APPENDIX I-4

REPORT BY PROFESSORS RATHJE & BRAY: EFFECT OF SLIDING MASS LENGTH ON THE SEISMIC PERFORMANCE OF SLOPES

Effect of Sliding Mass Length on the Seismic Performance of Slopes

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1. Introduction

It is hypothesized that due to the incoherence of the response of a long potential sliding mass and due to the spatial incoherence of the input bedrock motion over a significant length that the calculated seismic permanent displacement of a potential sliding mass will reduce as the length of the sliding mass length increases. The objective of this report is to evaluate this hypothesis.

2. Previous Work

A reduction factor for block length has not been extensively studied. Based on the early work of Seed and Martin, a Shannon & Wilson, Inc (1989) report employs an argument that it must decrease from one to zero as the length of the potential sliding block increases from 100 feet or less to 1,200 feet or greater based on the assumption that surface waves with wave lengths of 1,200 feet destabilize the sliding mass. However, severe strength loss or liquefaction is not typically the case being analyzed, so the primary seismic driving force is more likely resulting from vertically propagating horizontal shear waves (a body wave). Additionally, observations of large, coherent landslides that displaced as a result of earthquake shaking are at odds with the concept that the seismic coefficient is zero for sliding blocks greater than 1,200 ft.

It is conventional when employing a Newmark-type analysis for evaluating the seismic performance of clay slopes to use horizontal equivalent acceleration-time histories that are largely a result of vertically propagating horizontal shear waves. In his evaluation of the 4^{th} Ave. slide, Idriss (1985) remarks that if the predominant waves are body waves, then a reduction on the order of 5% to 10% could be expected for a sliding block of length 1000 to 2000 feet (i.e., a length reduction factor ~ 0.9 to 0.95 for L > 1000 feet). If the predominant waves were surface waves, then it would be only about 0.1 for L > 1000 feet. Idriss (1985) concludes: "To be conservative, only the effect of body waves was considered in the analyses." Likewise, Moriwaki et al. (1985) in their re-evaluation of the L St. slide did not employ a length reduction factor based on surface waves (only one based on body waves).

Based on an examination of these studies, there is not a satisfactory basis for utilizing a length reduction factor that decreases to zero for sliding block lengths greater than 1,200 feet. Although a length reduction factor that is less than one appears to be reasonable based on the incoherence of the response of a two dimensional (2D) system over its length, this factor appears to be more likely only a 10% effect. However, the incoming ground motions also exhibit incoherence over long horizontal separation distances, and this effect should be examined as well.

Spatial incoherence of motion is another phenomenon that can affect seismic coefficient values for large sliding masses. Most 2D dynamic response computer programs (e.g., QUAD4M, Hudson et al. 1993) use a coherent motion along the base elements, such that spatial incoherence of the input motion is not taken into account. Strong motion studies of the spatial coherence of recorded motions and the effect of this incoherence on the seismic response of other large systems (e.g., offshore oil platforms) can provide guidance regarding the impact of spatial incoherence on Kmax.

The May 1991 special issue of the journal of Structural Safety (Vol. 10(1-3), 1991) is dedicated to the topic of spatial variation of ground motion and contains several useful papers. Somerville et al. (1991) and Abrahamson et al. (1991) provide data and models to predict the spatial incoherence of motion as a function of separation distance and frequency. These studies show that motions are most incoherent at large separation distances and high frequencies. However, motions can be very coherent at lower frequencies (< 1 Hz), even at significant distances (500 ft). Nadim et al. (1991) analyzed the dynamic response of two offshore oil platforms that were separated by about 250 ft, and they found that when they accounted for the spatial incoherence of the input motion, the peak forces and deck accelerations were reduced by only 3% to 8%.

3. Study of the Sliding Length Effect on the Maximum Seismic Coefficient

3.1 General

The goal of this part of the study is to evaluate the effect of sliding mass length on computed seismic coefficients (k_{max}). Fifteen 2D slip surfaces were considered: nine within a hypothetical side-hill landfill (Figure 1, Mesh 3) and six within the actual geometry of the OII landfill in Los Angeles (Figure 2). For the hypothetical landfill, sliding mass heights (H) of 50 ft and 100 ft were considered, while only H=100 ft was considered for the OII analyses. The lengths of the sliding masses ranged from 100 ft to 865 ft, with the length defined as the length of the flat base of the sliding surface.

The program QUAD4M that was used in the Rathje and Bray (2001) study was used again to compute the seismic coefficients for the fifteen slip surfaces in Figure 1 and 2 subjected to 6 input rock motions (Table 1). For comparison, one dimensional (1D) seismic coefficients were calculated. QUAD4M, rather than SHAKE91 (Idriss and Sun 1992), was used to compute the 1D values of k_{max} to avoid issues related to the different numerical formulations incorporated in the two programs (frequency domain vs. time domain). Rathje and Bray (2001) showed that peak accelerations from QUAD4M and SHAKE91 can differ by as much as 20% for 1D soil columns.

