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Earthquake-Induced Lateral Displacement of a Landfill

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ABSTRACT In the wake of stability failure of the Kettleman Hills Waste Repository on March 19, 1988, the stability of landfill mass in earthquake-prone areas has become an important issue in the community. Based on a proposed landfill site in the Memphis, Tennessee area, this paper studies behaviors of landfills under various landfill and earthquake conditions (height and slope angle of the landfill, average unit weight of the landfill refuse, and peak acceleration and time duration of bedrock motion) by calculating lateral displacements induced by a design earthquake. Results indicate that lateral displacement of a landfill is proportional to the slope angle of the landfill, peak acceleration and time duration of bedrock motion, and is inversely proportional to the average unit weight of the landfill refuse. The slope angle of a landfill and the peak acceleration of bedrock motion have significant influence on the lateral displacement of a landfill compared with landfill height, average unit weight of landfill refuse and time duration of bedrock motion. Results also indicate that some landfill heights should be avoided to diminish landfill resonance, and the maximum slope angle of a landfill under certain seismic conditions depends on the internal friction angle of the landfill refuse. In addition, the lateral displacements calculated from actual and pseudo-accelerations are compared and discussed.

INTRODUCTION

Since the Kettleman Hills Waste Repository stability failure on March 19, 1988 [2], the stability of landfill mass in earthquake-prone areas has become an important issue. Federal regulations also mandate appropriate analysis and design for landfill in areas where the ground acceleration corresponding to 10% exceedance in 250 years is greater than 0.1 g. Advances in seismic engineering of solid waste landfills during the past several years [6, 7] permit seismic analyses of these landfills. But, because of complex physical properties and configurations of landfills, their seismic response is not well understood yet.

The main containment system used in modern landfills includes bottom liners (layers A and B), top cover (layer 1), and storm water management system (installed on layer 1)(Figure 1). The function of the bottom liners is to contain leachate from migrating into the ground water. The function of the top cover is to minimize seepage of precipitation into the refuse and to prevent displacement of the refuse to surrounding areas. The storm water management system in the top cover controls run-off on the landfill itself to prevent erosion of the top cover, and run-on from the surrounding areas. Liner and cover systems typically consist of multiple layers of soil and geosynthetic materials, and are susceptible to damage by earthquake induced displacements that can produce tensile stress and strain in geosynthetic materials and tensile cracks in the earth materials. Performance of geosynthetic materials in terms of stresses is expressed as a factor of safety with respect to the ultimate strength. Recognizing the difficulty in obtaining a minimum pseudo-static factor of safety, Title 14 of the California Code of Regulations allows that the seismic stability of landfill be evaluated in terms of earthquake-induced lateral displacements. A survey of engineering firms designing Municipal Solid Waste Landfill units [7] found that calculated earthquake-induced lateral displacements on the order of six inches were considered to be "acceptable" for most conditions.

Table I. Parameters of the proposed landfill and subsurface soils

Layer	Thickness (ft)	Unit Weight (pcf)	Vs (ft/sec)	ϕ(o)	c(psf)
1	3	115	950		1000
2	25-150	35-75	200-600	25	
3	3	120	1000	30	
4	3	120	960		1000
5	7	110	940		1300
6	13	100	920		2000
7	10	115	960	38	
8	170	125	980-1140	38	
9	–	150	4000	38	

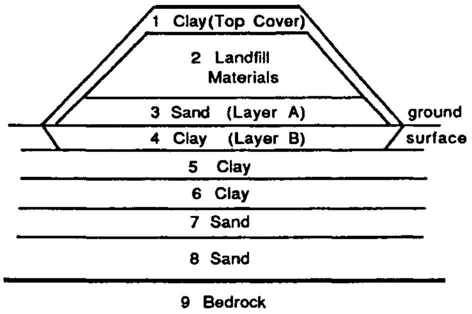

Fig. 1 Simplified model of the landfill site in Memphis.

Based on a proposed landfill site in Memphis, Tennessee area (Figure 1 and Table I), this paper studies the lateral displacements of top cover and liner system of the landfill induced in a design earthquake with parameters of height and slope angle of the landfill, average unit weight of the landfill refuse, and peak acceleration and time duration of bedrock motion by using the SHAKE91 program. The proposed landfill has a height H=100 ft, a slope angle A=13°, an average unit weight of refuse $\gamma = 55$ pcf, and an internal friction angle of refuse $\phi=25°$

Methods of Analysis

The main factors that influence the seismic ground motions at a specific site include the seismic source, wave propagation path, and local subsurface conditions (Figure 2). Most of the seismic energy that reaches a site is transmitted through the underlying bedrock as shear waves traveling vertically upward through the soil profile existing at the site.

