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ASPECTS OF LANDFILL DESIGN FOR STABILITY IN SEISMIC ZONES*

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ABSTRACT

In areas where seismic events occur frequently, the structural stability of waste disposal facilities may be threatened. Current design methods for landfills were developed under the assumption of static loading conditions. In seismically active areas, design and other ancillary measures need to be implemented to raise the factor of safety for the long-term stability of landfills. In this article, the seismological and geotechnical factors that control the risk of landfill damage are briefly discussed. A zonation scheme and geotechnical engineering measures for mitigating the hazards to landfills in earthquake-prone areas are proposed.

The Hazardous and Solid Waste Amendments (HSWA) made in 1984 (Public Law 98-616) to the Resource Conservation and Recovery Act (RCRA) of 1976 mandated the U.S. Environmental Protection Agency (USEPA) to develop standards for hazardous waste facilities in sensitive environments. Among the facilities covered are landfills. Seismic zones are high risk environments and can consequently be categorized as being sensitive. At such locations, there is a high probability of occurrence of detectable shaking of the ground and the structures which it supports. Ground shaking and failure modes which stem from it constitute threats to the stability of landfills located in such areas. The release of hazardous substances into the environment may result from landfill failure. Unfortunately, the design approaches and stability analysis methods that are currently

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employed in the design of landfill components address static stability primarily. The latter may suffice in non-seismic areas but may be inadequate with respect to resistance to earthquake-induced dynamic loads.

As is the case in other areas of the world, seismic areas of the United States closely mirror areas of high crustal stress. Earthquakes occur as a result of a sudden release of strain that accumulates slowly in the earth's crust over geologic time. They are typically concentrated at the edges of tectonic plates, volcanic regions and major faults. About 90 percent of the world's earthquakes occur at plate boundaries. Intraplate earthquakes are rare but they are equally damaging. In North America, earthquakes occur most frequently in the western margin. Much of this margin is a subduction zone, where the Pacific plate goes underneath the North American Plate, resulting in stress build-up and periodic releases. Major zones of seismic activity in the West include Southern California (especially around the San Andreas fault), Alaska and Washington. Other seismic areas of the United States include the Central Mississippi Basin around Missouri, New England States and Ohio. Within each of the zones mentioned above, the risk of seismic damage to landfills is not uniform. Risk magnitudes are sensitive to distances from potential causative fault, site soil properties and landfill design characteristics. Measures that are aimed at reducing the risks of seismic damages to landfills and possible releases of contaminants should influence one or more of the above-stated factors positively. In this brief article, discussions are focused on such aspects as the nature of seismic risk, potential landfill failure modes and possible mitigation measures.

THE NATURE OF SEISMIC RISK

Although several expansions of this traditional formulation have been made into more complex mathematical relationships, there is an additive relationship between the risk of occurrence and the probability of occurrence of a hazardous event such as an earthquake. This relationship is presented as equation 1.

$$R_s = 1 - (1 - P_e)^n \tag{1}$$

n = Number of years in the analysis period
R_s = The risk of occurrence of an earthquake
P_e = The probability of occurrence of an earthquake in any one year.

Fundamentally, R_s is the probability of the occurrence of an event in n years. Sometimes, cost or consequence factors are integrated into the definition for risk in multiplicative formulations. Equation (1) does not include such cost functions. On an annual basis, R_s is equal to P_e.

As presented above, equation 1 serves no useful design purpose unless the probability of occurrence of an earthquake with characteristics that can damage the landfill concerned is substituted in P_e. To determine the critical magnitude of an earthquake which damages will occur to a landfill, resistances of specific components of the landfill to specific loading modes must be established. The degree of damage at which the landfill is deemed to have failed should also be specified. The failure of a component would not necessarily imply that global failure of the landfill has occurred. For example, liquefaction underneath the landfill may cause cover slope failures that are insufficient to make the landfill non-functional as a whole.

