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A NUMERICAL INVESTIGATION INTO THE INTERACTION BETWEEN TOPOGRAPHIC AMPLIFICATION AND SOIL LAYER AMPLIFICATION OF EARTHQUAKE MOTION

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ABSTRACT

Amplification of earthquake motion due to the effect of topography has been identified as contributing to unusually severe damage in numerous earthquakes. Field observations and numerical studies of topographic amplification have identified a range of parameters affecting this amplification. In particular the presence of soil layering has been identified as contributing to some of the very high earthquake amplification values seen in the field records of topographic amplification.

To investigate the interaction between topographic amplification and amplification due to soil layering, a numerical investigation into the amplification of earthquake motion in the presence of both topography and soil layering has been carried out.

A time domain finite element analysis was carried out considering a slope in a soil layer over rigid bedrock, for different bedrock depths, and hence site frequencies. The model was subjected to wavelet time histories with a single predominant frequency. Both long duration (to approach a steady state response) and limited duration time histories were considered. To separate the amplification due to topography from the amplification due to soil layering, the ground motion derived from the analysis was normalised by the corresponding free-field response.

The results of the analyses showed amplification of the horizontal motion and generation of a parasitic vertical motion, which were found to vary with the normalised frequency of the input motion, as seen in other studies. It was also observed that the topographic amplification varied for the different site period cases considered, indicating an interaction between topographic effects and soil layer effects.

Keywords: topographic amplification, soil layer amplification, numerical analysis, slopes, earthquakes

INTRODUCTION

The effects of modification of earthquake motion by topography, referred to as topographic effects in this paper, have been observed in damage caused by various earthquakes. Observations of unusually severe structural damage near the tops of hills, slopes, and near the edge of canyons, have been attributed to the effects of topographic amplification in the Aegion 1995 (Bouckovalas et al 1999), Parnitha 1999 (Gazetas et al 2002), Chile 1985 (Celebi 1987) and Whittier Narrows 1987 (Kawase & Aki, 1990) earthquakes.

Field measurements of topographic amplification, from both large magnitude and small magnitude events, provide a quantitative measure of the magnitude of topographic amplification. Typically amplification is measured in terms of acceleration ratios (comparing maximum acceleration) or in terms of spectral ratios (comparing ratio of Fourier spectra) of a point on topography to a free field location. The measured amplification ratios reported in the literature vary widely. In some cases maximum observed ridge base to

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crest amplification ratios were of the order of 2-3, such as in the study by Pedersen et al (1994) at Sourpi, Greece. In other studies very high ratios have been observed, up to 30 in the case of Kagel Mountain and Josephine Peak described by Geli et al (1988) in their review of topographic amplification.

Numerical studies have been carried out to assess the mechanisms, and behaviour of topographic effects, and to allow investigation of parameters affecting topographic amplification. Numerical studies reviewed typically found amplification of horizontal motion and generation of vertical motion to occur at the crest of topography, and attenuation at the base. Studies also observed zones of amplification and attenuation occur both on the topography, and away from the topography, which decrease in magnitude with distance. The magnitude of amplification was typically found to be up to 2.5, with some values up to approximately 5 (Idriss & seed, 1967, Boore 1972, Ohtsuki & Harumi, 1983, Geli et al 1988, Ashford et al 1997, Bouckovalas & Papadimitriou 2005, Nguyen & Gatmiri 2007, Kamalian et al 2008). These values are considerably smaller than the values reported from instrumented case studies, as discussed above. It is suggested that for many studies this may be partly attributed to the way in which values are typically measured. Often the selected free-field reference point is at the toe of a slope of hill, a location where attenuation is found to occur, hence giving overly high amplification values at the crest of topography (Geli et al, 1988).

Other studies have suggested the additional effect of soil layer amplification (due to resonance of seismic waves within a soil layer) as the cause of some of the very high amplification values observed in field measurements (Geli et al 1998, Le Brun et al 1999, Grazier 2009). This increase in amplification has been confirmed by numerical studies (Geli et al, 1988, Ashford et al 1997), where the inclusion of soil layers of differing impedance ratios in the analysis of topography increases the magnitude of the surface motion compared to the homogeneous case.

