Seismic coefficients for steep slopes

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Abstract

As part of an effort to develop a simplified procedure to determine the seismic stability of steep natural slopes, average seismic coefficients for a range of steep slope angles are developed. A new numerical technique based on the Generalized Hyperelement (Deng[11]). is used to determine the seismic response of three steep slopes, composed of weakly cemented sand, known to have experienced seismically induced slope failures. The results show that, in general, the average seismic coefficient increases with slope angle, and is dependent on the frequency content of the earthquake. The results also show that the normalized average seismic coefficient profile for these slopes exceeds the upper- and lower-bounds presented by Makdisi & Seed,[10] but that Makdisi & Seed's results present a reasonable average, except for the steepest of slopes.

1 Introduction

There is a long history of seismically induced failures in steep slopes composed of weakly cemented sand. Examples of these failures can be found in the United States, China, Japan, and through Central and South America (Ashford & Sitar[1]). Weakly cemented sand often stands in slopes ranging from 30° to near vertical, and exhibits brittle behavior in both shear and tension. Failure surfaces are typically shallow and sub-parallel to the slope face. These characteristics often make stability analyses using conventional methods inappropriate for use in these steep slopes. The study described herein is part of an overall effort to develop a simplified procedure to assess the seismic stability of steep slopes.

Transactions on the Built Environment vol 14, © 1995 WIT Press, www.witpress.com, ISSN 1743-3509

Studies analyzing the seismic response of steep slopes are relatively limited, though early work was performed by Idriss & Seed[2] and Kovacs et al[3] on relatively shallow clay banks. To date, however, most of the research effort in seismic slope stability has been directed toward the assessment of the stability of earth dams. Some of the procedures and concepts developed for dams may also be extended to steep slopes.

Seed & Martin[4] applied the one-dimensional shear slice method, first proposed by Mononobe et al[5], to calculate average seismic coefficients for use in the stability analyses of earth dams. Using this procedure to calculate acceleration time histories throughout the height of the dam, they were able to develop an equivalent seismic force series that, in effect, represented the forces acting on the dam during the earthquake. Based on this analysis, an average seismic coefficient was developed that represented the effect of the earthquake on the dam. Other studies using the concept of average seismic coefficient were performed by Ambraseys & Sarma[6] and Sarma.[7]

Newmark[8] was the first to propose the concept that the stability of an earth dam should be assessed in terms of earthquake-induced deformations, rather than the minimum factor of safety. This concept was further developed by Seed & Goodman.[9] Finally, Makdisi & Seed,[10] making use of the earlier advances, developed a simple and rational procedure to estimate embankment deformations during earthquakes. This procedure has become a standard of practice for calculating embankment deformations. The procedure is based on Newmark's deformation concept and utilizes the average seismic coefficient, as proposed by Seed & Martin[4], and a yield acceleration which can be calculated by any number of methods. The simplicity of this procedure is very attractive, but it must be modified somewhat to be made applicable to steep slopes in brittle materials.

2 Method of Analysis

A new computer program, GROUND2D (Deng[11]), was used to perform the analyses. The program is based on the complex response method and works in the frequency domain. Soil is modeled as a linear visco-elastic solid. A Generalized Transmitting Element (GTE) is used to simulate the semi-infinite nature of real site boundaries, including those with irregular geometrical and material boundaries. A Generalized Hyperelement (GHE), is used to model regions of soil and rock of large lateral extent with irregular boundaries. Both elements essentially use finite element theory along element boundaries and continuum theory in the horizontal direction, making the GHE a semi-analytical method. Use of an analytical solution in the horizontal direction also makes GROUND2D ideal for the site response analysis of steep slopes.

The model shown in Figure 1 is an example of the mesh layout used in a typical slope response analysis. Each model consisted of a left and a right GTE divided into a number of horizontal layers, the thickness of each layer selected as at most one-tenth of the shortest wavelength (λ) under consideration. The

