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EARTHQUAKE ENGINEERING FOR LANDFILLS

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ABSTRACT

This technical article presents an overview of a methodology for engineering analysis and design of municipal solid waste (MSW) and hazardous waste (HW) landfills for earthquakes. The methodology has evolved over many years from the author's various experiences with earthquake engineering and landfill design and seismic monitoring and evaluation of Civil Engineering structures including landfills in the highly active southern California tectonic environment.

The paper addresses the following:

- Current United States Regulatory Requirements for Landfill Earthquake Design
- Important Basic Factors in Seismic Design of Landfills
- Evaluation of Seismic Hazard and Design Ground Motions
- Predicting Seismic Response and Deformation of Landfills
- Summary of Stability Analysis Procedures
- Optimization of Stability Analysis
- Applicability of the Process to Various Waste Management Systems

Conventional practice (e.g. pseudo-static with displacements estimated by Newmark-type methods) and more refined 2D finite element modeling procedures for evaluating dynamic response and deformation of landfills are described and a process for facilitating/optimizing the analysis and landfill design is presented and discussed.

The analysis procedure is applicable to natural, cut, interim or temporary and final waste slopes, and landfill cover systems. Ultimately the basis for design is whether or not predicted displacements caused by ground motions can result in irreparable or costly damage to critical landfill environmental protective elements or other life or health threatening conditions. Application of the methodology to three major landfills located in California has been completed by the authors for the landfill owners. The sites include a 100-million-ton expansion of an operating MSW landfill, a major hazardous waste landfill, and an abandoned mixed MSW and liquid hazardous waste disposal facility.

For each of the three landfills the more rigorous analysis was used to optimize the design configurations, and in two of the cases, to evaluate the potential stresses in liners in order to set limiting deformations (i.e., allowable deformations which would not damage the liner systems during earthquakes).

A summary of the methodology and benefits of implementation is presented. Finally, applicability to other waste management facilities is discussed and a brief comparison is made between the relative cost of performing the refined analysis and the benefits.

KEYWORDS

Landfills; Earthquake; Response; Stability; Optimization; Deformations.

CURRENT UNITED STATES REGULATORY REQUIREMENTS FOR LANDFILL EARTHQUAKE DESIGN

Effective October, 1993 the United States Environmental Protection Agency (United States EPA) promulgated the requirements for design and operations of Municipal Solid Waste Landfill Facilities (MSWLFs) in one comprehensive regulation; Resource Conservation and Recovery Act (RCRA) Subtitle D located in the Code of Federal Regulations (CFR), Title 40, Part 258. Regarding seismic design the regulation includes the following requirements:

- New MSWLF units and lateral expansions shall not be located within 200 feet (61 meters) of a fault that has had displacement in Holocene time unless the owner or operator demonstrates that an alternative setback distance of less than 200 feet (61 meters) will prevent damage to the structural integrity of the MSWLF unit and will be protective of human health and the environment (40 CFR §258.13).
- New MSWLF units and lateral expansions shall not be located in seismic impact zones unless the owner or operator demonstrates that all containment structures, including liners, leachate collection systems, and surface water control systems are designed to resist the maximum horizontal acceleration (MHA) in lithified earth material (bedrock) for the site (40 CFR §258.14[a]).
- Seismic impact zone means an area with a 10 percent or greater probability that the MHA in lithified earth material, expressed as a percentage of the earth's gravitational pull (g), will exceed 0.10g in 250 years (40 CFR §258.14[b][1]).
- MHA in lithified earth material means the maximum expected horizontal acceleration depicted on a seismic hazard map (such maps have been published by the United States Geologic Survey [USGS]), with a 90 percent or greater probability that the acceleration will not be exceeded in 250 years, or the maximum expected horizontal acceleration based on a site-specific seismic risk assessment (40 CFR §258.14[b][2]).

In 1995 the United States EPA Risk Reduction Engineering Laboratory published "RCRA Subtitle D (258) Seismic Design Guidance for Municipal Solid Waste Landfill Facilities" (United States EPA, 1995) which includes clarification with respect to selection of design earthquake ground motions which will be discussed briefly in a later section of this paper.