The geometry of the topography has also been found to have an effect on amplification values. 2D numerical studies typically find that the steeper the topography, the greater the amplification observed (Ashford et al, 1997, Bouckovalas & Papadimitriou 2005, Kamalian et al 2008, Kamalian et al 2006, Nguyen & Gatmiri 2007).

Variation in soil parameters are reported as having a relatively small effect on the amplification of topographic motion, with respect to the free-field motion. For example, variation of soil damping was found to vary the absolute response at the crest, however when normalized by the free field response to have a small effect (Ashford et al 1997, Bouckovalas & Papadimitriou 2005). In addition Kamalian et al (2006 & 2008) showed that changing Poisson's ratio values has small effect on amplification. It should be noted that all the reviewed studies considered elastic soil parameters.

In addition to the nature of the topography itself, studies have found the nature of the incoming wave field to affect the magnitude of amplification values. One of the main parameters is the frequency of the incoming wave field. Numerical studies have shown that when the wavelength (λ) of the input motion is much larger than the dimensions of the topography, there is little topographic effect (Boor, 1972; Geli et al, 1988; Ashford et al, 1997; Bouckovalas and Papadimitriou, 2005; and Kamalian et al 2006 & 2008). The wave type is also reported to affect amplification values. Vertically polarised shear waves (S_v) waves have been found to cause greater amplification than horizontally polarised shear waves (S_h) waves (Ashford et al 1997, Geli et al 1988), and compression (P) waves (Geli et al 1988, Kamalian et al 2008).

A review of the literature identified other parameters affecting topographic amplification, not discussed further as part of this study, particularly:

- Wavefield inclination (Ashford & Sitar, 1994) and orientation (Pedersen et al, 1994)
- 3D nature of topography (Bouchon et al, 1996; Bouchon & Barker, 1996; Grazier, 2009; Nechtshein et al, 1995)

The combination and interaction of these different parameters affecting topographic amplification, contribute to the highly variable nature of topographic effects. Reviewing numerical studies modelling field instrumented topography under earthquake loads, it was observed there was little success in accurately reproducing measured topographic effects.

From a review of seismic codes, only Eurocode 8 (EC8) (British Standards Institution, 2004) was found to give specific recommendations on the magnitude and inclusion of topographic effects in seismic design. EC8 recommends that for important structures, that elastic design spectra should be scaled by a topographic amplification factor, S_T. The code also requires that S_T is included in the determination of the design seismic inertia force (for pseudo static slope stability analysis). EC8 makes no specific discussion of the generation of vertical motions, however as vertical motions are derived as a proportion of horizontal motions, S_T is implicitly incorporated. EC8 requires that the vertical design ground acceleration is 0.45 to 0.9 of the horizontal design ground acceleration, dependent on the size of the expected earthquake.

The code gives the following recommendations for S_T particularly relevant to slopes:

- S_T is applied as a scalar at all frequencies
- S_T is applied for slopes with height greater than 30m, and slope angle greater than 15°
- S_T is ≥ 1.2, and for slope angles greater than 30° S_T is taken as 1.4.
- S_T should be increased by at least 20% where loose surface layers are present

Topographic amplification is considered separately to soil layer effects in EC8. These are accounted for by use of different spectra ordinance points for different soil conditions, generally increasing with decreasing soil shear wave velocity (v_s). The above EC8 recommendations are further discussed later in this paper.

Of the reviewed numerical studies of topographic effects of slopes the majority of parametric studies have investigated topographic effects on their own, by considering the case of a slope in a homogeneous half space. For this study it was decided to investigate the interaction of topographic effects and soil layer effects, identified as a key cause of large amplification ratio values. This was investigated by considering topographic effects of a slope in the presence of soil layer overlying bedrock.

METHODOLOGY

A parametric analysis of the effect of changing dimensionless frequency (slope height (H) / wavelength (λ)), and slope angle on topographic amplification, in combination with soil layer effects, was carried out. A numerical finite element (FE) investigation was carried out of a 2D slope, of angle i, within a soil layer over bedrock (upslope depth to bedrock Z), subject to vertically propagating horizontally polarised shear (S_v) waves. The geometry of the analysis is shown in Figure 1.