As shown in Table 1 and portrayed in Figure 1, several categories of factors influence the damage potential of specific seismic events. Traditionally, ground motion has been commonly described in terms of horizontal acceleration for design purposes, although it is recognized that other parameters presented in Table 1 may affect structural stability. The probable ground acceleration expressed as a fraction of the gravitational acceleration of 9.81 m/s^2 is used to compute forces which act on landfill components. Due to the variabilities in rock strength and intactness, proximity to potential sources of seismic activity, and frequency of earthquake occurrences in different parts of the United States, the risk of landfill damage by earthquake stresses is not uniform.

Table 1. A Simplified Classification of Earthquake Factors
(Some of the factors can be cross-classified)

Factor Type	Factor
Source factors	Focus Epicenter Magnitude Intensity Seismic moment Rupture length
Travel path factors	Wave types generated Attenuation with distance Distances to earthquake source
Local site factors	Acceleration Velocity Displacement Period Spectral content Frequency Amplitude Amplification

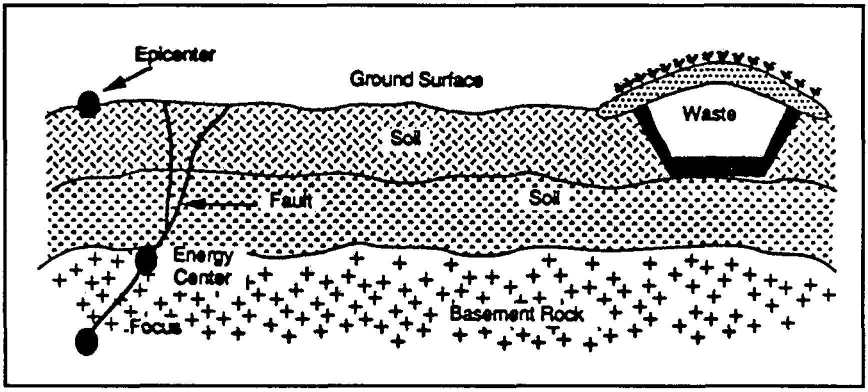

Figure 1. A schematic of the spatial relationship between an earthquake focus, fault and epicenter.

With respect to relevant risk computations, two major approaches exist as presented below:

(1) computation of the probability of occurrence of an above-critical magnitude earthquake that would generate sufficiently high ground acceleration to damage the landfill concerned, and

(2) computation of the ground acceleration magnitude with specification of a high probability of not being exceeded within a given time interval.

The first approach corresponds to the determination of P_e in equation 1. This approach is suitable for analyses that pertain to overall risk assessment for a containment facility. In this regard, the risk of a release from a landfill is tied to the occurrence of an event, hence relevant probabilities are conditional in nature and Bayesian approaches may be adopted in their assessment. The risk to which reference is made herein should not be confused with toxicological risk, the assessment of which is required in contaminated site remediation programs.

With respect to the analyses which may be conducted for landfills, toxicological risk assessment would address the hazards to human health and the environment that may result from the release of contaminants due to seismic events. In contrast, seismic risk analysis and the landfill stability analysis deal with the initiating event. Both categories of hazard or risk assessment are related but geotechnical risk analysis (dealing with earthquakes and other geohazards) should precede toxicological risk assessment.

Approach (1) involves the computation of P_e as follows:

$$P_e = 1/T \tag{2}$$

T = the return interval of an earthquake of specified magnitude (years)

Historical data on earthquake frequency are obtainable from establishments such as the U.S. Geological Survey and the National Oceanic and Atmospheric Administration. The analysis period should exceed the design life of the landfill concerned. The design life far exceeds the operational life. Generally, P_e values are larger for western United States than for the East since earthquakes of above-critical magnitude have smaller return periods in the West than in the East.