California regulations for design of MSWLFs, which were approved by United States EPA, require preparation of a slope or foundation stability report by a registered civil engineer or certified engineering geologist for final site face slopes steeper than a horizontal to vertical ratio of three to one. The report must include the maximum expected horizontal acceleration in rock at the site determined for the Maximum Probable Earthquake (MPE) (CCR Title 14, §17777[c][7]).

The maximum expected acceleration in rock derived from the Maximum Credible Earthquake (MCE) may be used instead of the MPE (CCR Title 14, §17777[c][7][A]). The MPE and MCE are as defined by the California Division of Mines and Geology (CDMG Note 43, 1975) as follows:

- MPE is the maximum earthquake that is likely to occur during a 100-year interval and shall not be less than the maximum historical event. It is to be regarded as a probable occurrence, not as an assumed event that will occur at a specific time.
- MCE is the maximum earthquake that appears capable of occurring under the presently known tectonic framework. It is a rational and believable event that is in accord with all known geologic and seismologic facts. In determining the maximum credible earthquake, little regard is given to its probability of occurrence, except that its likelihood of occurring is great enough to be of concern.

The California regulations also state that in lieu of achieving a factor of safety of 1.5 under dynamic conditions, a more rigorous analytical method that provides a quantified estimate of the magnitude of movement may be employed. In this case, the stability report must demonstrate that this amount of movement can be accommodated without jeopardizing the integrity of the final cover or the environmental control systems (CCR Title 14, §17777[c][11]).

These United States EPA and California regulations for MSWLFs also prescribe the use of composite liner/cover systems which involve layers of low permeability soil (e.g., clay) and geomembranes.

In the case of Hazardous Waste Landfill Facilities (HWLFs), United States EPA regulations state that portions of new facilities where treatment, storage, or disposal of hazardous waste will be conducted will not be located within 61 meters (200 feet) of a fault which has had displacement in Holocene time (40 CFR Subtitle C Part 264 §270). State of California regulations for hazardous waste landfills require the final cover be designed and constructed to accommodate lateral and vertical shear forces generated by the MCE so that the integrity of the cover is maintained (CCR Title 22, Article 14). These United States EPA and California regulations for HWLFs also prescribe the use of multiple liner elements including low permeability soils and geomembranes.

IMPORTANT BASIC FACTORS IN SEISMIC DESIGN OF LANDFILLS

Landfill stability is of great concern because:

- Failures can be very costly.
- Overly conservative designs result in the loss of valuable air space and increased construction costs.
- Slope reinforcement techniques to enhance stability can be very expensive.
- United States EPA Subtitle C and D liner/cover regulations result in weak interfaces affecting liner/cover stability.
- United States federal regulations can result in conservative seismic requirements (e.g., high ground accelerations), thus requiring detailed analyses to avoid overconservatism due to use of simplified analytical methods.
- Recent large earthquakes in the United States, Chile, Japan and other Asian countries are likely to focus greater owner and regulator attention toward seismic design issues.

Experience has shown that in most of the United States (which is not highly seismically active), regional seismic hazard maps such as the ones suggested in United States RCRA Subtitle D (USGS seismic hazard maps) give a conservative estimate of site MHA. However, in highly seismic areas, such as California, use of the USGS seismic hazard maps might result either in large overconservatism, or in some cases, unconservative estimates of site MHA. Thus, in these areas, a site-specific detailed analysis, as allowed by United States federal and state regulations, provides a more reliable estimate of ground motions than using regional seismic hazard maps.

The following are significant factors to be considered in landfill seismic design analyses:

- Seismic design ground motion predictions:
  - Ground motion parameters can be either deterministically or probabilistically predicted for many sites.
  - A landfill can either attenuate or amplify site ground motions, depending on the landfill geometry and waste properties and the earthquake distance and characteristics.
- Material strength and dynamic properties:
  - Consolidated or compacted trash can be stronger than most soils.
  - Geosynthetic interfaces are much weaker than most soils.
  - Therefore, failures are most likely to occur along the liner or cover systems.
- More sophisticated analyses usually provide more reliable estimates of landfill dynamic stability and deformation (e.g., less predicted deformation in the case of liner stability) than calculations based on simplifying assumptions
  - This allows for optimization between analysis and construction/operation costs.
- Construction materials should be flexible to sustain calculated strains whenever practical.