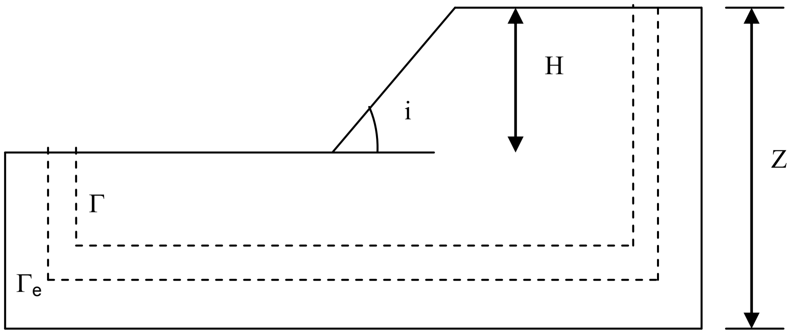

Figure 1: Geometry of analysis and domain reduction boundaries

Topographic effects were assessed by considering the amplification, or attenuation, of accelerations at the ground surface on the crest of a slope relative to the corresponding free field motions. Free-field motions were determined by analysis of a 1D soil column, of the same soil depth to bedrock (Z), and same properties as the main model. To allow a parametric assessment of the effect of dimensionless frequency (H/λ), input motions of a single predominant frequency were considered.

Two different site periods were examined by analysing two meshes with different upslope depths to bedrock (Z), and hence different fundamental soil frequencies. To investigate the effect of varying slope angle, different meshes with differing slope angles were considered.

Model Parameters

The problem geometry and the soil parameters were selected to give a relatively realistic range of input frequencies over the range of H/λ values of interest, and to allow comparison to the previous studies of topographic effects of slopes by Bouckovalas and Papadimitriou (2005) and Ashford et al (1997).

A slope height of 50m was considered, while the width of the model was 1 km. The soil was modelled as a linear elastic material, and Rayleigh damping employed to mimic material damping. The Rayleigh damping parameters were varied for different input frequencies to give the same level of damping for all input frequencies. All other soil parameters are given in Table 1 below.

Table 1. Soil Parameters

v_s, shear wave velocity	500 m/s
ρ, mass density	2.0 Mg/m^3
υ, Poisson's ratio	1/3
K_0, horizontal coefficient of earth pressure	1.0
ξ, damping ratio	5 %

Time Histories Considered

To allow the investigation of differing H/λ values, an artificial input motion was used, with a single predominant frequency. Two different time history types were considered. The first was a sinusoidal time history, of constant amplitude 1, of a sufficiently long duration so that the response approached a steady state. The second time history considered was a short duration wavelet, Chang's motion, presented in Equation 1. This time history was adopted to mimic the build up and decay of a real earthquake motion. By variation of the parameters α, β, and γ, all the motions were adjusted to have a maximum amplitude of 1, with the same number of cycles. A constant number of cycles, and hence varying duration, was adopted to mimic real earthquake motion, where shorter duration motions tend to have higher predominant frequencies.

$$a(t) = \sqrt{\beta e^{-\alpha t} t^{\gamma}} \sin(2\pi/T) \tag{1}$$

Finite Element Methodology

The investigation was carried out with the Imperial College Finite Element Program (ICFEP) (Potts and Zdravkovic, 1999), using 2D dynamic time domain analysis in plane strain.

The domain reduction method (DRM) of Bielak et al (2003) in conjunction with the standard viscous boundaries of Lysmer and Kuhlemeyer (1969) were used as boundary conditions for the analysis. A detailed description of the implementation and benefits of this method are given in Kontoe et al (2009). The domain reduction method is applied in two stages. In the first stage a 1D model corresponding to the crest stratigraphy, with the time history applied as a horizontal acceleration at its base was used to calculate the free field response in terms of effective forces at various depths. In the 2nd stage the forces were applied at corresponding nodes of the 2D slope model, located between the boundaries Γ_e and Γ, indicated on Figure 1. Along the lateral boundaries of the mesh normal and tangential dashpots were applied, and along the base vertical and horizontal displacements were restricted. The dashpots and the domain reduction are combined to prevent reflections from the lateral boundaries, by approximating free-field conditions at the lateral sides of the mesh.

Table 2 presents a summary of the different slope, and time history cases analysed. In the plots presented in this study, the symbol 'ch' is used to represent Chang's time history analyses, and the symbol 'SS' is used to represent steady state sinusoidal time history analyses.