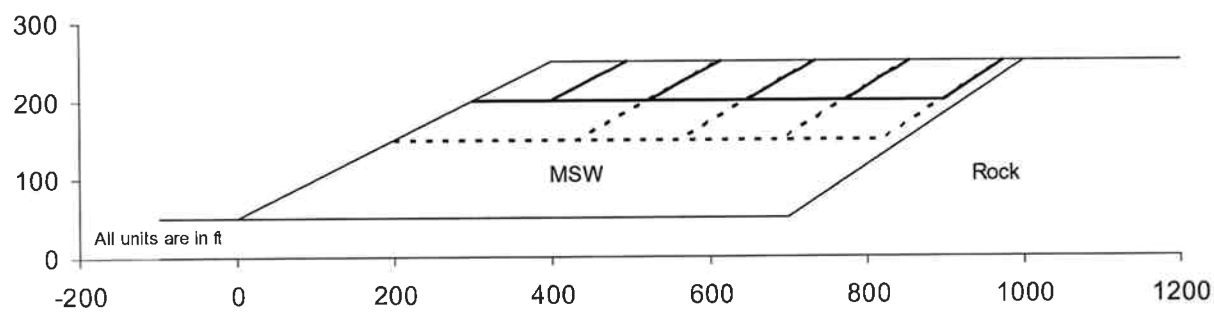

Figure 1. Slip surfaces (H=50 ft, 100 ft) considered for hypothetical Mesh 3

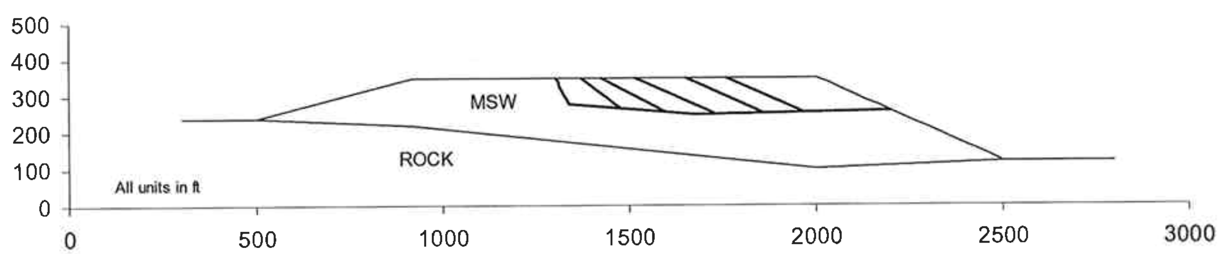

Figure 2. Slip surfaces (H=100 ft) considered for OII landfill

Table 1. Input rock motions used in study

Motion	Earthquake	M_w	PGA (g)	T_m (s)
Caleta	Michoacan	8.0	0.14	0.44
E Grand Avenue	Northridge	6.7	0.26	0.36
Kobe	Kobe	6.9	0.31	0.70
LA City Terrace	Northride	6.7	0.32	0.32
LGPC	Loma Prieta	6.9	0.64	0.72
WBB	Synthetic	8.0	0.57	0.51

3.2 Results

The 2D/1D Kmax ratios are plotted versus sliding mass length in Figure 3. Generally, the ratio decreases with distance, but note that many of the ratios fall above 1.0. These large values are the result of topographic effects modeled in the 2D analysis and missing in the 1D analysis. Rathje and Bray (2001) observed 2D topographic amplification factors between 1.1 and 1.25; thus the 1D Kmax values were scaled by 1.15 to account for 2D effects. The resulting 2D/1D k_{max} ratios are shown in Figure 4. The result is that most of the data now fall below 1.0.

The data for the different configurations and heights are distinguished in Figures 3 and 4. The data for the three different sets of data are in general agreement for L < 400 ft, but at larger distances there is a systematic difference between the data sets with the largest values observed for OII and the smallest values observed for Mesh 3, H=50 ft. These differences are most likely the inherent variability for the various configurations.

A power law relationship was fit to the data developed in this study and is shown in Figure 5. Although the R^2 value is quite low (~0.26) because of the large scatter in the data, the curve indicates that the ratio tends to level off at large values of L. At L =1000 ft, the ratio predicted by the curve is 0.74. Because the data at L > 600 ft only represents the OII configuration and these data were systematically larger than the other data, a curve was fit to the L ≤ 600 ft data (Figure 6). The resulting curve has a larger R^2 and predicts a ratio of about 0.66 at L = 1000 ft. Finally, Figure 7 shows the data from only Mesh 3, which removed any variability between configurations. As a result, the R^2 is again improved (~0.62) and the predicted ratio at L=1000 ft is reduced (~0.59).