First, a horizontal acceleration time history in hypothetical outcrop bedrock was generated for the study. The Memphis area is situated at the southeastern end of the New Madrid seismic zone (NMSZ). In this study, we choose an earthquake of magnitude M_W 8.0 as a potential event corresponding to 10% exceedance in 250 years [4]. Since we cannot predict the epicenters of the potential earthquakes, we take an average distance of 65 km from the Memphis area to the southern segment of the NMSZ as the epicentral distance of the potential earthquakes. An average value of focal depths for the potential earthquakes is assumed as 10 km. Stress drop for NMSZ earthquakes is a controversial topic. We assume the average stress drop is 150 bars for large potential earthquakes in the NMSZ. An approach that employs random vibration theory applied to a Brune's spectrum is applied to predict seismic motion on the outcrop bedrock [1]. To study the lateral displacements with the parameters introduced above, a peak acceleration of 0.25 g at outcrop firm base at a depth of 200 ft is used for the design earthquake.

After the input bedrock motions have been selected, the program SHAKE91 is used to analyze the wave propagation through the overlying soil-landfill system. The dynamic properties of the soils at the landfill site are estimated from the results of dynamic tests on the soil samples obtained in the Memphis area [3]. This analysis provides us the time history of horizontal accelerations, shear stresses and strains at different depths within the soil-landfill system.

EQUIVALENT PSEUDO-ACCELERATION

When a landfill is subject to an earthquake, an equivalent pseudo-acceleration time history can be calculated to estimate the earthquake-induced lateral displacement of the landfill. At any specific time during an earthquake, acceleration values in a landfill mass not only differ in different layers, but may also have opposite directions. In addition, the peak acceleration in each layer does not occur at the same time. Equivalent pseudo-acceleration values can be obtained at the specific time, by averaging the acceleration values at that time acting on each unit mass within the landfill above the potential failure surface being analyzed [6]. That is,

$$a_{epa}(t)=\Sigma\, a_i(t) h_i \gamma_i / \Sigma\, h_i \gamma_i \qquad (1)$$

where

a_{epa} = equivalent horizontal pseudo-acceleration,
a_i = acceleration of *i*th element of the landfill,
h_i = thickness of the *i*th element,
γ_i = unit weight of the *i*th element, and
Σ = sum for the elements above the potential failure surface.

This equivalent pseudo-acceleration represents an average acceleration time history acting on the target layer resulting from the acceleration in each layer above the target layer within the fill mass at a particular time during the earthquake. The equivalent pseudo-acceleration, in addition to the actual acceleration time history, also provides a reasonable and practical measure for calculating the lateral displacement in a target layer induced by the input bedrock motion.

CALCULATION OF LATERAL DISPLACEMENT OF LANDFILLS

Newmark's method was used to calculate the earthquake-induced lateral displacements of landfills [5]. The method calculates the displacements by double integration of those parts of the earthquake-induced acceleration time history in which the earthquake-induced acceleration exceeds the acceleration level required to initiate slope yielding from an associated slope stability analysis. That is,

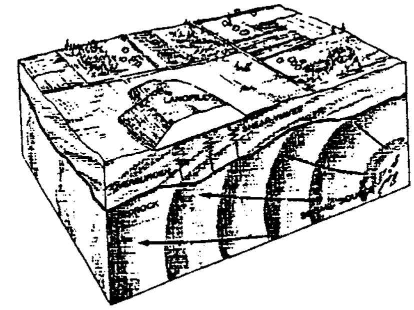

Fig. 2 Propagation of seismic waves (adapted from Repetto et al., 1993)

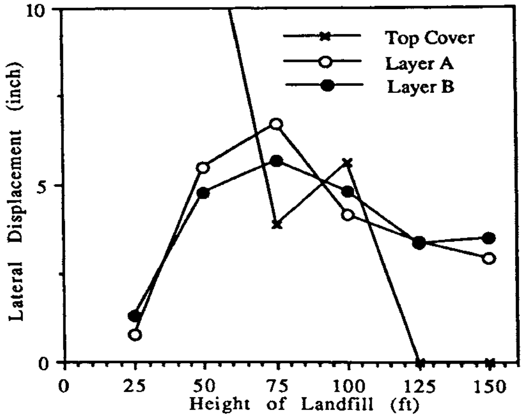

Fig. 3 Influence of height of landfill (unit weight of refuse 55 pcf, slope angle 13°, bedrock peak acceleration 0.25 g, and time duration 32 sec.)

$$d=\iint (a_i(t)-a_y)dt^2 \quad \text{or} \qquad (2)$$
$$d=\iint (a_{epa}(t)-a_y)dt^2 \qquad (3)$$

where
d = the earthquake-induced permanent lateral displacement, and
a_y = the threshold yield acceleration (TYA).