Approach (2) is essential to the selection of ground acceleration values for use in design. The spatial variability of acceleration values has necessitated the presentation of results as contours on maps of the United States. An example for 90 percent probability of not being exceeded in 250 years is shown in Figure 2 as developed by [1]. Previously, similar maps were developed for fifty-year periods. For landfills, a fifty-year analysis period is too short considering that they may remain permanently at their respective sites after closure. Fortunately, most of the new seismic probability contour maps are based on a 250-year period which is conservative enough for landfill design purposes. On these maps, regions of large areal extent are lumped into zones of uniform ground acceleration. Such "macro-zonations" are useful primarily for identifying historically problematic areas and zones that are near to stressed crustal areas. Moreover, contoured accelerations are those of bedrock and do not reflect amplifications that may occur on site-specific basis. Depending on the thickness and types of soils at a landfill site, contoured acceleration data should be multiplied by factors that range in magnitude between 1.0 and 2.0 for use in landfill component design. Sites with thick overburdens of loose, coarse-grained soils may amplify bedrock accelerations. In Table 2, amplification factors are suggested based on results of investigations by various researchers [2-8].

POTENTIAL FAILURE MODES

The potential failure modes of landfills in seismic zones can be classified into three main categories on the basis of causes. These categories are as stated below.

1. Faulting through a landfill.
2. Ground and component strains without liquefaction.
3. Ground and component strains due to liquefaction.

For most locations in the United States, the probability of occurrence of the first mode is low because it is tied to the distribution of Holocene faults. This risk is magnified close to such faults. Also, it is very difficult to establish beforehand, the line of ground partitioning that could potentially damage a landfill. Holocene