Figure 8 compares the data developed in this study with the data presented by Rathje and Bray (2001). Rathje and Bray (2001) compared 2D k_{max} values from QUAD4M with 1D k_{max} values derived from SHAKE91 analyses. The 1D k_{max} values reported by Rathje and Bray (2001) are computed by calculating k–time histories at the base of several 1D columns within a sliding mass (Figure 9), and averaging the k-time histories in the time domain, weighting each by the percentage of the sliding mass upon which they act. The various k-time histories represent different 1D sections through the failure masses, including columns that have thinner layers of material above the sliding surface. Because using multiple 1D columns (some with thin layers of material above the sliding surface) typically results in a 10% to 30% increase in the 1D k_{max} value, the 2D k_{max} values from Rathje and Bray (2001) were not adjusted for topographic effects. Figure 8 shows that the data from Rathje and Bray (2001) are consistent with the data from this study, although there is significant scatter.

3.3 Partial Findings

It is reasonable that translational sliding block failures typically initiate as blocks that are on the order of a hundred feet or so and that coherent sliding of very long blocks is less likely (e.g., Turnagain Heights landslide during the 1964 Alaskan earthquake). Once a block of this order of length moves, it then allows a block of similar length to move behind it, which in turn can lead to a progressive failure as is sometimes observed for these types of translational failures from earthquakes. Hence, preference should be given to evaluating the seismic instability of the shorter potential sliding blocks when evaluating the seismic stability of long potential sliding masses. This study confirms that it is reasonable to reduce the maximum seismic coefficient by multiplying the 1D calculated k_{max} value by a sliding block length reduction factor (C_L) to account for 2D incoherence in the horizontal direction.

This preliminary study of the sliding block length reduction factor is based on a set of two-dimensional analyses performed as part of our previous research (details of the 2D QUAD4M dynamic analyses are described in Rathje and Bray 2001). In terms of estimating k_{max}, the sliding block length reduction factor (C_L) was found to reduce to C_L = 0.7 for sliding block base lengths (L) greater than 1000 feet and remain C_L = 1.0 for block base lengths less than 200 feet. For intermediate sliding block base lengths a linear transition captured the trends in the data reasonably well. More work is required before this recommendation can be finalized.