Different approaches for the site-specific analysis of ground motion parameters can be followed. The approach described below has been successfully used for design and permitting of several major landfill expansions and new landfills by the authors.

EVALUATION OF SEISMIC HAZARD AND DESIGN GROUND MOTIONS

To establish the nature of the earthquake risk at a landfill site location, a detailed evaluation is made of the potential for fault rupture and the potential degree of the ground shaking to be experienced at the site. This evaluation is based on studies of regional seismicity, proximity of active or capable faults, geologic conditions, and historic records. The process involves review of available literature on geologic and seismic conditions and site-specific field geologic reconnaissance. In particular, the critical information required for seismic hazard evaluation are: (1) fault maps; (2) aerial photographs; (3) geologic/soil maps; (4) boring, well, and trench logs in the vicinity of the site; (5) historical seismic activity; (6) recent regional seismic source models; and (7) attenuation relations and mathematical models correlating seismic source parameters. Regional geologic and fault maps can generally be obtained from the United States Geologic Survey (or its equivalent in many other countries) or other government agencies and universities. Faulting and seismologic studies for the site vicinity can often be obtained from the same sources or from public or private records for other major projects previously planned or constructed in the vicinity. Site-specific fault investigations may include some or all of the following resources:

- Preexisting topographic maps.
- Area residential/commercial geotechnical investigations.
- Oil and gas field data.
- Aerial photographic analyses.
- Geologic mapping.
- Subsurface investigation (trenching and drilling).
- Geophysical surveys (seismic, electromagnetic).
- Age dating (by soil stratigraphy or radioactivity).

The collected data requires synthesis into detailed geologic/faulting maps and cross sections; seismicity maps showing location of the site, active and potentially active faults, and local and regional seismic activity; and a table summarizing information on local and regional seismic source models. In particular, the seismic source model contains information on seismic sources identified and modeled as line, area, or dipping plane sources based on geologic evidence, geotectonic province, geodetic and seismic data. Information on seismic source parameters such as length and width (geometric dimensions), fault type (e.g., dip-slip or strike-slip), dip angle, maximum magnitude, slip rate, and parameters related to source recurrence relationship such as moment rate, characteristic rate, and Gutenberg-Richter rate are usually included in a seismic source model summary table. The largest event or the maximum credible earthquake (MCE) magnitude associated with a fault is determined based on the magnitude-length relationships.

Site-specific analyses are commonly preferred to use of generic seismic hazard maps for assessing seismic design parameters due to the ability to achieve a higher degree of precision and incorporate the latest information on regional and local geologic and seismologic conditions at a site. Depending on the geologic and seismologic data available, deterministic, probabilistic or a combination of both methods may be used to determine seismic design parameters (e.g., peak ground acceleration, response spectra, design earthquake, and ground motions) for the site. Site seismic design parameters for different levels of risk (probabilities of exceedance) and for the probable and maximum credible earthquakes during the lifetime of the project are computed. Choice of proper attenuation relations is a critical ingredient of the above seismic hazard evaluations. The earthquake sources are translated into ground motion using empirical attenuation relationships that relate magnitude and distance to horizontal or vertical ground accelerations. Many empirical attenuation relations have been formulated using regional; such as California or North America and global strong motion data, and recent relations have incorporated effect of both style of faulting (e.g., strike-slip or dip-slip) and general site classification and topography. The site to source distance is defined differently for many of these attenuation relations and thus the fault plane geometry is important for calculating distances. The seismic hazard should be evaluated using recent attenuation relations that incorporate effects of type of faulting and site conditions and topography (e.g., Boore *et al.*, 1993; 1994; Campbell and Bozorgnia, 1994; and Abrahamson and Silva, 1995).