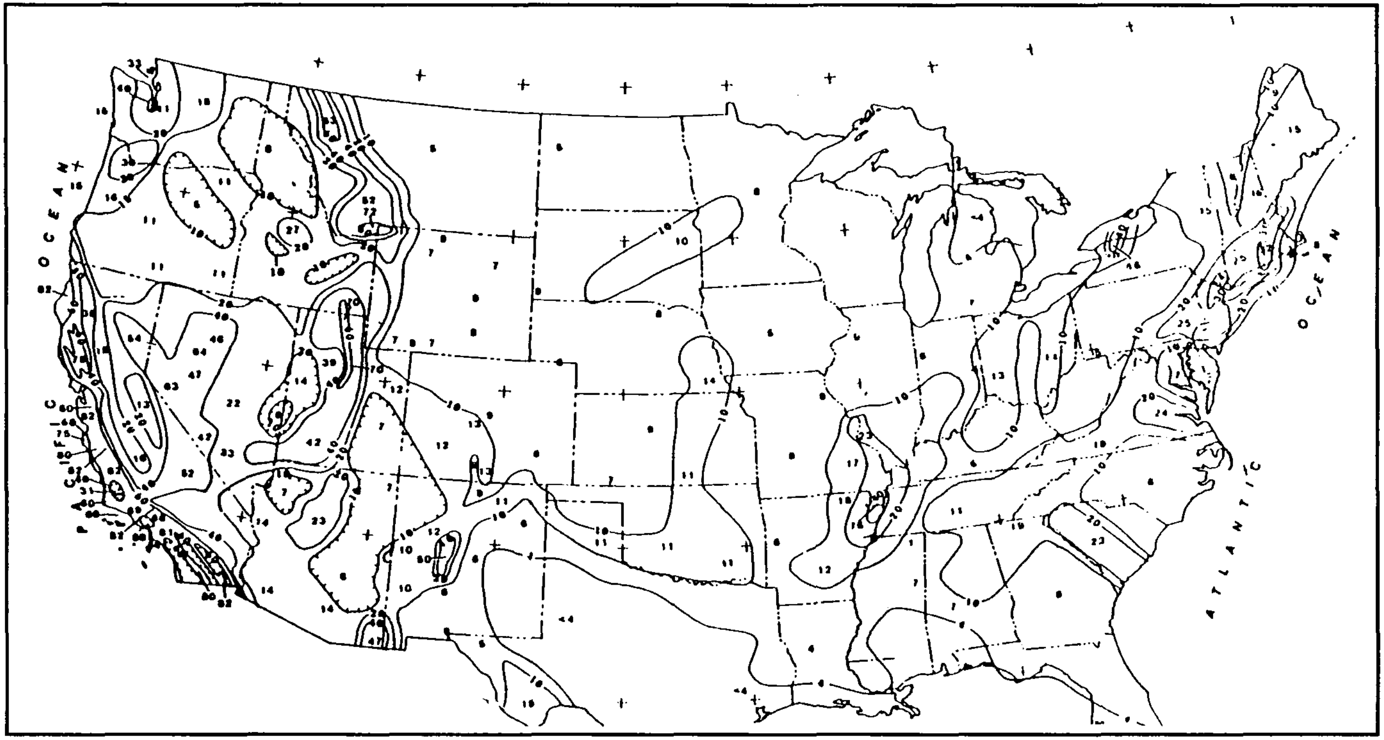

Figure 2. A preliminary map of horizontal acceleration (expressed as percent of gravitational acceleration) in rock with 90 percent probability of not being exceeded in 250 years [1].

faults are those for which ground motion has been recorded with Holocene time (within 10,000 to 12,000 years ago). The second and third modes of failure are related to the magnitude and duration of ground vibration. Conventionally, horizontal ground acceleration has been the major parameter used in seismic stability analysis.

Ground strains can cause damages to pipes that are part of the leachate collection and removal (LCR) system of a landfill. Connections are very critical due to possible stress concentrations. Figure 3 is an illustration of the distortion of landfill soil layers and pipes under dynamic stresses. Liquefaction is the partial or total loss of shear strength of largely loose, saturated fine sands as a result of the exceedance of the initial effective stress by pore pressures induced during cycles of dynamic loading. When liquefied, the soil acts as a liquid and loses its load-carrying capacity. The concern is not with the liquefaction of the landfill itself but with damage to its components as a result of the liquefaction of soils that underlie it. Among these potential damages are settlements of landfill liners and covers; disruption of the slopes of the drainage layer such that leachates do not flow to

Table 2. Design Amplification Factors for Soil on Rock Seismic Accelerations to be Used in Landfill Design in Seismic Areas

Situation Category	Amplification Factor	Soil Type	Soil Depth
(i)	1.0	Rock Dense to very dense coarse-grained soils, and very stiff to hard fine-grained soils	All depths
		Compact coarse-grained soils, and firm to stiff fine-grained soils	0-50 ft.
(ii)	1.5	Compact coarse-grained soils, and firm to stiff fine-grained soils	>50 ft.
		Very loose and loose coarse-grained soils, and very soft to soft fine-grained soils	0-50 ft.
(iii)	2.0	Very loose and loose coarse-grained soils, and very soft to soft fine-grained soils	>50 ft.

design directions; and forced entry of groundwater into the landfill interior. The latter could be caused by sand boils that may develop.

Liquefaction represents the largest seismic induced threat to the stability of landfills. However, it does not necessarily mean that all sites that comprise fine-grained, saturated materials can liquefy. To borrow the terminologies used by [9], two conditions are necessary for the liquefaction of sites, namely, liquefaction opportunity and liquefaction susceptibility. Both parameters can be explained in terms of the general cyclic stress ratio equation presented below [10].

$$t/S_e = 0.65aS_o r_d/S_e g \tag{3}$$

t = average peak shear stress
S_e = initial vertical effective stress
a = maximum acceleration at the ground surface
S_o = total overburden stress at the depth considered
r_d = stress reduction factor which decreases from 1.0 at the ground surface to 0.9 at a depth of 35 feet
g = acceleration due to gravity

The quantity t/S_e is called the cyclic stress ratio and its magnitude relative to the strength (or density) of fine sands determines whether or not liquefaction is likely. The cyclic stress ratio must be sufficiently high to induce liquefaction. The threshold values are discussed in the next section.