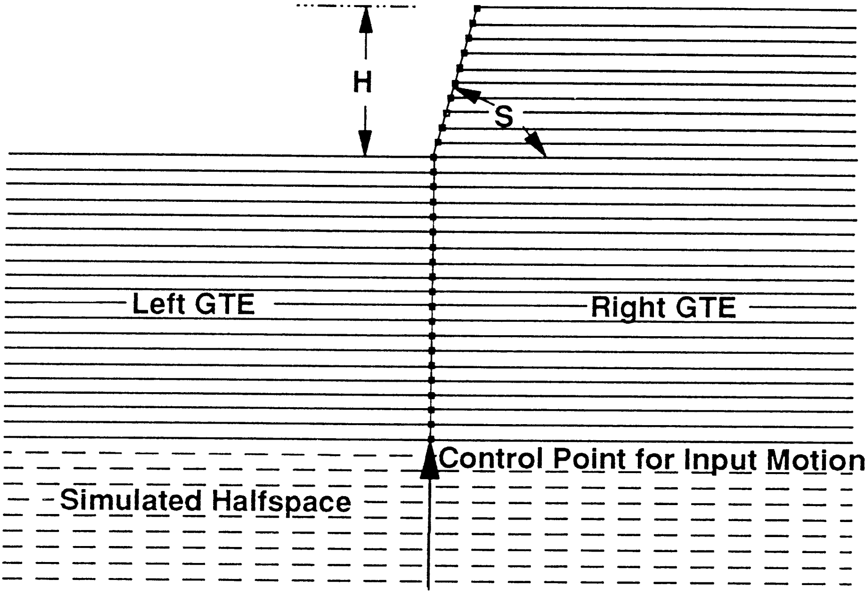

Figure 1: Example hyperelement mesh used in analyses.

frequencies considered in the analyses were between 0.1 and 10 Hz, which is in the general range of engineering interest and contains the dominant frequencies of the seismograms used in the analyses. All of the elements sit atop a simulated visco-elastic halfspace, where the thickness varies as a function of the frequency under consideration. The earthquake motion is input at a control point at the surface of the halfspace.

An approach similar to that used by Seed & Martin[4] and Makdisi & Seed[10] can be used to develop average seismic coefficients for steep slopes, as long as the conditions particular to steep slopes are met. In this study, the average seismic coefficient (k_{ave}) is calculated using a weighted average summation procedure within the potential failure wedge:

$$k_{ave} = \sum \frac{m(y)}{M} \ddot{u}_a(y) \tag{1}$$

where m(y) is the mass of a given horizontal slice within the failure wedge, M is the total mass of the wedge, and $\ddot{u}_a(y)$ is the acceleration within the slice. The shear slice method was not used because of the steepness of the failure surface and the semi-infinite extent of the material behind the crest. For convenience, the accelerations used in the analysis herein are those computed at the slope face, which was found to be reasonable and conservative.

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3 Site Specific Analyses

The slopes analyzed include typical sections from sites in California which have a history of seismically induced failures (Ashford & Sitar[1]). The analyses of the selected sites used 3 different seismograms from earthquakes recorded in California: the 1940 El Centro N/S record (ECNS), the 1989 Loma Prieta UCSC0 record, and the 1992 Landers JOS90 record. The intent was to evaluate the relationships between crest amplification and average seismic coefficient based on a variety of realistic conditions. Strain-compatible soil properties were used in the analysis that were obtained from one-dimensional equivalent-linear site response analysis (Schnabel et al[12]). Damping in the halfspace was assumed to be 0.5 percent.

The first model is a 90-ft high, 75-degree slope which is representative of the specific conditions occurring at Seacliff State Beach near Santa Cruz, California, which failed during the 1989 Loma Prieta earthquake. The second model consists of a 380-ft high, 45-degree slope that is representative of the specific conditions at Daly City, California, where slopes failed during earthquakes in 1906, 1957, and 1989. The final model is based on the geometry of slopes that failed in the Pacific Palisades, near Los Angles, during the 1994 Northridge Earthquake. This model consists of a 200-ft high, 60-degree slope. Since there is no site specific data available for this site, the soil properties used in the analyses are based on the properties determined at the two other sites, which are believed to be typical for cemented sands.

4 Results

Since space is limited, only a few selected results are discussed in this paper. Time histories of average seismic coefficient were developed from the 3 input seismograms for each of the site models as a function of the depth of the toe of the failure wedge. From each time history, the maximum average seismic coefficient (k_{max}) was selected, and a k_{max} profile for each model was developed. Similar to the procedure used in Makdisi & Seed[12], the k_{max} profiles were normalized by the maximum crest acceleration of the model a_{max}. Profiles of k_{max}/a_{max} versus normalized depth, h/H, are presented in Figures 2 and 3 for two of the site models.

Review of Figures 2 and 3 indicate that the shape of the profiles are similar, with the upper bound created by the JOS90 input motion in each case. The results from the UCSC0 and ECNS input motions are very similar within each set, the lower bound being formed by one or the other, or a combination of the two, indicating a dependency on the frequency content of the earthquake. A comparison between Figures 2 and 3 show that the k_{max}/a_{max} profile tends to increase (i.e. shift to the right) with increasing slope angle. This is consistent for all input motions.