The seismic parameters needed for the earthquake analysis and design of landfills depend on the degree of accuracy and rigor of the analysis method (e.g., pseudo-static versus pseudo-dynamic deformation analysis such as Newmark-type methods or full nonlinear dynamic deformation analysis). Peak acceleration is only one characteristic of the earthquake ground motion at a site. The damage potential of seismically-induced ground motions also depends on the frequency content, duration, and overall intensity of vibrations. Large magnitude and more distant earthquakes may generate ground motions at a site that are of lower intensity but, depending on the landfill characteristics, have greater damage potential than a small magnitude nearby event associated with a larger peak ground acceleration. Therefore, it is important, particularly in a probabilistic hazard analysis, to develop a design earthquake associated with the site design acceleration. For this reason faults are usually divided into near, intermediate, and far field sources and, depending on the landfill characteristics and fault distance and maximum earthquake magnitude, controlling seismic sources (having highest damage potential in a distance range) are determined. Dynamic analysis of landfill response and deformations require development of representative site design earthquake time histories. Ground motions can be estimated either by selection of natural time histories or generation of a synthetic time history whose spectral ordinates are comparable to those of the design site (target) spectrum for the period range of interest. It is generally good practice to use both synthetic and natural time histories in the analysis. The approach to develop design earthquake and time histories for dynamic analysis of landfills is detailed in a recent guidance document published by the United States EPA Risk Reduction Engineering Laboratory on seismic design of MSW landfill facilities (United States EPA, 1995).

These geologic and seismologic studies form the basis for the subsequent analyses of the landfill dynamic response and deformations including the effects of local soil conditions, liquefaction potential, slope stability, and soil-structure interaction during seismic events.

PREDICTING SEISMIC RESPONSE AND DEFORMATION OF LANDFILLS

The state of practice in seismic stability evaluation of landfills in the United States is evolving toward predicting seismically-induced landfill deformations rather than performing a pseudo-static analysis which requires a great deal of judgment in selection of pseudo-static earthquake acceleration which might result in overly conservative and in some cases unconservative solutions. However, a pseudo-static stability analysis can be used as an initial minimum analysis before embarking on a more detailed dynamic analysis (if needed). A deformation analysis properly incorporates the dynamic characteristics of ground motions and landfill mass in predicting waste slope, liner and cover displacements which might result in damage and disruption of landfill environmental control elements.

As the base material beneath a landfill is being shaken back and forth during an earthquake permanent displacements may occur in landfill elements. The purpose of a seismic response analysis is to predict attenuated/amplified ground motions in the landfill to use for calculating seismically-induced permanent displacements (Fig. 1). Theoretically the approach is to use the dynamic properties of the subsurface and waste materials together with various analysis methods to include effects of material nonlinearity and damping (e.g., shear beam, one-dimensional finite difference, two-dimensional finite elements) to predict seismic response motions in the landfill. Observations from the only landfill instrumented with accelerographs in the United States (OII Landfill) show the effects of ground motion characteristics such as frequency content and landfill geometry and waste properties on amplification and/or attenuation of input base motions for use in model calibrations and back calculation of waste dynamic and strength properties.

