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S. A. Ashford
Asian Institute of Technology, Bangkok, Thailand

N. Sitar
University of California at Berkeley, Berkeley, California

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Analysis of Inclined Shear Waves in Vertical Bluffs

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S.A. Ashford
Assistant Professor, School of Civil Engineering, Asian Institute of Technology, Bangkok, Thailand

N. Sitar
Professor, Department of Civil Engineering, University of California at Berkeley, Berkeley, California

SYNOPSIS

The effect of inclined shear waves on the seismic response of vertical bluffs is analyzed using the generalized hyperelement. The bluffs are modeled as a stepped halfspace in the frequency domain. It is shown that the response, normalized as a function of slope height (H) divided by wavelength (λ), is amplified for waves travelling into the slope and attenuation for waves travelling away from the slope. This amplification can be as much as twice the amplification for vertically propagating waves. The results of the analysis suggest that wave orientation and inclination in relation to the slope may need to be considered in performing stability analyses.

INTRODUCTION

The effect of topography on seismic response has been observed in numerous earthquakes, however, these effects have been difficult to quantify in engineering analyses. Qualitative understanding of the effects of topography developed following observations from several earthquakes suggests that earthquake-related damage tends to be more extensive on ridge tops (e.g. Celebi, 1987) and the crest of cliffs (Sitar and Clough, 1983). Some of the observations suggest an effect on the response due to direction of wave propagation and wave inclination in relation to the slope. In the 1976 Guatemala earthquake, landslides were observed to be concentrated on one side of a ridge and not the other (Harp et al, 1978), and in the 1989 Loma Prieta earthquake, spurs from ridges were observed to experience massive failure, while nearby cliff appeared unaffected. In the 1994 Northridge earthquake, the authors observed damage to be concentrated within one slope height of the crest of coastal bluffs in the Pacific Palisades, on bluffs perpendicular to the wave travel path. Examples such as these give qualitative support the concept of energy focussing in topographic structures, and point to the effect of wave direction and inclination. Unfortunately, quantitative data on the effect of topography are generally limited to small strain response from blasting or earthquake aftershocks. The corresponding attempts to model these effects have shown qualitative, but not quantitative, agreement with the observed behavior. In this study, the effects of shear wave direction and inclination on the seismic response of vertical bluffs are quantified in the frequency domain using a new numerical model based on the generalized hyperelement.

One of the first numerical studies of the effect of topography on seismic response was carried out by Boore (1972). This study, prompted by observations of high accelerations near Pacoima Dam during the 1971 San Fernando earthquake, considered the effect of simple topography on vertically propagating SH-waves. Boore concluded that the motion within a ridge consisted of 3 phases: a direct wave, a reflected wave, and a diffracted wave. The results showed that there was amplification at the ridge crest, and that both amplification and attenuation could occur along the side slopes, depending on the slope geometry and the frequency of motion. The effect of topography was found to vary with frequency, and amplification up to 100 percent was noted over the free-field. The amplification was found to decrease with slope angle and as the wavelength became large compared to the characteristic length.

May (1980) studied the effectiveness of vertical scarps on reducing the seismic energy transmitted to a site above or below the scarp. May used the finite element method to analyses horizontally propagating SH- and Love waves passing through 60- to 150-m high vertical scarps in a halfspace and a layer over a halfspace. The frequencies of motion considered ranged from 1.5 to 6 Hz. May found that refection off the scarp face played a large role in the response, and that the effect of the scarp could be related to the ratio of scarp height and the wavelength of the motion under consideration.

Geli et al. (1988) analyzed a two-dimensional ridge with a layered profile and introduced nearby ridge effects, but arrived at conclusions similar to those of the previous researchers. In addition, they found that neighboring ridges may have greater effect on site response than layering, and concluded that future models should be able to analyze SV- and surface waves and three dimensional geologic configurations.