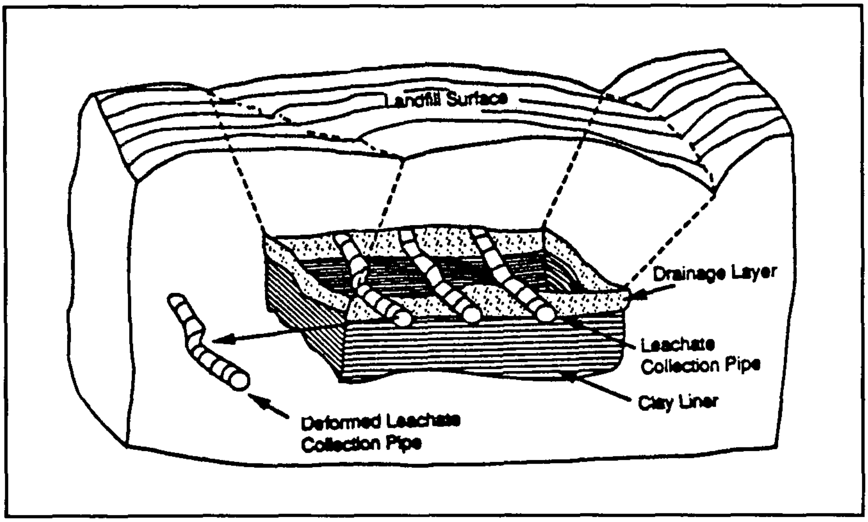

Figure 3. A schematic diagram of a landfill showing potential deformation of the leachate collection and removal (LCR) system by seismic stresses.

The arrangement of parameters in equation 3 implies that for any landfill site, both liquefaction opportunity and susceptibility must exist before liquefaction can occur. The opportunity relates to the probability that the extent of ground vibration measured in terms of acceleration or other relevant parameters would be high enough to cause liquefaction. It depends on such factors as the distance of the landfill site from potential earthquake sources and intensity attenuation relationships for seismic wave travel paths to the site. Plots provided by [11] have indicated that for an earthquake of the same intensity, the zone of influence around the epicenter is much larger in the central and eastern areas of the United States than in the western areas. This may be caused by the entrapment of seismic waves in the relatively fractured crust of the West such that they decay quickly. The earth's crust in the Interior and East is relatively intact. However, earthquakes are more frequent in the West. Recent reviews of historical data [9, 12, 13, 14] indicate that except in rare cases for earthquakes of magnitude 7.5 or greater, liquefaction has not occurred for peak horizontal accelerations under 0.1 g. In addition, there is an indication [9] that accelerations do not generally exceed 0.05 g at rock sites that are more than 200 km from seismic sources. Liquefaction has also been absent for earthquakes with magnitudes less than 5.0. These situations

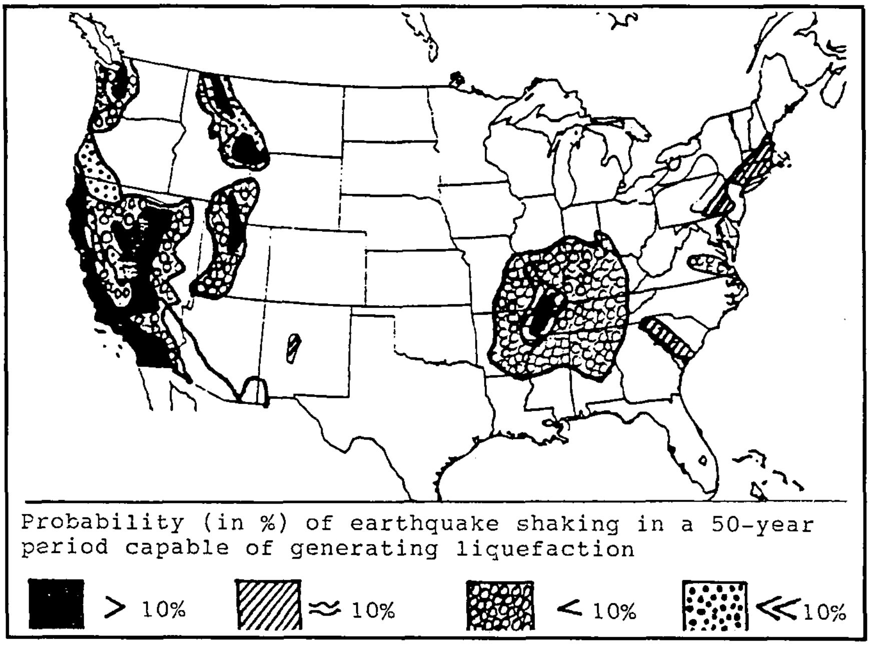

Figure 4. A crude liquefaction opportunity map of the contiguous United States [15].