Table 2: Summary of Analyses

Upslope depth to bedrock, Z (m)	**Slope angle, i (degrees)**	**Time history type**	**Predominant H/λ of time history considered**
125	10	Chang	0.05, 0.1, 0.2, 0.3, 0.5, 1
	30	Chang	0.05, 0.1, 0.2, 0.3, 0.5, 1
	45	Chang	0.05, 0.1, 0.2, 0.3, 0.5, 1
	90	Chang	0.01, 0.05, 0.1, 0.2, 0.3, 0.5, 1
		Sinusoidal	0.05, 0.1, 0.2, 0.3, 0.5, 1.0
250	90	Chang	0.01, 0.05, 0.1, 0.2, 0.3, 0.5, 1
		Sinusoidal	0.01, 0.05, 0.1, 0.2, 0.3, 0.5, 1.0

TYPICAL RESULTS

The study identified general trends in topographic effects. Typically the results show that:

- the acceleration response of points on the topography ground surface is modified from the free-field response,
- "parasitic" vertical motion is generated,
- zones of both amplification, and attenuation occur on the topography surface,
- the topographic effect is seen to vary along the ground surface, reducing with distance from the crest of the slope.

These observations are in general agreement with other studies of topographic effects.

The above typical effects can be seen in the results of the analysis of upslope depth of 125m (Z=125m), for a vertical slope (i=90), for steady state time history, with H/λ of 0.2, presented in Figure 2, in terms of maximum steady state horizontal acceleration (a_{hmax}) with horizontal distance along the ground surface (measured from the slope). The plotted accelerations are the absolute maximum acceleration computed at individual points on the ground surface. The maximum horizontal acceleration of the free-field is plotted for comparison. Figure 3 plots the absolute maximum vertical response, the plotted points obtained in the similar manner to the horizontal values. Amplification values (A_{hmax}, A_{vmax}), presented in the next section, are determined by normalising the acceleration response from the 2D model by the maximum horizontal free-field response, obtained from the 1D model. In determining acceleration and amplification values for the sinusoidal time histories the steady state absolute maximum acceleration response is considered.

Topographic effects below the slope have not been considered in detail in this study as the toe is not considered to be modelled accurately. The use of the 1D crest response to generate the input for the second stage 2D analysis means that the free-field response of the toe is not well modelled in the analysis.

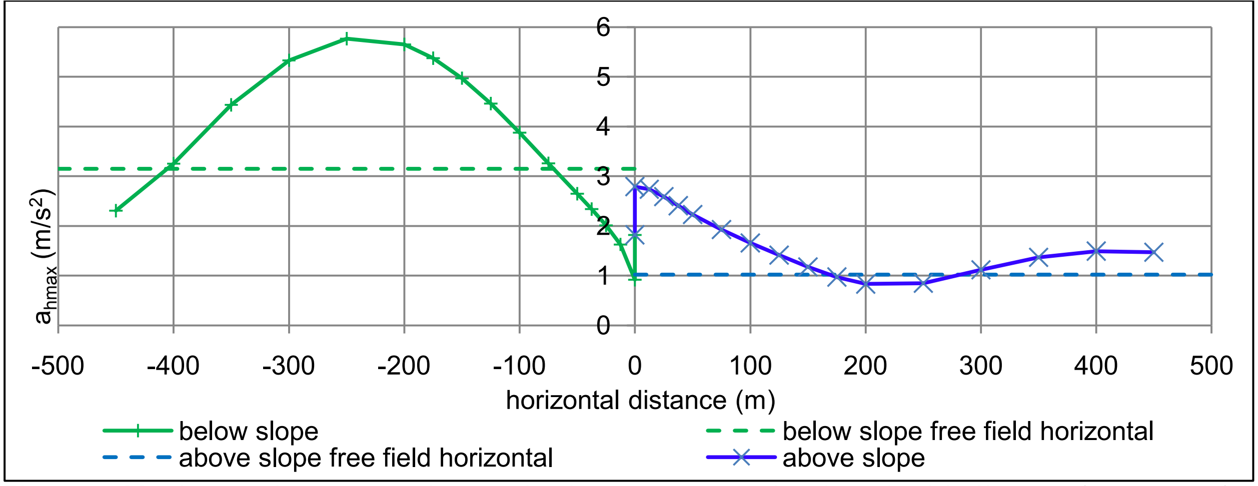

Figure 2. Maximum absolute steady state horizontal acceleration (a_{hmax}) with distance from slope for **Z=125m, i=90˚, H/λ** = 0.2