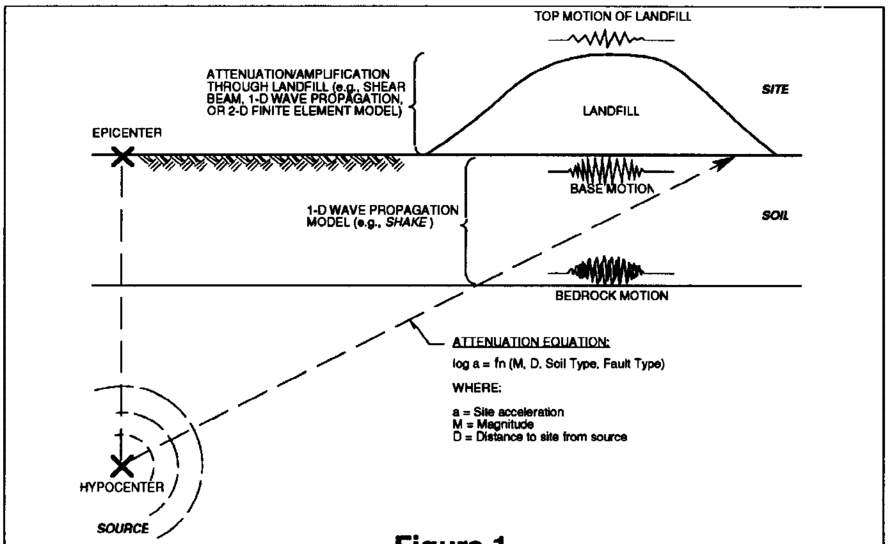

Figure 1
Schematic Representation
of Seismic Energy Propagation

Fig. 1. Schematic Representation of Seismic Energy Propagation

The steps involved for seismic deformation analysis are illustrated in Fig. 2.

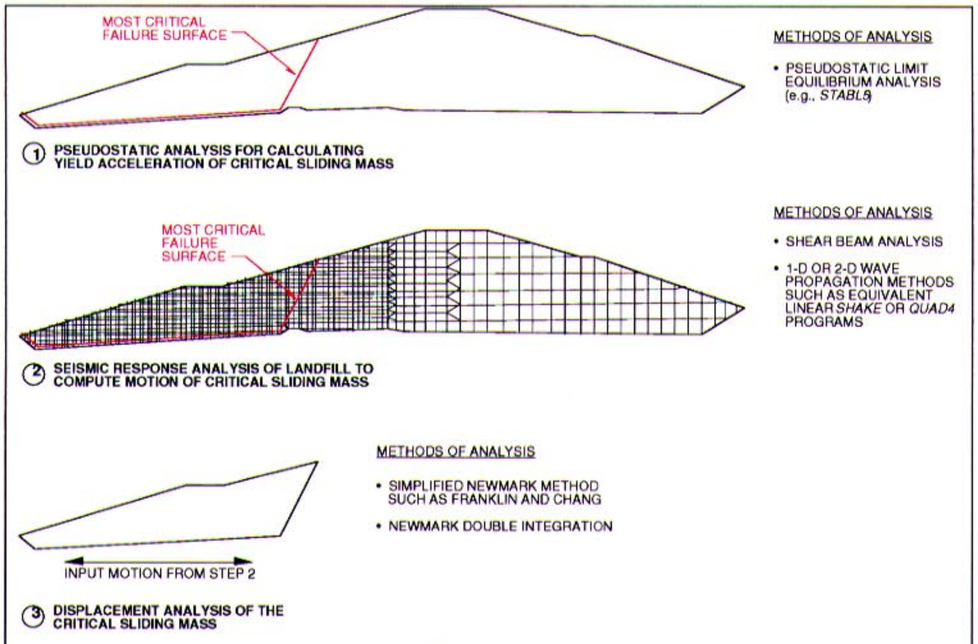

Figure 2
Steps Involved for Seismic Deformation Analysis

Fig. 2. Steps Involved for Seismic Deformation Analysis

Results from two-dimensional models indicate that with appropriate landfill properties reasonable predictions can be made of landfill dynamic response and deformations.

Deformation analysis methods used for landfills derive from the traditional methods used in analysis of earth dams. Presently, in the United States, the state of practice in deformation analysis of landfills is to use either simplified Newmark-type analysis methods such as the one developed by Franklin and Chang (1977) or Makdisi and Seed (1978) or perform a dynamic response analysis of the landfill followed by a Newmark double integration analysis of deformation. The latter approach consists of the following steps:

- Pseudo-static stability analysis of the landfill to determine the critical potential failure mass and its associated yield acceleration (Ky) that result in a factor of safety (FS) of 1.
- Dynamic response analysis of the landfill to compute average acceleration-time history of the potential failure mass.
- Newmark double integration analysis of the potential sliding mass average acceleration time history and summing of the displacements resulting from accelerations exceeding the yield acceleration. The sum for the duration of shaking is equal to the predicted permanent displacement of the critical sliding mass.