imply that soils that are capable of liquefying may never get the opportunity to experience seismic stresses that are adequately high to cause liquefaction. With a reasonable degree of confidence, the threshold for liquefaction opportunity is 0.1 g, and the sites at which the opportunity exceeds 10 percent are illustrated in Figure 4 after [15]. Delineations in Figure 4 are approximate.

Liquefaction susceptibility is an index of the vulnerability of saturated soil materials at the landfill site to loss of shear strength under seismic-induced shaking. It depends on the engineering properties of the site materials. In general, loess, deltaic soils, floodplain soils and loose fills are highly susceptible to liquefaction under saturated conditions.

MITIGATION MEASURES

Three approaches are herein identified for mitigating the potential damages to landfills by seismic events. They are choice of suitable sites; design conservatism; and redundant precautionary measures.

Within each seismic zone, the magnitude of risk varies from one site to another. Before a landfill site is selected, potential sites should be screened on the bases of proximity to Holocene fault zones; ground motion in terms of acceleration, liquefaction potential of site materials and other cost/consequence factors [16] that are not directly related to seismicity. The zone of permanent deformation around a causative fault can range in size from a few meters to several hundred meters. Macro-zonation maps are useful mainly for first level screening of sites. Detailed geologic mapping within a minimum of 3000 ft of the proposed perimeter of the landfill should be conducted. Locations with zones with high probabilities of exceedance of about 0.75 g acceleration should be avoided. Conservative designs may not be adequate to protect landfills against damages by ground motions of that regime.

For zones with high probabilities of high accelerations (horizontal) within the moderate range of 0.1 g to 0.75 g, seismic designs should be implemented. Seismic stability analysis of landfill slopes should be performed before selection of materials and gradients for slopes. Flexible pipes should be used. Where *in situ* and laboratory tests indicate that a potential landfill site is susceptible to liquefaction, ground improvement measures like grouting, dewatering, heavy tamping and excavation should be implemented. The scale of macro-zonation maps is such that they can not be used for design purposes. More detailed geologic information is usually available from Geological Surveys in the states concerned. This information should be augmented with data obtained through direct testing, and the appropriate amplification factor should be selected.

If the liquefaction criterion described in equation 3 is satisfied, then ground improvement techniques and appropriate landfill design measures should be implemented. On the basis of field studies, Figure 5 has been developed [17] to facilitate the assessment of liquefaction potential. To use Figure 5, the cyclic