Sitar and Clough (1983) used a two-dimensional finite element model to analyze the seismic response of steep slopes in weakly cemented sands. They found that accelerations tended to be amplified in the vicinity of the slope face and noted that these topographic effects tended to be small relative to the amplification that occurs in the free field due to the site period.

More recently, Gazetas and Dakoulas (1992) performed an analytical parametric study on the effect of inclined SH-waves on the seismic response of rockfill dams. The results were normalized as a function of the ratio of the wavelength and the length of the dam. They found that waves inclined 20 to 30 degrees amplified the response by as much as 25 percent, but that the wave inclination had the greatest effect on the spatial variation of motion. Also, for waves traveling from left to right, the amplification was concentrated on the right end of the crest.

In our previous study, (Ashford and Sitar, 1994), we used the generalized hyperelement to analyze the effect of topography on the seismic response of steep slopes subjected to vertically propagating shear waves. The response of the slope was normalized as a function of the ratio of the slope height (H) and the wavelength of motion (λ). In this paper, we concentrate on the effect of wave inclination and direction on the seismic response of vertical bluffs subjected to shear waves.

METHOD OF ANALYSIS

A new computer program, GROUND2D (Deng, 1991), 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. The incident wave used as the input motion at the surface of the simulated visco-elastic halfspace can be either a surface or a body wave, which includes Rayleigh and Love waves, and inclined SH-, SV-, and P-waves. For clarity, the definition of the wave types as used herein is illustrated in Figure 1. The SV-wave is the in-plane shear wave with displacement in the plane of the slope cross-section, i.e. within the plane shown in Figure 1. The SH-wave is the out-of-plane shear wave with displacement normal to the slope cross-section, i.e. out of the plane shown in Figure 1. These definitions are consistent with those commonly used for the case of a wave traveling normal to the slope face, i.e. in the plane of Figure 1.

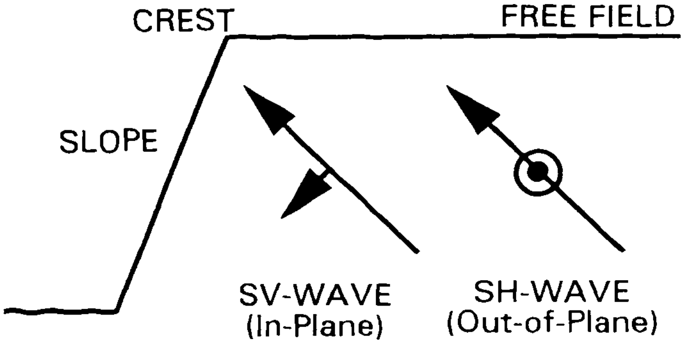

Figure 1: Definition of wave types.

A new type of transmitting element, the 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 new type of hyperelement, the Generalized Hyperelement (GHE) (Deng, 1991), is used to model regions of soil and rock of large lateral extent with irregular boundaries. The GHE essentially uses finite element theory along element boundaries and continuum theory in the horizontal direction, making the GHE a semi-analytical method. Using an analytical method in the horizontal direction, the GHE significantly reduces the fineness of the required discretization.

The problem of a vertical bluff in a uniform visco-elastic material can be simplified to that of a stepped uniform halfspace. The analysis of this problem is very useful for the development of an understanding of the fundamental parameters necessary to quantify the effect of topography on seismic response, because the only variables are the slope height, wavelength, wave direction, and wave inclination. Though our ability to determine the angle of incidence for the purposes of a site-specific stability analysis of an actual slope is questionable, the purpose of the analyses presented herein is to determine if the incident angle and direction of wave propagation is, in fact, important to the response.

The model used in the analyses, shown in Figure 2, consists of a left and right GTE connected along a single line of nodes at the boundary of the elements. The term "generalized" in GTE indicates that the boundary between elements can be irregular, thus allowing for the slope angle to vary with little modification to the mesh. Each GTE is divided into a number of horizontal layers, the thickness of each layer selected as a fraction of the shortest wavelength, λ, under consideration (in this case $\lambda/12$). The layers within each GTE can have different thicknesses and material properties, though in this study the material properties are uniform. 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. If material properties vary in the horizontal direction, then any number of GHE's can be included between the left and right GTE.