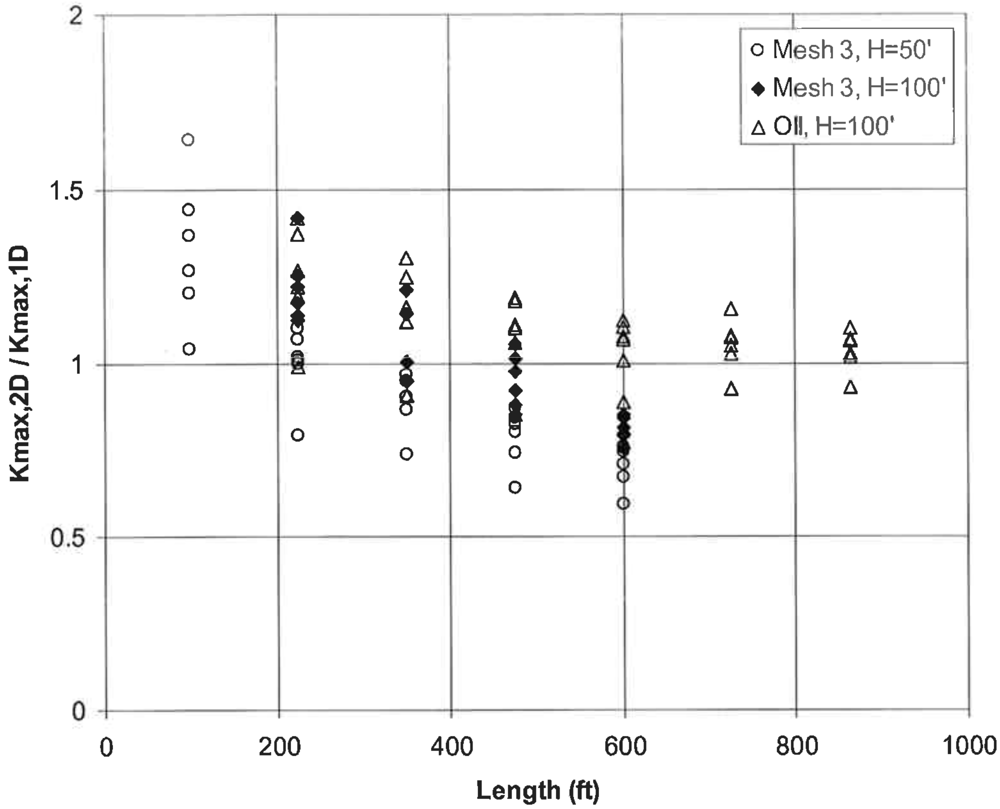

Figure 3. Ratio of 2D and 1D k_{max} values vs. sliding mass length

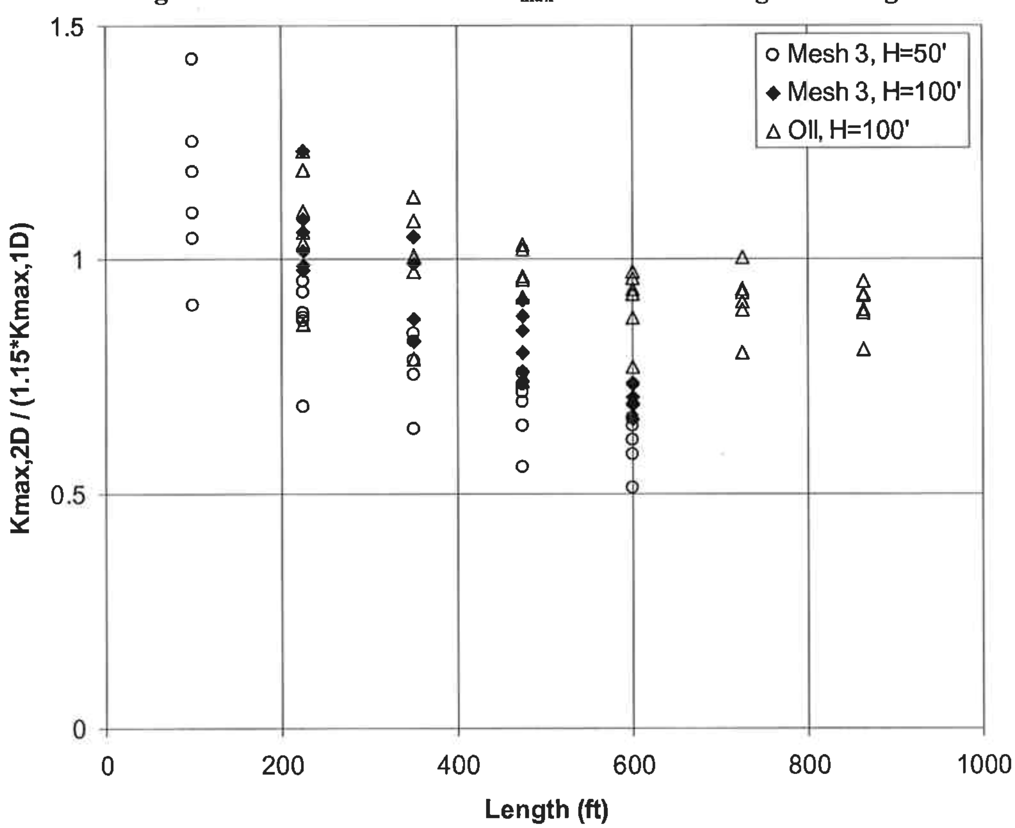

Figure 4. 2D / 1D k_{max} ratio (adjusted for topographic effects) vs. sliding mass length

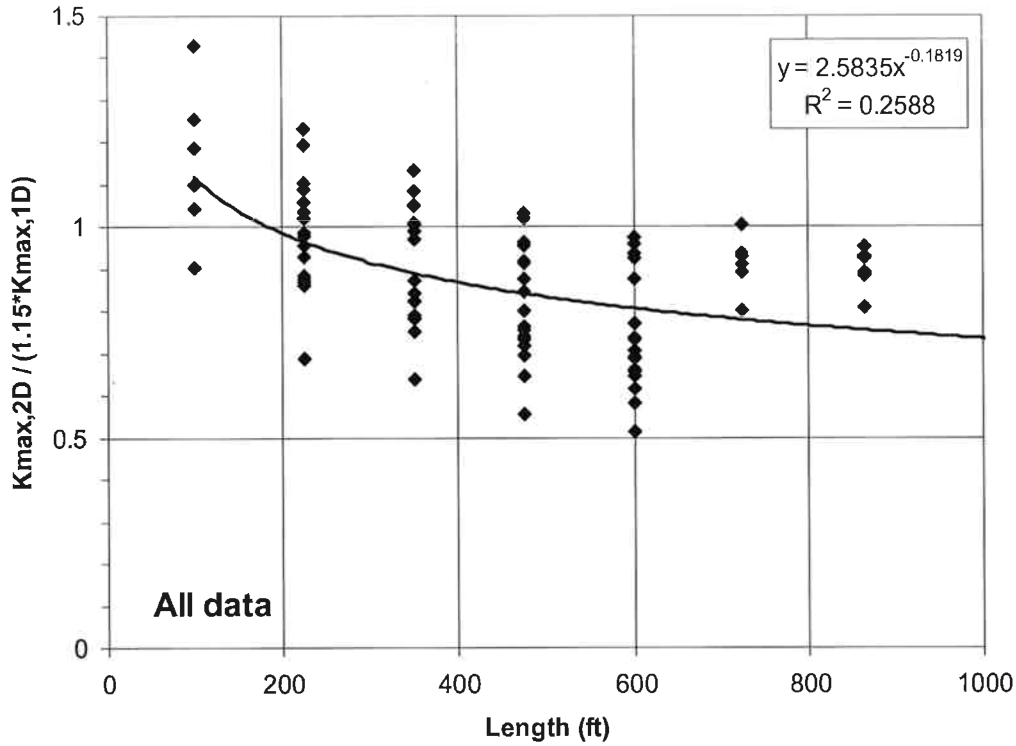

Figure 5. Best fit line for 2D / 1D k_{max} ratio (adjusted for topographic effects)

