio Profile	Modulus Reduction and Damping Curves	Viscous Damping
Fernald (Ohio)	1-D Equivalent-Liner	N/A	Constant (19.6 kN/m^3)	Constant (235 m/s)	N/A	Vucetic and Dobry [1991] (PI=15)	N/A
RMA (Colorado)	1-D Equivalent-Liner	N/A	Constant (18.1 kN/m^3)	Lower/Upper Bound Profiles(1)	N/A	Vucetic and Dobry [1991] (PI=15)	N/A
OII (Southern California)	2-D Equivalent-Linear FEM	SASW, Drilling and Sampling; Large-Diameter Lab. Testing	Site-Specific(3) (15.7 kN/m^3)	Site-Specific	Site-Specific	Site-Specific	N/A
Casmalia P/S Landfill (Central California)	1-D Non-Linear	SASW; CPT; borrow source lab. testing	Constant (15.7 kN/m^3)	Site-Specific	N/A	Vucetic and Dobry [1991] (PI=30)	1%

Notes: (1) Lower-bound shear wave velocity profile: V_s increases from 125 m/s immediately below the cover system to 450 m/s immediately above the liner system. Upper-bound shear wave velocity profile: V_s increases from 200 m/s immediately below the cover system to 575 m/s immediately above the liner system.
(2) Parameters of the non-linear model fitted to the Vucetic and Dobry (1991) modulus reduction curve.
(3) Evaluated based upon site-specific in situ unit weight measurements.

FEM = Finite Element Method.
N/A = Not Applicable.

TABLE 4. SEISMIC DESIGN CRITERIA AND PERFORMANCE STANDARDS (KAVAZANJIAN ET AL., 1998)

Cover System Component	Design Criteria And Performance Standard	Interim Remediation To Restore Compliance	Repair To Pre-Earthquake Condition
Final Cover			
Soil Monocover on Side Slopes	150 mm of soil deformation. Partial failure contained on site.	3 months to strip vegetation, regrade and recompact areas of cracking.	12 months to restore vegetation.
Landfill Gas Control			
Collection Wells	Up to 25 percent of wellheads broken.	1 month to route headers around broken wellheads.	12 months to repair/replace broken wells heads.
Headers	Up to 25 percent of header pipes cracked or broken.	1 month to bypass broken header pipes.	3 months to repair/replace broken headers.
Vacuum Pumps	Power loss. No structural damage.	None required.	1 month to restore off-site power.
Leachate Transmission Pipes	Acceptable breakage of pipes with double containment.	1 month to bypass broken pipes.	3 months to repair broken pipes.
Surface Water Management			
Conveyance Systems (Bench Channels, Down Drains, Culverts)	Cracking and up to 300 mm of displacement.	2 months to completely restore surface pathways.	9 months to replace/rebuild surface pathways.
Sedimentation Basin	Minor cracking of concrete.	2 weeks to 1 month to patch the cracks.	9 months to rebuild the basin (if needed).
Access Roads	300 mm displacement (cracking).	2 months to patch the cracks.	12 months for full repair.