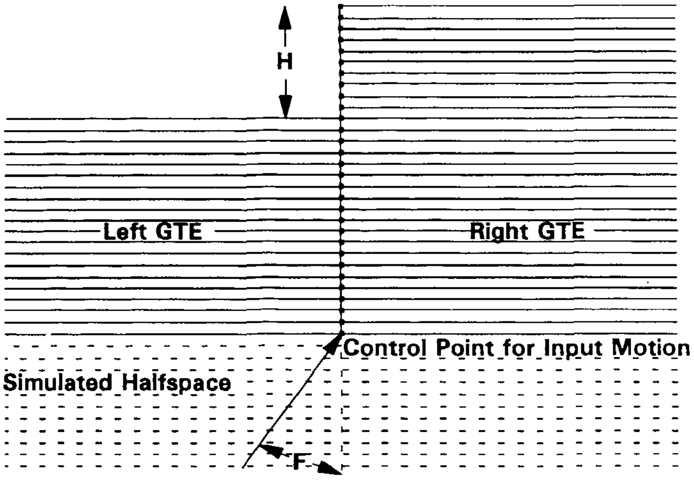

Figure 2: Stepped halfspace model for inclined wave incident on a vertical slope.

In Figure 1, the angle of incidence, F, is measured clockwise from the z-axis. Waves with positive incident angles will be referred to as travelling away from the slope, and those with negative incident angles are referred to as travelling into the slope. The effect of inclined SH- and SV-waves on the seismic response of a vertically stepped halfspace is evaluated in the frequency domain over the range of 0.5 to 10 Hz for SH-waves and 0.1 to 10 Hz for SV-waves. The uniform halfspace has a shear wave velocity of 300 m/s, a Poisson's Ratio of 0.3, and the fraction of critical damping equal to 1 percent, and the angle of incidence ranging from +30 to -30 degrees.

RESULTS

The response of the stepped halfspace to SH-waves is presented in Figures 3 through 6. In each case, the response due to the wave travelling into the slope is greater than for the wave angle travelling away from the slope. For all angles considered, waves travelling into the slope result in greater amplification than for vertically propagating waves, and this effect increases with increasing frequency. The amplification at $H/\lambda = 0.2$ increases from 25 percent for the vertically propagating wave, to nearly 70 percent for a wave inclined at 30 degrees. The opposite case is true for waves travelling away from the slope. The motion is attenuated with increasing incident angle, and the attenuation increases with frequency. At $H/\lambda = 0.2$, the response is the same as that for the free field for inclinations of 20 and 30 degrees. Though

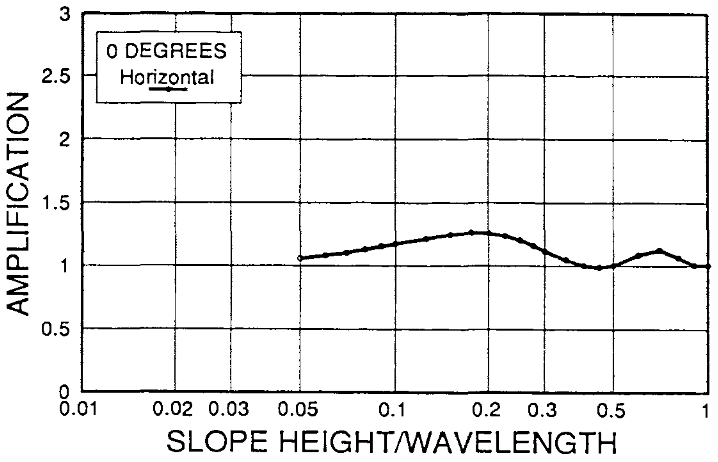

Figure 3: Amplifications at the crest for inclined SH-wave incident on a vertical slope, F = 0°, $\beta = 1\%$.