All results from the study, including some not discussed herein, are presented in Figure 4, along with the range of values from Makdisi & Seed.[10]

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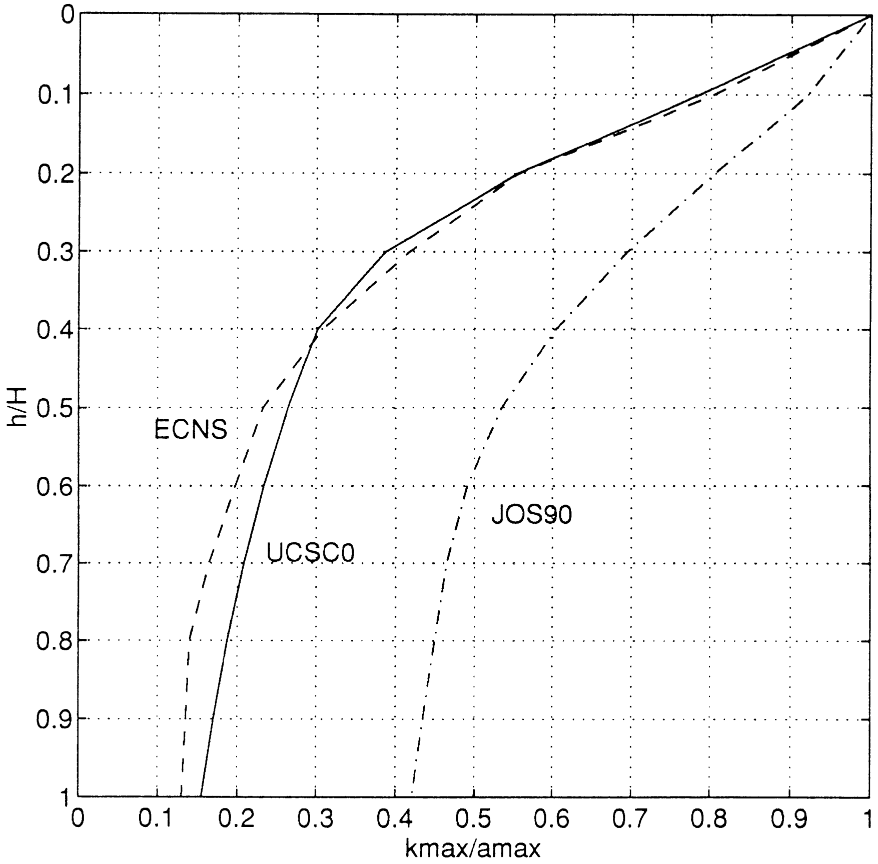

Figure 2: Normalized maximum seismic coefficient profile for Pacific Palisades model.

An overall review reveals a wider range values than presented by Makdisi & Seed, exceeding both the upper and lower bounds. The upper bound of this data is the Seacliff Model with the JOS90 motion, while the lower bound is Daly City Model with the UCSC0 motion.

These results indicate that the k_{max}/a_{max} profile is dependent on the frequency content of the earthquake, as exhibited by the comparison within sets, and the slope angle, as exhibited by the comparison between sets. The contrast between the profile shapes for the 75- and 60-degree slopes can be explained by focussing of the motion at the crest of the slope, and attenuation of the motion along the face of the flatter slope. This effect would result in the reduction of k_{max}/a_{max} as the failure surface extends down the slope. In addition, points along the flatter slopes may be more out of phase with the crest motion