The TYA is the horizontal acceleration acting on the landfill mass above the potential slope failure plan and produces a slope stability safety factor of unity, which is in a critical condition to trigger the instability of the landfill.

Results and Discussion

The lateral displacements of the top cover and bottom liners subject to various landfill and earthquake conditions are studied using SHAKE91 and discussed below:

(1) INFLUENCES OF HEIGHT AND SLOPE ANGLE OF LANDFILL

To study the influence of height of landfill to the earthquake-induced lateral displacements, the height of the landfill varies from 25 ft to 150 ft. The results are shown in Figure 3. Other parameters are assigned reasonable values and remain the same for different heights of the landfill. The average unit weight of the refuse is taken as 55 pcf, the time duration of bedrock motion is 32 sec, and the yield acceleration is 0.135 g which is the yield acceleration of the proposed landfill with a slope angle of 13°. As shown in Figure 3, height of landfill has more significant influence on the lateral displacement of the top cover than that of the bottom liners. The bottom two liners exhibit similar lateral displacement magnitude with change of the landfill height. For the bottom liner system the displacement has a peak value at the height of landfill of 75 ft. If the height of the landfill is less than 60 ft or greater than 85 ft, the displacement will be less than six inches. The peak value of the displacement probably represents the effect of resonance of the landfill under the seismic condition. Therefore, for a safety design we should avoid some landfill heights depending on landfill and seismic conditions in the area where the landfill is located.

To study the influence of the slope angle of a landfill, we assume the height of the landfill is 100 ft, and change the slope angle of the landfill from 10° to 25° The relation between the TYA and slope angle of a landfill was established first by slope stability analyses of landfills with slope angles of 10°, 15°, 20°, 22° and 25°. The slope stability safety factors (F) were calculated for each slope angle under various horizontal accelerations [8]. As shown in Figure 4, safety factor of the landfill is decreased with the increases of slope angle and horizontal acceleration of the landfill. Based on Figure 4, the TYA corresponding to F=1 can be determined for each slope angle. As shown in Figure 5, the TYA deceases significantly with increasing slope angle. Figure 6 shows the influence of slope angle of the landfill to the earthquake-induced lateral displacement. For the bottom liner system the displacement is linearly proportional to the slope angle of the landfill. If six inches is used as a acceptable displacement for the bottom liners, the slope angle of the proposed landfill should be less than about 13°, which is about one half of the internal friction angle of the landfill refuse.

(2) INFLUENCE OF AVERAGE UNIT WEIGHT OF REFUSE

The average unit weight of landfill was varied from 35 pcf to 75 pcf to study the influence of unit weight of refuse on the lateral displacement of the selected layers. For each case, the unit weight of refuse increases gradully from top to bottom of the landfill. The height of the landfill is 100 ft, slope angle 13° and subject to a peak bedrock acceleration of 0.25 g and a time duration of 32 sec. As shown in Figure 7, the denser the refuse is the less the lateral displacements of the studied layers. For the proposed landfill studied, increasing the unit weight of the refuse to more than 70 pcf may reduce the lateral displacement to less than 3 inches, significantly lower than the acceptable tolerance for both the top cover and bottom liners. The lateral displacement of the landfill is inversely proportional to the average unit weight of landfill, and the displacement is less than six inches when the average unit weight of the proposed landfill is greater than 45 pcf.