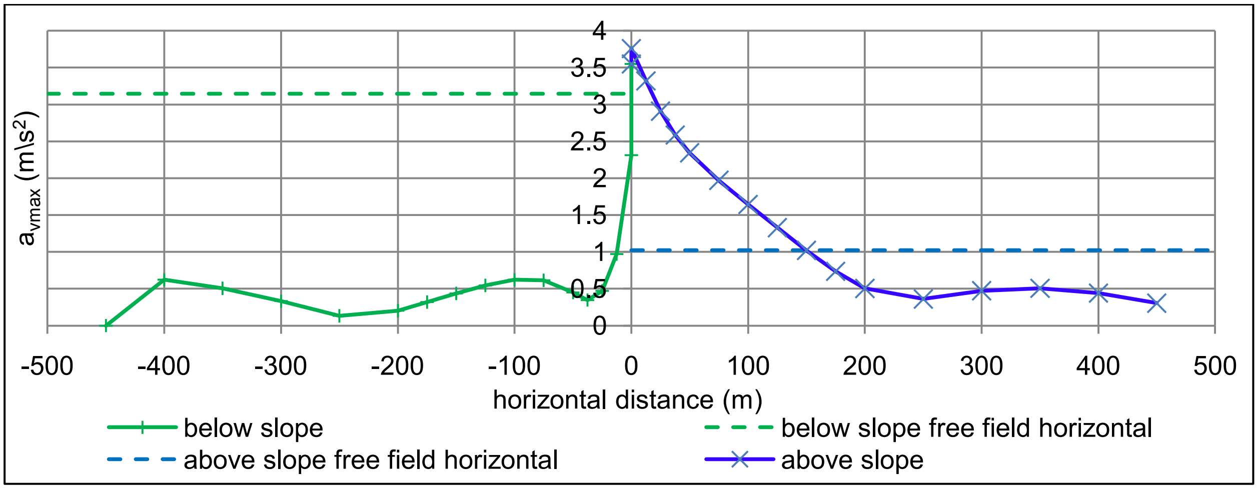

Figure 3. Maximum absolute steady state vertical acceleration (a_{vmax}) with distance from slope for **Z=125m, i=90˚, H/λ** = 0.2

DISCUSSION

Variation with H/λ

Similar to the findings of other studies, topographic amplification was found to vary with H/λ. Figures 4 and 5 plot horizontal and vertical amplification respectively at the crest of the slope (horizontal distance = 0 in Figures 2 & 3) for the different H/λ cases considered. It is seen that at low values of H/λ, where the wavelength is much larger than the slope dimension, there is little topographic effect. This finding is similar to the results of studies of homogeneous slopes subject to single frequency harmonic loading by Ashford et al (1997), and Bouckovalas & Papadimitriou (2005), the results of which are also shown in Figures 4 and 5.

Effect of slope angle

With reducing slope angle the topographic effect was found to reduce. In Figures 4, and 5, it is seen that the amplification generally reduces as the slope angle reduces. This is similar to the results of Bouckovalas and Papadimitriou (2005) and Ashford et al (1997), presented in Figures 4 and 5, and typical of the trend from studies of other topography types, as discussed in the introduction.