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For finite difference or finite element techniques the approach involves setting up a model of the landfill (refer to Fig. 2) and use of a 1-D or 2-D wave propagation method such as equivalent linear SHAKE (Schnabel, *et al.*, 1972) or QUAD-4 (Idriss, *et al.*, 1973) computer programs to simulate the shaking process and predict seismic response. The methods are well established but the level of confidence in the results depends on good definition of subsurface, waste and construction material properties and conditions.

SUMMARY OF STABILITY ANALYSIS PROCEDURES

Given the type of landfill facility (e.g., MSWLF, HWLF), the designer establishes the regulatory design basis or performance criteria, stability analysis scenarios (see Fig. 3 for examples), and material properties. Example design basis/performance criteria are given in Table 1.

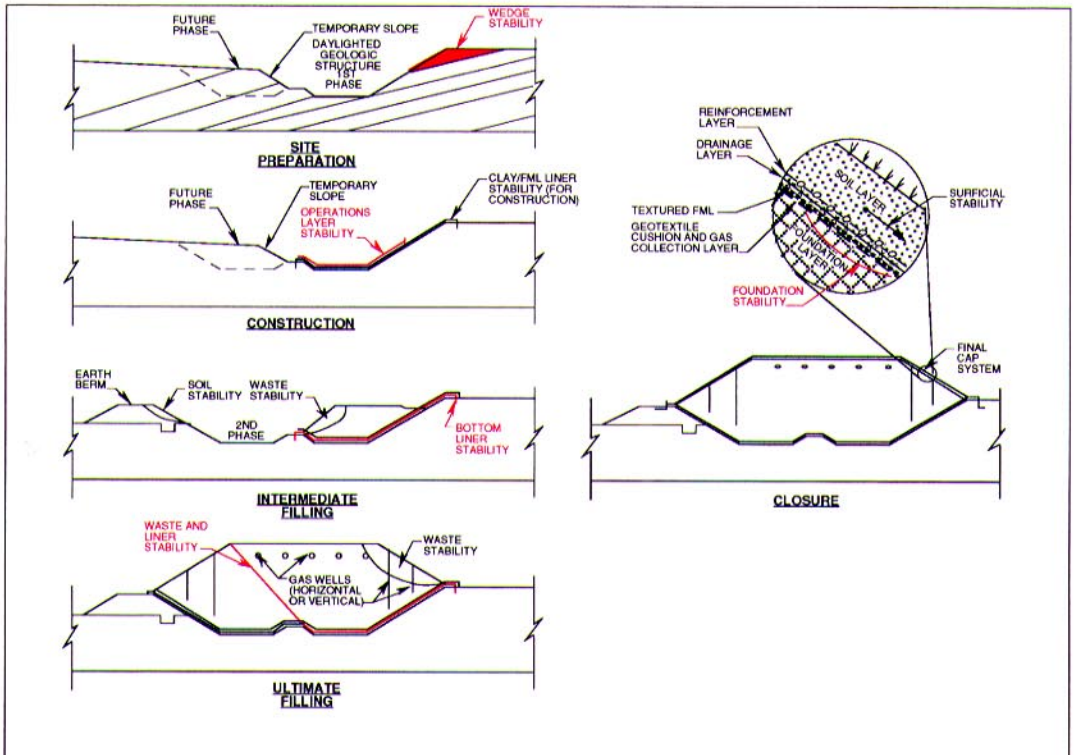

Figure 3
Stability Analysis Scenarios

Fig. 3. Stability Analysis Scenarios

Table 1. Example of Seismic Design Criteria

DESIGN CRITERIA	HAZARDOUS WASTE LANDFILL(1)	MSWLF(2)
Design Earthquake	MCE	MPE and Subtitle D Criteria
Maximum Allowable Slopes	-	1 3/4 : 1
Static Factor of Safety	≥1.5 or 1.3(3)	≥1.5 or 1.3(3)
Peak Ground Accelerations	Mean(4)	Mean
Pseudo-static Factor of Safety	≥1.0(5)	≥1.5(6)
Allowable Deformations(7)	Liner: ≤6" (if liner element stresses and strains do not approach yield). Cover: Varies for different elements and site conditions	Liner: ≤6" (if liner element stresses and strains do not approach yield). Cover: Varies for different elements and site conditions

(1) From California Code of Regulations (CCR) Title 22, 23 and 40 Code of Federal Regulations (CFR) Part 264 and 265 (Subtitle C).