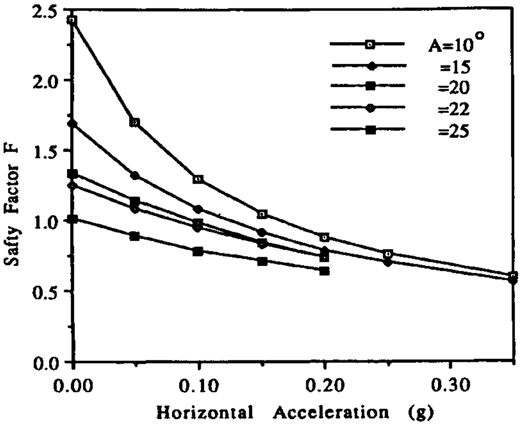

Fig. 4 Safty factor F versus horizontal acceleration in various slope angles A

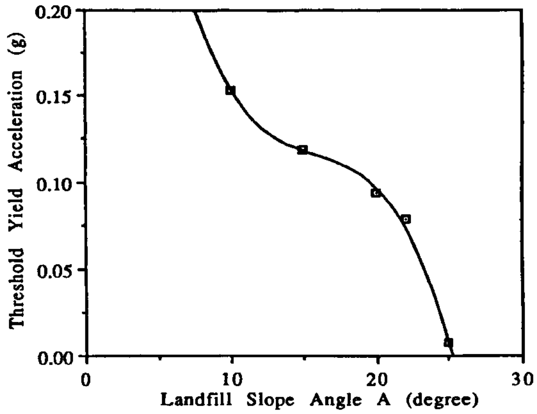

Fig. 5 Threshold yield acceleration versus landfill slope angle for the proposed landfill (unit weight of refuse 55 pcf, internal friction angle of refuse 25°)

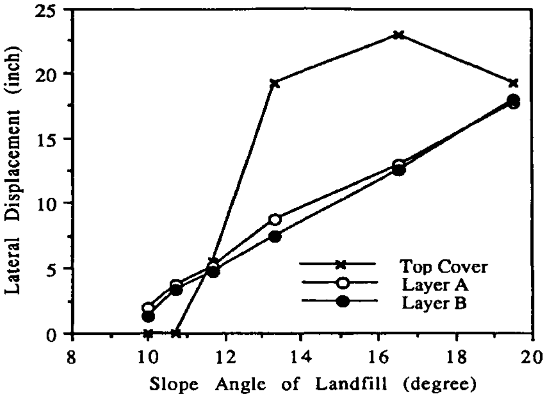

Fig. 6 Influence of slope angle of landfill (height of landfill 100 ft, unit weight of refuse 55 pcf, internal friction angle 25°, bedrock peak acceleration 0.25 g, and time duration 32 sec.)

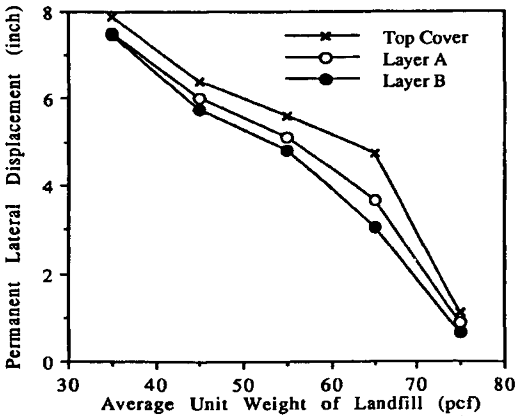

Fig. 7 Influence of average unit weight of landfill (height of landfill 100 ft, slope angle 13°, bedrock peak acceleration 0.25 g, and time duration 32 sec.)

(3) INFLUENCE OF BEDROCK ACCELERATION AND DURATION

The peak acceleration of bedrock motion was varied from 0.15 g to 0.45 g (with duration of 32 sec) to study the influence of bedrock acceleration, and the time duration was varied from 20 sec to 38 sec (with the peak acceleration of 0.25 g) to study the influence of time duration of bedrock motion. The landfill height was taken as 100 ft, slope angle 13° and the average unit weight of landfill was 55 pcf. As expected, Figures 8 and 9 indicate that the lateral displacement of both the top cover and bottom liners increases with increasing peak accelerations and durations of the bedrock motion. Results indicate that the peak acceleration seems to be more influential than the duration of the earthquake shaking for inducing the lateral displacement. Based on the results of the study, the proposed landfill (height = 100 ft, slope angle = 13°, unit weight of refuse = 55 pcf and internal friction angle of refuse = 25°) may withstand a peak bedrock acceleration up to about 0.25 g, whereas the lateral displacement will be near or less than the acceptable limit of 6 inches for both the top cover and the bottom liners.

(4) EQUIVALENT PSEUDO-ACCELERATION VS ACTUAL ACCELERATION

The lateral displacement can be calculated based on both equivalent pseudo-acceleration and actual acceleration time history in the target layers of the landfill. For layers near the top of the landfill, the lateral displacements are not very different when calculated from actual and pseudo accelerations. However, for layers in the bottom of the landfill, because the equivalent pseudo-acceleration is much less than the actual acceleration, the lateral displacement of the layers computed by equivalent pseudo-acceleration is much less than that computed by actual acceleration. Figure 10 compares the lateral displacements of the bottom liners of the landfill based on the two accelerations. The lateral displacement calculated from actual acceleration time history may be overestimated, but the lateral displacement calculated from pseudo-acceleration may be underestimated. Employment of an adjust factor for both calculations could be feasible to obtain a more reasonable estimate of lateral displacement of landfill layers for practical applications. Further study and field measurements of landfill movements are necessary to determine whether equivalent pseudo-acceleration or actual acceleration is the more accurate for calculating the earthquake-induced lateral displacement in target layers within a landfill.