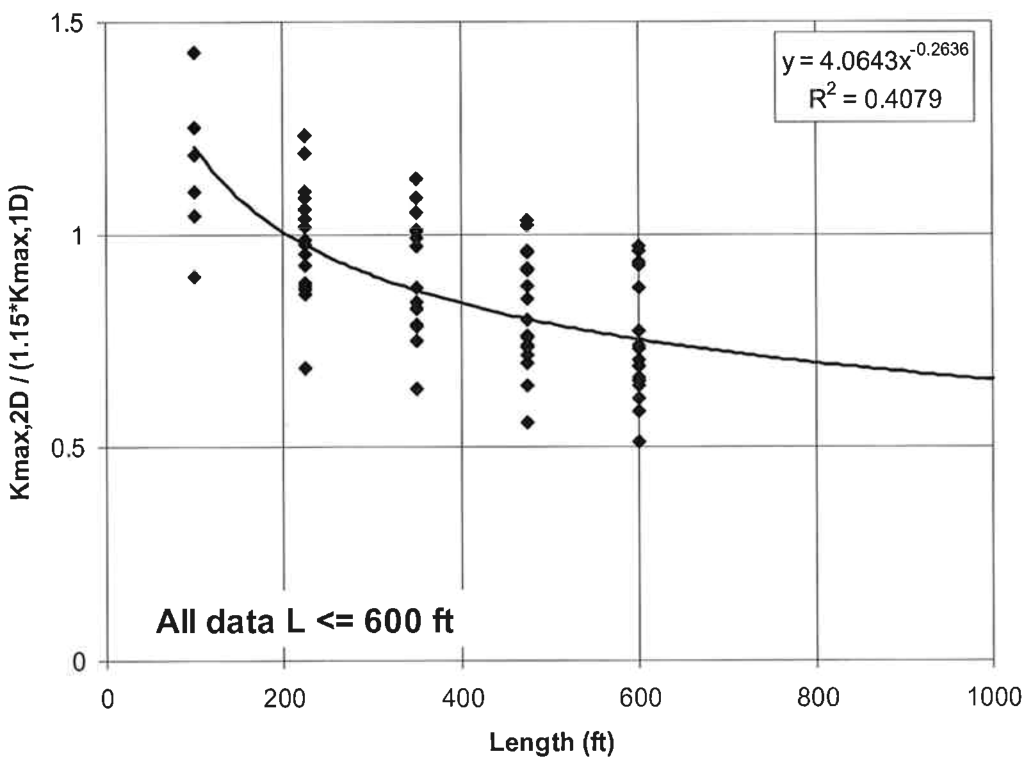

Figure 6. Best fit line for 2D / 1D k_{max} ratio (adjusted for topographic effects), $L \leq 600$ ft