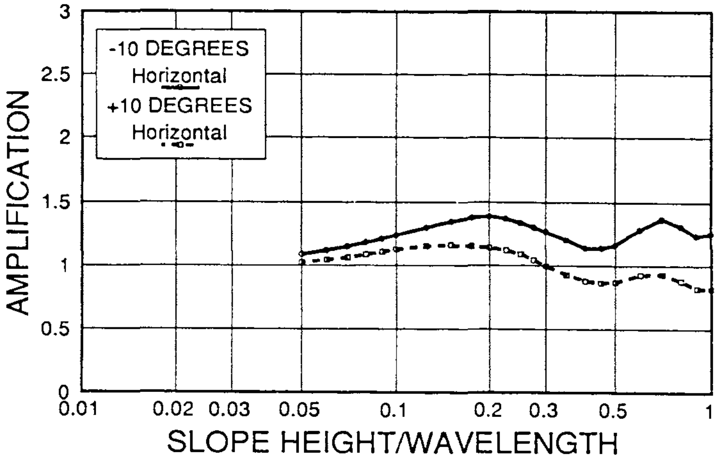

Figure 4: Amplifications at the crest for inclined SH-wave incident on a vertical slope, F = -10° and +10°, $\beta = 1\%$.

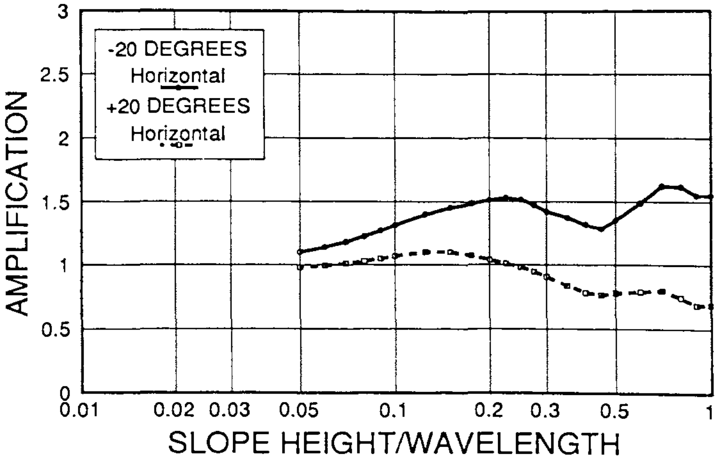

Figure 5: Amplifications at the crest for inclined SH-wave incident on a vertical slope, F = -20° and +20°, $\beta = 1\%$.

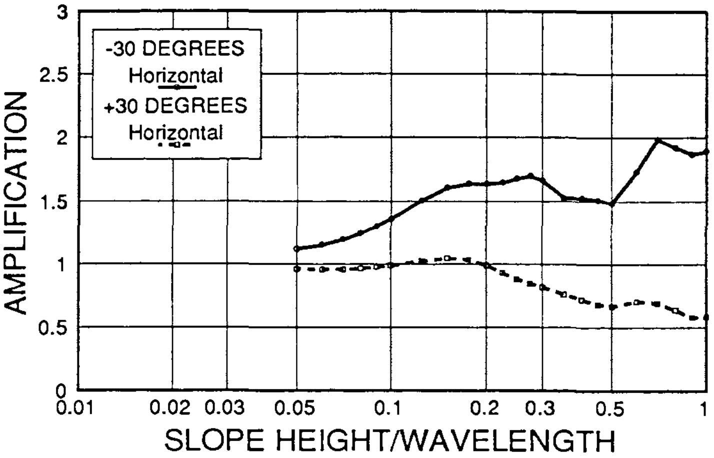

Figure 6: Amplifications at the crest for inclined SH-wave incident on a vertical slope, F = -30° and +30°, β = 1%.