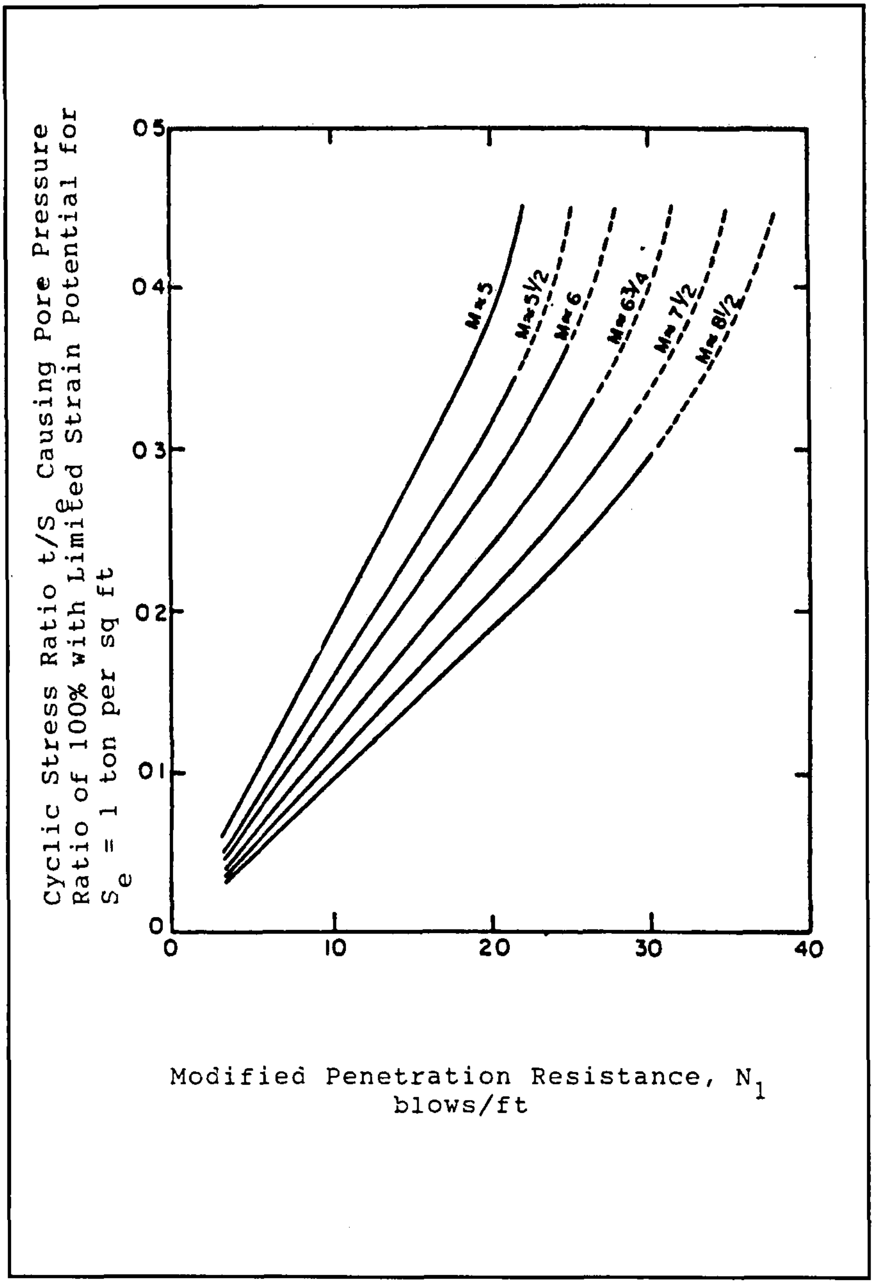

Figure 5. A chart for evaluation of liquefaction potential of sands for earthquakes of different magnitudes [17].

stress ratio has to be computed using equation 3. Then, the modified penetration test data for the site should be obtained. Each set of these two data should be plotted into Figure 5. For each set, if the plot exists above the magnitude curve of interest, then there is a very high risk of liquefaction of soils at the depth of concern at the landfill site. This author suggests that the magnitude (M) = 5 line be used for landfill sites.

At landfill sites with potential ground deformation parameters close to the upper limit (0.75 g), there may be a need to incorporate redundancy into the overall design of the system to minimize the risk of environmental pollution. Redundancy is based on "what if" analysis. It is an effective way of handling uncertainties. For example, a secondary containment system such as a slurry wall can provide additional protection in the event of a seismic-induced release of hazardous substances from a landfill.

SUMMARY

In addition to static loads that are usually considered in the design of containment facilities, potential dynamic loads on landfill components should be analyzed especially in seismic zones. Where highly probable ground motion parameters are excessively high, the only safe option is to select a less risky site. For locations at which highly probable accelerations are moderate, current geotechnical techniques can be employed to implement design measures that can mitigate potential damage. Below the threshold horizontal acceleration level of 0.10 g, the threat is largely negligible and seismic design is not necessary for landfill components. The latter is the case for a majority of regions is the United States.

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