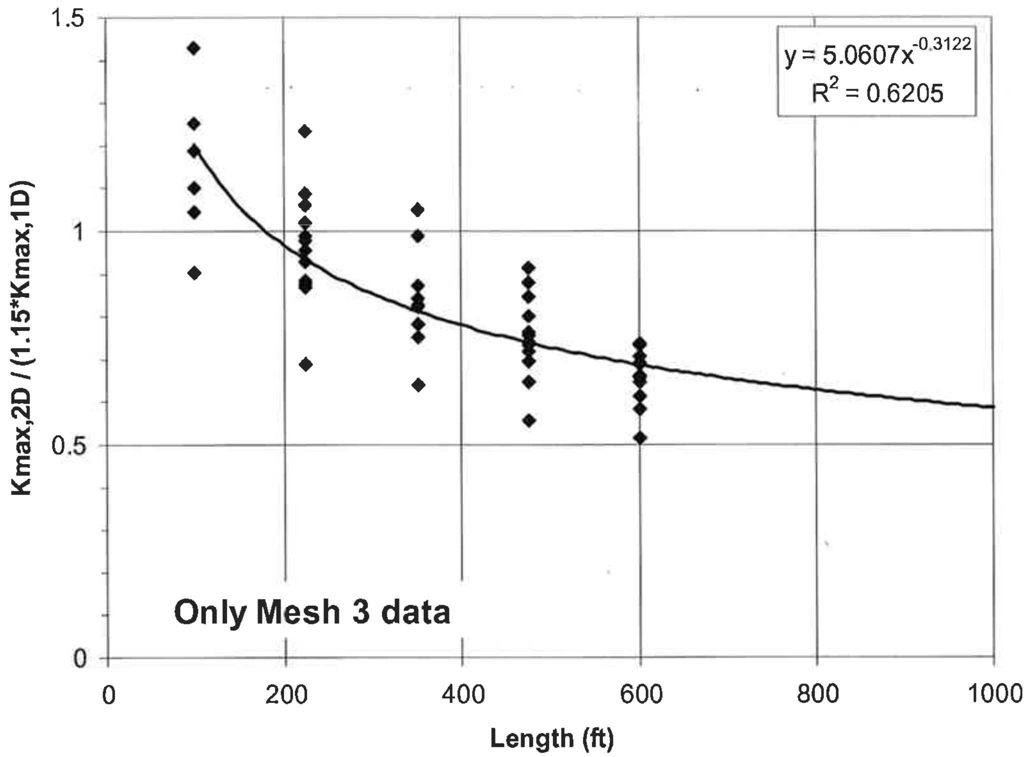

Figure 7. Best fit line for 2D / 1D k_{max} ratio (adjusted for topographic effects), Mesh 3 only

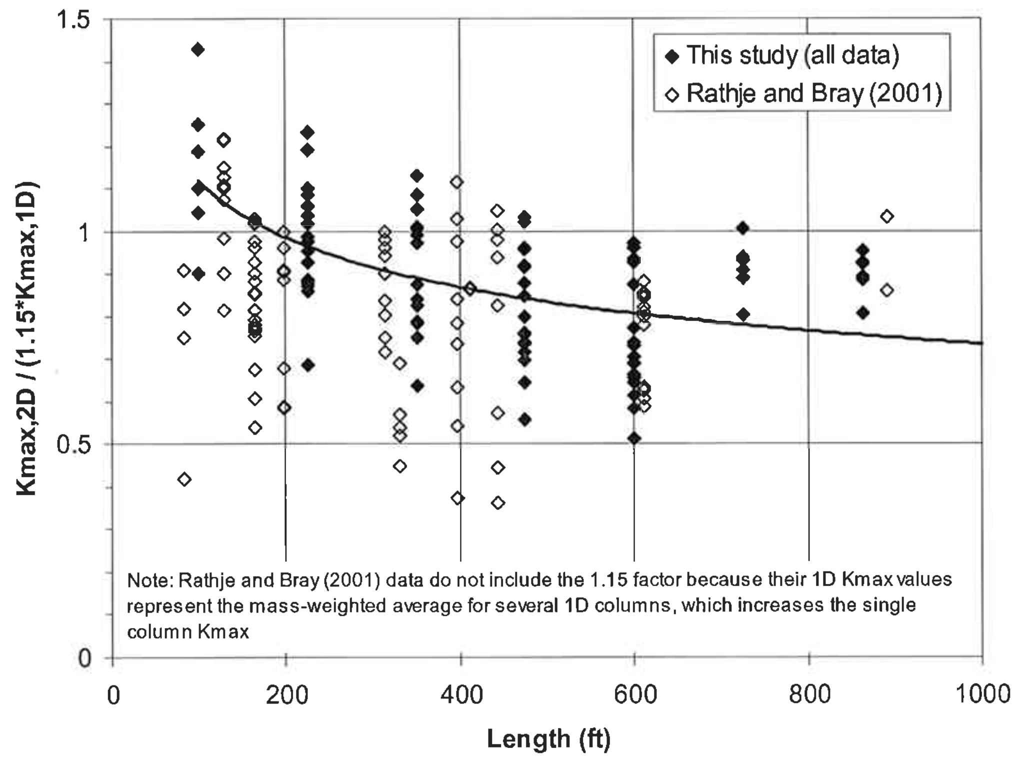

Figure 8. Best fit line for 2D / 1D k_{max} ratio (adjusted for topographic effects), this study compared with data from Rathje and Bray (2001).

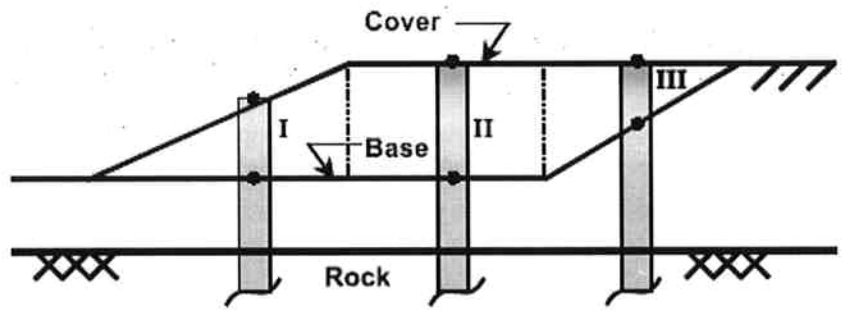

Figure 9. Use of several 1D columns to model 2D structures (from Rathje and Bray 2001). The 1D approximation of a 2D system requires calculating k–time histories at the base of several 1D columns within a sliding mass, and then averaging the k-time histories in the time domain, weighting each by the percentage of the sliding mass upon which they act. Note that columns I and III include thinner layers of material above the sliding mass, which lead to larger values of k_{max}.