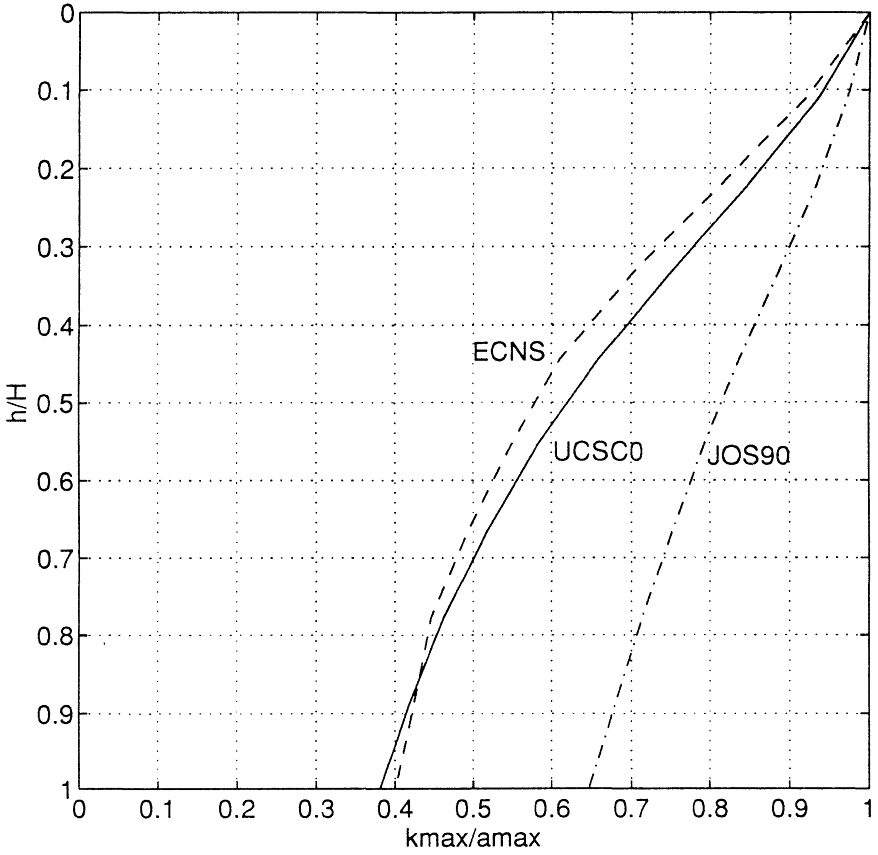

Figure 3: Normalized maximum sesimic coefficient profile for Seacliff model.

than points along steeper slopes.

5 Conclusions

The k_{max}/a_{max} profiles presented herein are of the same general shape, but cover a broader range, as compared to the profiles presented by Makdisi & Seed[10] using the one-dimensional shear slice method. Moreover, the k_{max}/a_{max} profiles vary with the frequency content of the earthquake and the slope angle. The ratio of k_{max}/a_{max} increases with slope angle, with the steepest slopes forming an upper bound to the data. When selecting a value of k_{max}/a_{max} for a particular slope, it would seem reasonable to use an upper bound value for steep slopes (greater than 60 degrees), and average values for moderately steep slopes (less than 60 degrees).

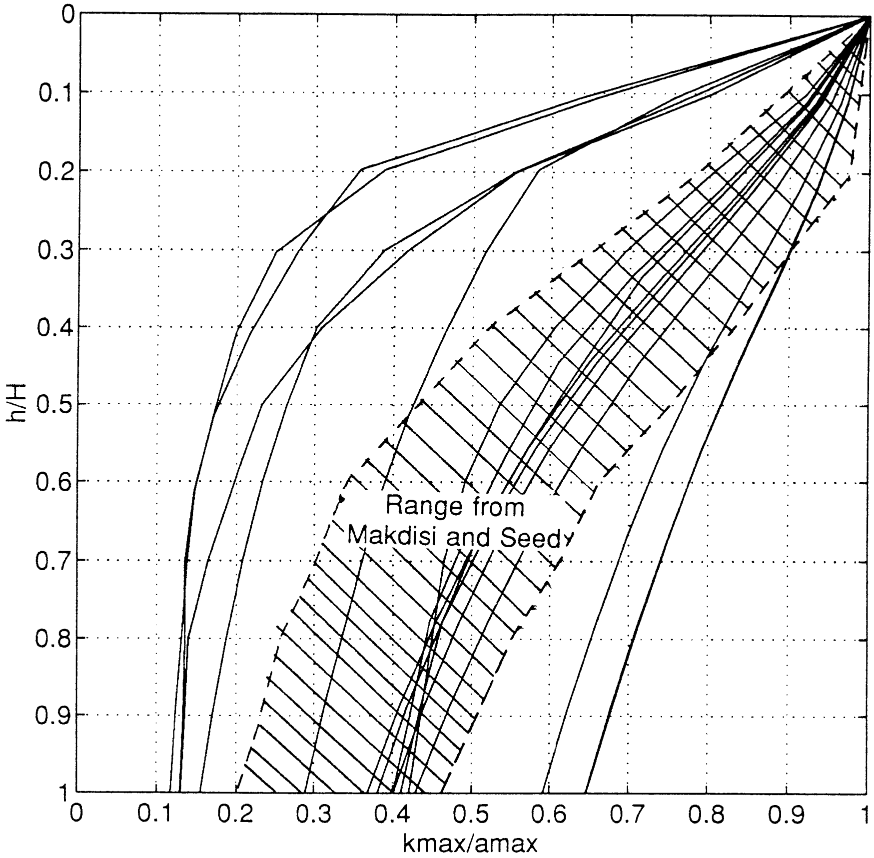

Figure 4: Summary plot of all normalized maximum seismic coefficient profiles compared to Makdisi & Seed.[10]

Acknowledgements

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 14-08-0001-G2127. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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