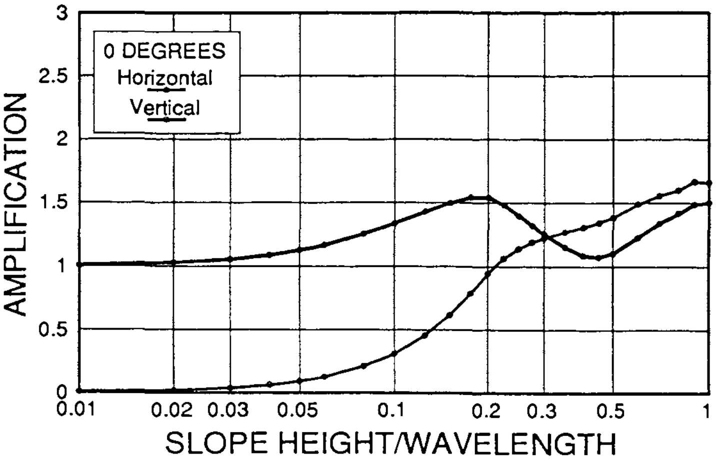

Figure 7: Amplifications at the crest for inclined SV-wave incident on a vertical slope, F = 0°, β = 1%.

greater amplification and attenuation was observed at higher frequencies for waves travelling into and away from the slope, these motion tend to get damped out at higher levels of damping.

The results for inclined SV-waves are presented in Figures 7 through 10. Results similar to those for SH-waves are obtained for the horizontal component of the SV-wave response, except that the amplification is much greater, in excess of 100 percent, for waves travelling into the slope, and there is less attenuation for waves travelling away from the slope. However, in contrast to the horizontal response, the direction of wave propagation appears to make little difference in the vertical response to SV-waves. Also, there is a notable increase in the vertical response due to SV-waves at low frequencies, which increases with incident angle independent of the direction of propagation due to wave splitting on the free surface. An SV-wave of amplitude 0.5 incident on a free surface will result in both horizontal and vertical motions, depending on Poisson's ratio, as shown in Figure 11. For material with a Poisson's Ratio = 0.3, the effect is relatively minor on horizontal motion, but is pronounced on the vertical response for the angles of incidence considered.

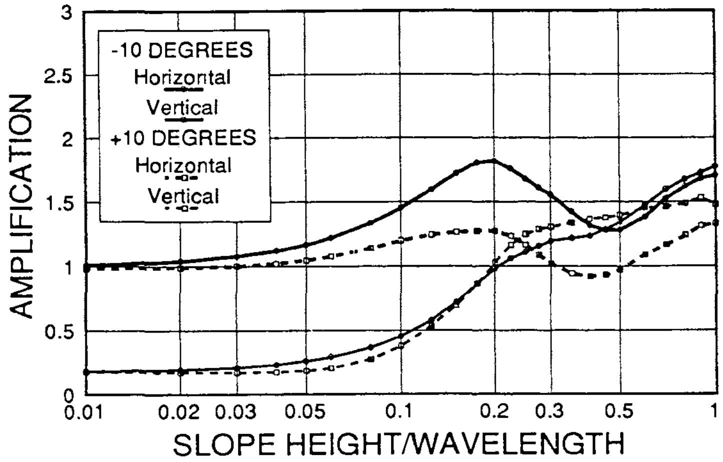

Figure 8: Amplifications at the crest for inclined SV-wave incident on a vertical slope, F = -10° and +10°, β = 1%.