4. Potential Effect of Sliding Length on the Calculated Seismic Displacement

Seismically induced permanent displacements (U) often form the basis of assessing the likely seismic performance of slopes or earth/waste structures. In the Rathje and Bray (2001) study, they found that the use of 1D analyses as illustrated in Figure 9 to capture the 2D response of the earth/waste structure had a larger effect on the calculated value of k_{max} than on the calculated seismic displacement.

The ratio of k_{max} values calculated using 1D vs. 2D procedures in shown in Figure 10. For most cases the median ratio of $k_{max,1D}$ to $k_{max,2D}$ is about 1.2. This suggests that one could apply a reduction factor of 0.8 to the results of 1D analyses to adjust them to match the results of 2D analyses.

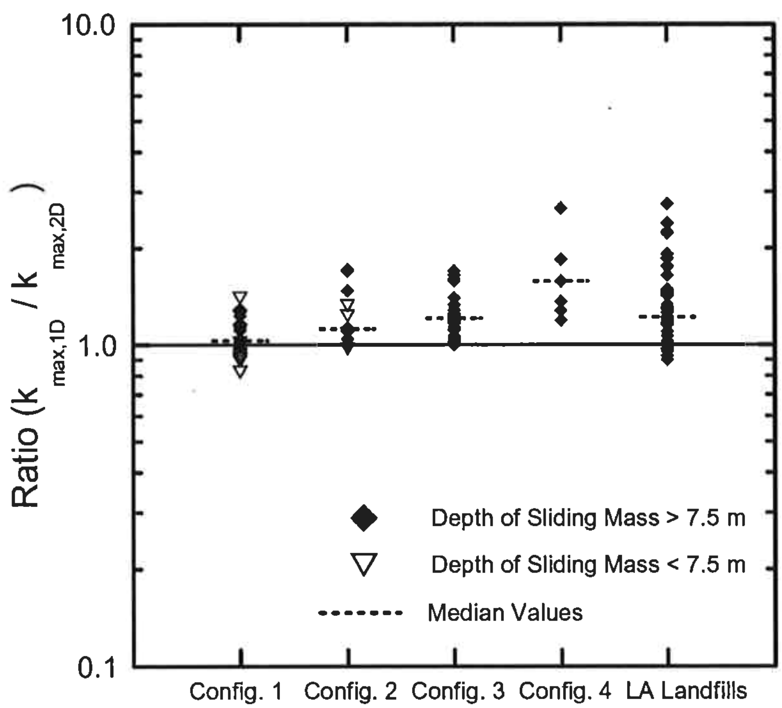

Figure 10. Comparison of k_{max} from deep sliding calculated by 1D and 2D analyses (Rathje and Bray 2001)

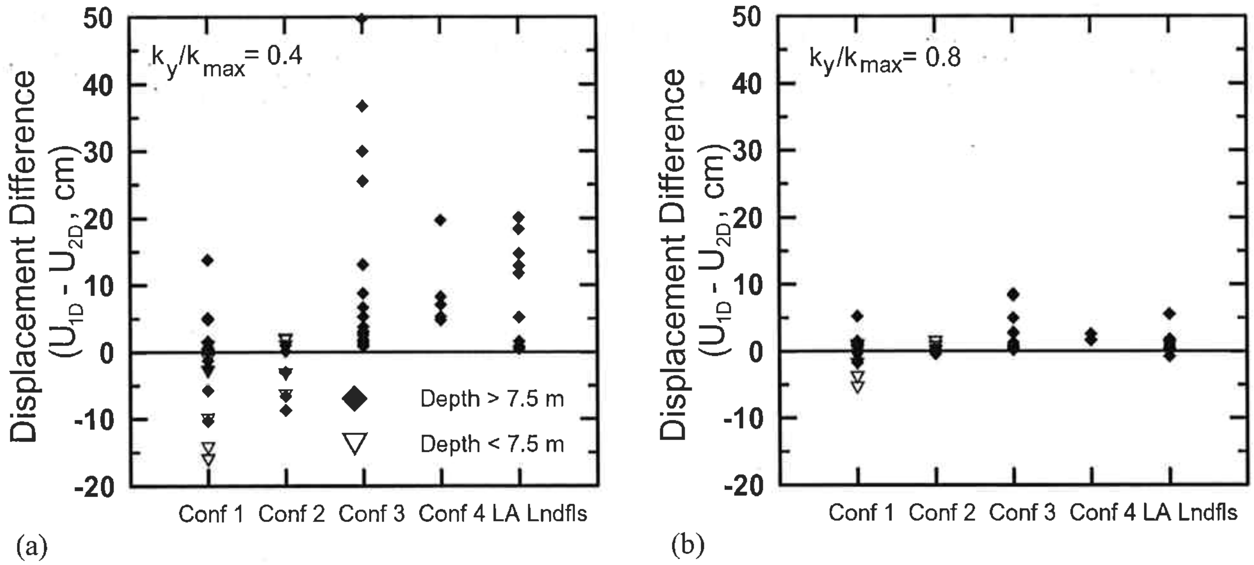

Figure 11. Displacement difference ($U_{1D} - U_{2D}$) for deep sliding for both k_y/k_{max} = 0.4 and 0.8 (Rathje and Bray 2001)