(2) From CCR Title 14, 23 and 40 CFR Part 257 and 258 (Subtitle D).

(3) FS = 1.3, with special consideration for reliability of parameters, consequences of failure and available maintenance.

(4) Use of mean ground motions is currently the "state-of-practice" in California.

(5) Regulation requires design to function after MCE without decrease in level of public health and environmental protection afforded by original design. If FS <1.0, deformation analysis should be performed.

(6) If FS <1.0, deformation analysis should be performed as allowed in regulations.

(7) Consistent with "state of practice" in California (Seed and Bonaparte, 1992).

General "state-of-practice" in California is to use an allowable deformation of 6 to 12 inches (Seed and Bonaparte, 1992). However, the authors in their detailed dynamic analysis of landfill deformation and liner stresses for a recent project showed that the maximum deformation along landfill liner should be equal to or less than 4 inches for the specific landfill geometry and material properties to avoid yielding of geomembrane liner.

Material properties must be carefully selected from published data or based on site investigations and laboratory testing. It is highly recommended that interface strength parameters for liner and cover systems be determined by site-specific laboratory testing.

For a minimum stability analysis the steps involve:

- Identify type of landfill:
  - HWLF, MSWLF
  - Planned or existing
- Establish design basis/performance criteria as cited above (Table 1).
- Construct representative cross sections considering:
  - Excavation plan or as-built contours
  - Fill plan or as-built contours
  - Subsurface geology/prepared subgrade
  - Liner and leachate collection and removal system (LCRS)
  - Waste prism
  - Cover system
  - Liquid conditions
- Establish material properties:
  - Published, site-specific testing, or back calculate
  - Unit weights
  - Shear strengths
  - Shear wave velocities

  - Poisson's ratios
  - Damping relationships
  - Modulus reduction curve
  - Liquid condition considerations (if applicable)
- Establish interface strength envelopes:
  - Liner system
  - Cover system
- Perform 2D or 3D limit equilibrium analysis to determine static stability of critical potential slip surfaces:
  - Use a conventional limit equilibrium (2D) stability analysis computer program
  - Search for critical failure surfaces
    - Deep seated (liner or waste prism)
    - Surficial
    - Circular or Block (2D)
    - Spherical, ellipsoidal, or wedge block (3D)
  - Static stability acceptable if FS ≥ 1.5
- If static FS not satisfactory, evaluate use of geogrids, anchors, buttress or other structural components and/or modify geometry or change liner and/or cover materials and reanalyze stability.
- If static FS satisfactory, perform dynamic analysis.
- Establish ground motion parameters for design earthquake(s):
  - Geology
  - Faults
  - Seismicity
  - Seismic source model and parameters
  - Perform a deterministic and/or probabilistic analysis to predict site seismic design parameters
  - Mean peak ground accelerations or site response spectra (or other more conservative values if conditions warrant)
- Estimate pseudo-static acceleration based on established practice, experience and judgment or perform a simple analysis (such as shear beam or SHAKE) to estimate pseudo-static acceleration based on ground motion attenuation/amplification through the landfill.
- Perform pseudo-static stability analysis:
  - Deep seated (liner and waste prism)
  - Surficial
  - Is pseudo-static stability acceptable? If not perform deformation analysis.
- Perform a simplified Newmark type deformation analysis such as Franklin and Chang (1977) or Makdisi-Seed (1978). If deformations not acceptable for conservative estimates of landfill ground motion parameters perform detailed dynamic response deformation analysis.
- Has disposal volume been maximized at a minimized unit cost?
  - If not, revise configuration and reanalyze

OPTIMIZATION OF STABILITY ANALYSIS

In many cases simplified analysis provides potentially conservative estimates of deformations. Designs using simple analysis therefore do not maximize disposal volumes. To optimize disposal volume for a planned facility or avoid long-term stability problems and reduce maintenance cost in closure cap design of an existing landfill a detailed seismic deformation analysis is often warranted.