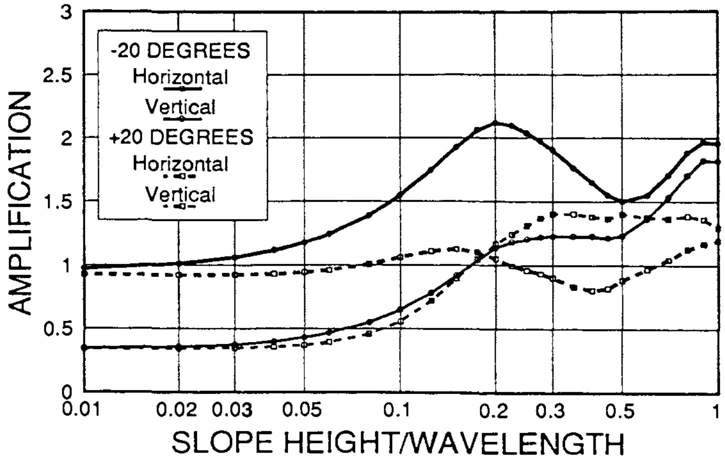

Figure 9 : Amplifications at the crest for inclined SV-wave incident on a vertical slope, F = -20° and +20°, β = 1%.

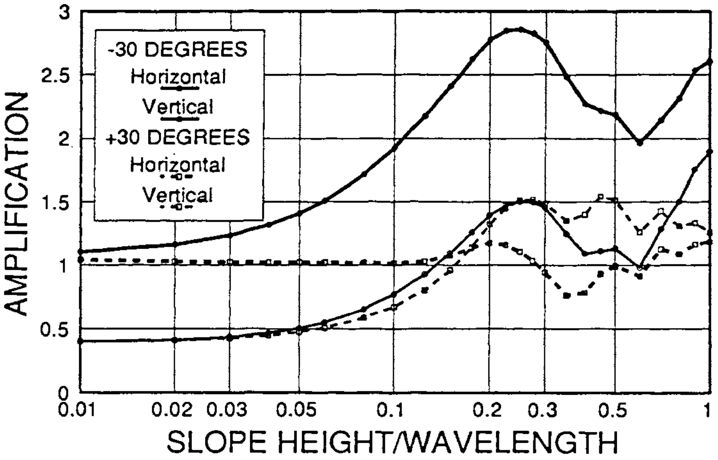

Figure 10: Amplifications at the crest for inclined SV-wave incident on a vertical slope, F = -30° and +30°, β = 1%.

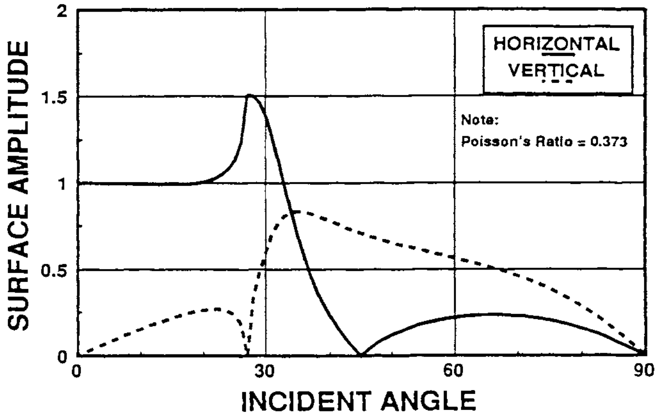

Figure 11: Variation of surface amplitude with incident angle.

CONCLUSIONS

The results of our study show that the horizontal response of a vertically stepped halfspace to inclined shear waves is amplified for waves travelling into the slope, and attenuated for waves travelling away from the slope. This amplification can be in excess of twice the amplification due to vertically propagating waves. In contrast, the vertical response to due SV-waves appeared to be independent of direction of wave propagation, and amplification at lower frequencies was due to wave splitting at the ground surface, rather than the focussing of energy at the crest of the slope.

While these results may have been intuitively guessed, our results provide a quantitative basis for the evaluation of the amplification of inclined shear waves travelling into the slope may partially explain field observations of failures on slopes facing in a particular direction, while slopes in the same material, but of different orientation, showed no distress. More importantly, these analytical results suggest the need to account for wave orientation and inclination in relation to the slope in performing stability analyses.

ACKNOWLEDGEMENT

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