In that same study by Rathje and Bray (2001), they calculated the seismically induced permanent displacement using the seismic coefficient-time histories calculated by 1D and 2D analyses. A decoupled Newmark sliding block analysis was used to calculate permanent sliding displacement at various k_y/k_{max} ratios, where k_y is the yield acceleration coefficient. Figure 11 displays the displacement difference (i.e., $U_{1D} - U_{2D}$) calculated for the several landfill configurations. For k_y/k_{max} = 0.8 (Fig. 11(b)), the 1D calculated displacement is typically greater than the 2D calculated displacement, which supports a length reduction factor less than one. However, the 1D and 2D calculated displacements provide an overall consistent assessment of seismic performance, because both methods calculate small displacements and hence, their difference is small.

For k_y/k_{max} = 0.4 (Fig. 11(a)), most configurations produce conservative 1D sliding displacements (i.e., displacement difference greater than 0), but some configurations produce several 1D displacement values that are smaller than the 2D displacement values (i.e., displacement difference less than 0). Many of these cases are for shallower sliding surfaces, within 25 ft of the landfill surface, where due to topographic effects, the 2D value of k_{max} was greater than the 1D value. A few of the data points in Figure 11 that fall below zero, however, are for deeper sliding surfaces where the 1D k_{max} was greater than the 2D k_{max}. For these cases, although the 1D k_{max} value was greater than the 2D value, other peaks in the k–time history were larger for the 2D analysis and the 1D and 2D k-time histories had different frequency contents. These factors combined to produce larger 2D displacements than 1D displacements in these cases.

Although these results indicate that seismic displacements calculated with the 1D approximation illustrated in Figure 9 are generally larger than those calculated using 2D analyses, the ratio of U_{1D}/U_{2D} does not appear to be as large as the ratio of $k_{max,1D}/k_{max,2D}$. Until a more comprehensive study is completed that examines the results of seismic displacement calculations using 1D and 2D seismic coefficient-time histories, caution is warranted in directly applying the length reduction factor developed based on the comparison of k_{max} values calculated using 1D and 2D analyses (as presented in the previous section).

5. Conclusions

The use of several 1D columns to approximate a 2D potential sliding mass was found by Rathje and Bray (2001) to be generally conservative for deep sliding cases (i.e., H > 25 ft). They found that as the base length of the 2D potential sliding mass increased, the maximum seismic coefficient calculated using the1D approximation tended to become more conservative. This trend was confirmed by the study of the effect of sliding block length on k_{max}, which was presented in this report. Both studies support reducing the value of k_{max} by a length reduction factor (C_L) as the base length of a 2D potential sliding mass increases.

The Rathje and Bray (2001) study also found that the use of the 1D approximation illustrated by Figure 9 was generally conservative for calculating seismic displacements for deep sliding masses that were inherently 2D. However, the level of conservatism involved in calculating seismic displacements with the 1D approximation appeared to be less than that involved in calculating k_{max} values. Until this issue is explored more thoroughly, a conservative interpretation of the C_L factor in its application to the seismic coefficient-time history calculated using the 1D approximation for use in seismic displacement calculations is warranted. Based on the results of this study and the Rathje and Bray (2001) study, this could be accomplished by increasing the minimum C_L factor from 0.7 for L > 1000 ft to 0.85.

The 2D dynamic analysis program QUAD4M was employed in this study and in the Bray and Rathje (2001) study. QUAD4M imposes a coherent input rock motion along the base of the finite element model. Hence, it ignores spatial incoherence of the input motion as well as the wave passage effect. Previous studies (e.g., Nadim et al. 1991) suggest that spatial incoherence alone can lead to a 5% reduction in the peak forces induced by ground shaking over long separation distances. This suggests that the minimum C_L factor overall can be reduced slightly from 0.85 to 0.8 for L > 1000 ft.

6. Final Recommendation

The sliding block length reduction factor (C_L) can be applied to the seismic coefficient-time history calculated using the 1D approximation illustrated in Figure 9 to capture the incoherence of the ground motion and the seismic loading of a potential sliding mass over significant horizontal distances. We recommend that $C_L = 0.8$ for sliding block base lengths (L) greater than 1000 feet and that $C_L = 1.0$ for block base lengths less than 200 feet. For intermediate sliding block base lengths, $C_L = 1.0 - 0.00025(L - 200 \text{ ft})$ for 200 ft < L < 1000 ft. Additional work is warranted to refine this approximation.

7. References

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