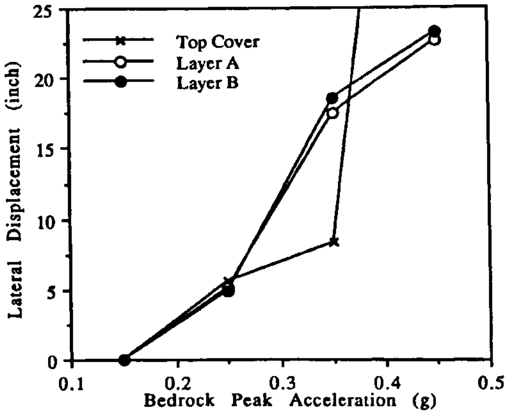

Fig. 8 Influence of bedrock peak acceleration (height of landfill 100 ft, unit weight of refuse 55 pcf, internal friction angle 25°, slope angle 13°, and time duration 32 sec)

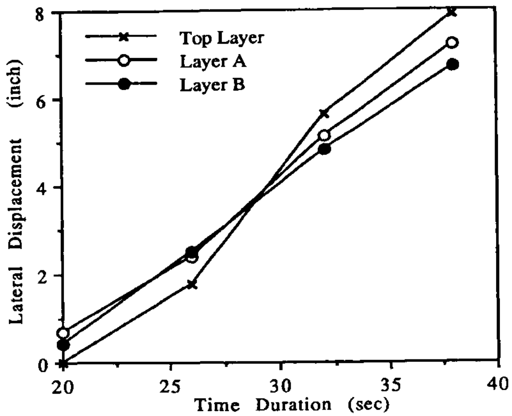

Fig. 9 Influence of time duration (height of landfill 100 ft, unit weight of refuse 55 pcf, internal friction angle 25°, slope angle 13 , and bedrock peak acceleration 0.25 g).

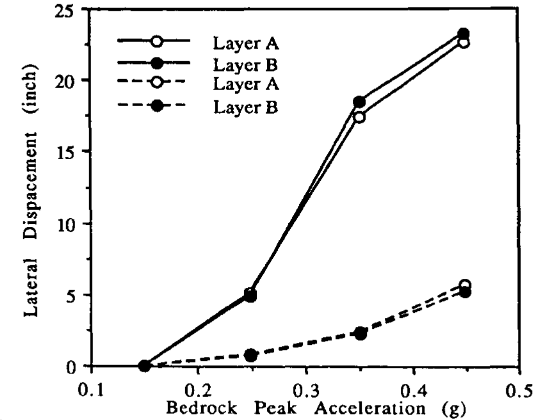

Fig. 10 Comparison between the dispacements computed by pseudo-acceleration and actual acceleration (solid line for actual acceleration; dash line for pseudo-acceleration)

Conclusion

Based on the results of the study on the proposed landfill in the Memphis area, conclusions are summarized below:

(1) Depending on landfill and seismic conditions in the area where the landfill is located, the height of the landfill should be examined to avoid amplified lateral movements of the landfill layers due to resonance between the landfill and earthquake shaking.

(2) For the proposed landfill, the slope angle should be less than 13° so that the lateral displacement of the landfill layers is less than the acceptable 6 inches when subject to an earthquake of peak acceleration of 0.25g with a duration of 32 sec. It suggests that for the design earthquake used in the study, the landfill slope angle should be less than half of the internal frictional angle of the landfill refuse to reduce the lateral movement potential.

(3) Compaction of the landfill is useful to reduce the lateral movement of the landfill. For the proposed landfill, increasing the average unit weight of refuse from 55 pcf to 75 pcf significantly reduces the lateral displacement of the bottom liners.

(4) Both peak acceleration and duration of the earthquake influence the lateral movement of the landfill. Results show that peak acceleration has a more significant influence than duration of the earthquake.

(5) Lateral movement of the landfill based on actual acceleration time history induced by an earthquake is much greater than that calculated by an equivalent pseudo-acceleration time history. Further study and field data are necessary to determine whether equivalent pseudo-acceleration or actual acceleration is more accurate for calculating the earthquake-induced lateral displacement in target layers within a landfill mass.

(6)More studies on physical properties of landfill refuse such as shear wave velocity, damping, unit weight and internal friction angle are essential for further understanding of earthquake-induced lateral displacement of landfill.

Acknowledgments

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