More detailed dynamic response/deformation analysis of landfill includes the following:

- Perform shear beam analysis, SHAKE (1-D equivalent linear wave propagation analysis) or QUAD-4 (2-D equivalent linear finite element analysis) to develop detailed dynamic response.
- Perform Newmark displacement double integration analysis using results of detailed dynamic response analysis.

or

- Perform nonlinear dynamic stress-strain analysis of landfill waste/liner system using a finite element computer code such as LINOS (Bardet, 1986) to obtain deformations and stresses in the liner and cover systems.
- If calculated displacements are acceptable proceed with design otherwise consider the use of structural components (e.g., geogrids, anchors) to take the loading.
- If calculated stresses and strains in liner and/or cover elements are not acceptable, consider modifications to geometry or changing liner and/or cover materials.
- Has disposal volume been maximized at a minimized unit cost?
    - If not, revise configuration (where possible) and reanalyze.

A comparison of results from the simplified method and a more detailed analysis for the three landfills reviewed is provided in Table 2.

Table 2. Comparison of Results of Minimum and Optimized Stability Analyses for Three Landfills

LANDFILL	RESULTS OF MINIMUM ANALYSIS	RESULTS OF OPTIMIZED ANALYSIS
El Sobrante MSW	Static FS >1.5.	Predicted deformations <1 inch.
	Pseudo-static FS <1.0. Predicted deformations 3-7 inches.	Stresses and strains in liner and cover acceptable (i.e., percent strain and stresses well below yield).
	Slopes to be flattened unless perform detailed deformation analysis.	Slope steepness and waste volume maximized.
Kettleman HW	Static FS >1.5. Pseudo-static FS <1.0. Predicted deformation limited fill height.	QUAD-4 with double integration and LINOS analysis show deformations <4 inches and stresses and strains in liner acceptable (i.e., <2 percent strain and <65 percent of yield stress) for increased landfill height and increased air space (nearly 20 percent) within permitted footprint.
OII Mixed HW & MSW	Deformations predicted from pseudo-static Newmark-type analysis FS for steep existing slopes were large (i.e., >12").	Refined analysis using revised waste properties(1) indicate slopes are likely stable (deep seated deformations negligible) and only a potential concern with cover soil sliding. Special analysis currently being completed for existing cover soil stability.

(1) Per back calculations performed by Idriss *et al.* (1995).

Results can often support designs with steeper side slopes in both excavation areas and final waste slopes or higher top elevations which yield greater disposal volume within the permitted area.

APPLICABILITY OF THE PROCESS TO VARIOUS WASTE MANAGEMENT SYSTEMS

This paper has presented a brief overview of a methodology used to design new and analyze existing landfills for earthquakes. The basis for the methodology derives from interpretation of regulations, evaluation of known seismic response of landfills to recent major earthquakes, and the authors' combined experience with design and engineering analysis of several major facilities in the most seismically active area of the United States (i.e., southern California).

Landfill stability is important to the protection of human health and the environment. In seismically active areas worldwide, this importance is becoming increasingly recognized and emphasized. At the same time it is desirable to maximize air space on each square foot of liner in order to minimize unit cost. The engineering tools are available to perform the optimized designs for landfills (MSW and HW), temporary waste storage facilities, onsite and in situ treatment facilities (e.g., biotreatment cells), liquid impoundments, sludge drying or composting piles and many other waste management systems. Depending upon the amount of data available and the complexity of the facility optimization analyses can cost in the range of $25,000 to $150,000 United States In many cases the optimization analyses can result in hundreds of thousands to millions of tons of additional air space within the same original footprint. In the United States this air space has a value of $30 to $50 United States per ton. In cases of closure of existing landfills, detailed analyses can eliminate unnecessary flattening of slopes or buttresses (for deep seated stability) and/or aid in developing designs which avoid long-term cover stability problems and reduce maintenance cost.

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