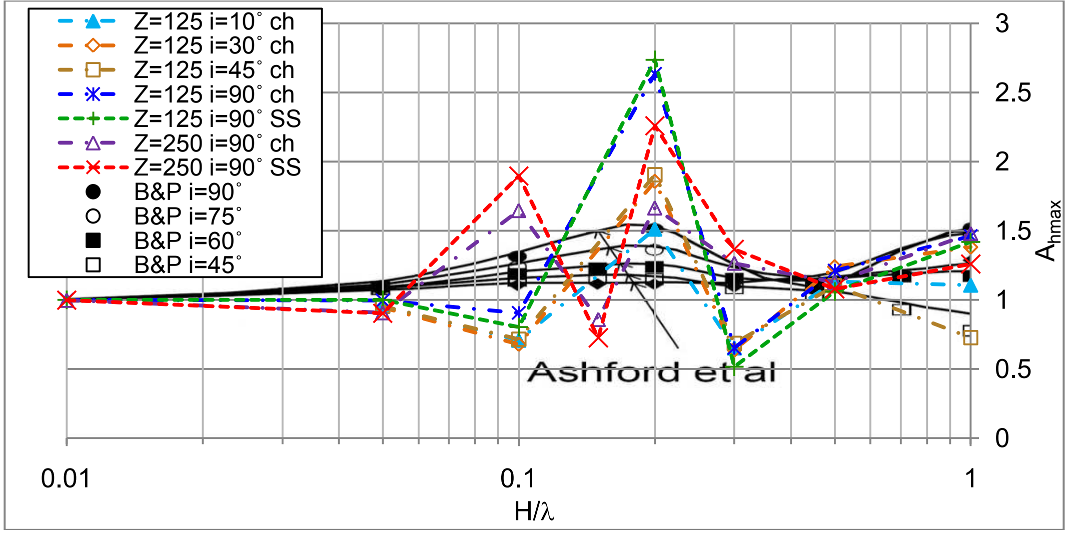

Figure 4. Horizontal amplification (A_{hmax}) at the crest, with results of Ashford et al (1997) and Bouckovalas & Papadimitriou (2005) (B&P) adapted from Bouckovalas & Papadimitriou (2005)

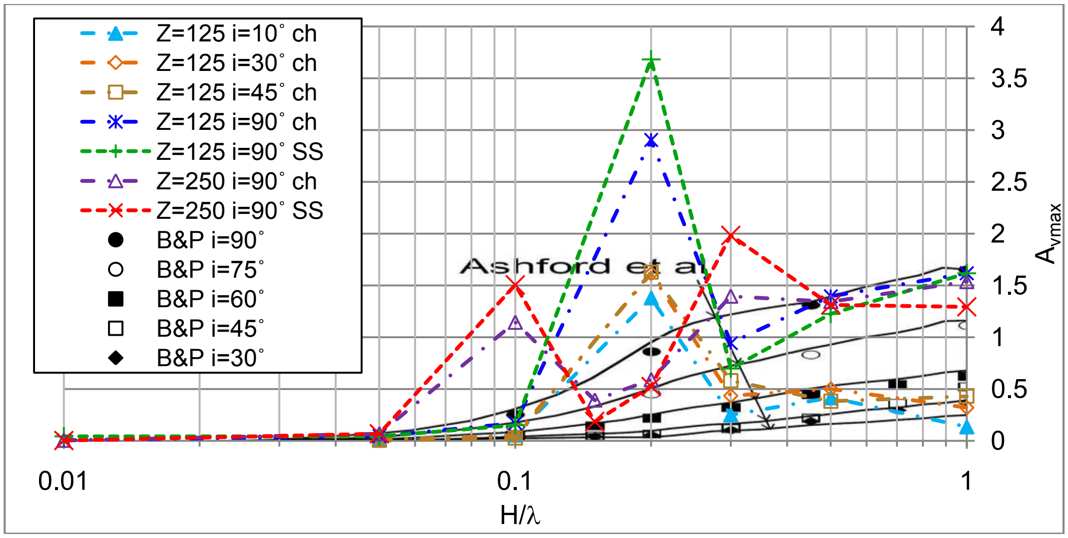

Figure 5. Vertical amplification (A_{vmax}) at the crest, results of Ashford et al (1997) and Bouckovalas & Papadimitriou (B&P) (2005) adapted from Bouckovalas & Papadimitriou (2005)

Effect of motion type

The type of motion made relatively little difference to the trend in behaviour. Both the sinusoidal steady state time history results and the Chang's motion time history results give reasonably similar amplification values, as seen in Figures 4 and 5. Some difference is observed where the short duration of the Chang's motion did not allow the full response to develop.

Interaction of Soil Layer & Topographic Effects

For the examined cases it was found that the amplification due to soil layer effects makes a larger contribution to the total response than topographic effects. This is seen in Figure 6, where the accelerations at the crest of the slope, and the maximum free field acceleration are plotted against H/λ. Here the magnitude of the accelerations due to the effects of topography and soil layer effects are not much larger than the accelerations due to soil layer effects alone. A similar conclusion was reached in the studies by Sitar & Cough (1983) and Ashford et al (1997).

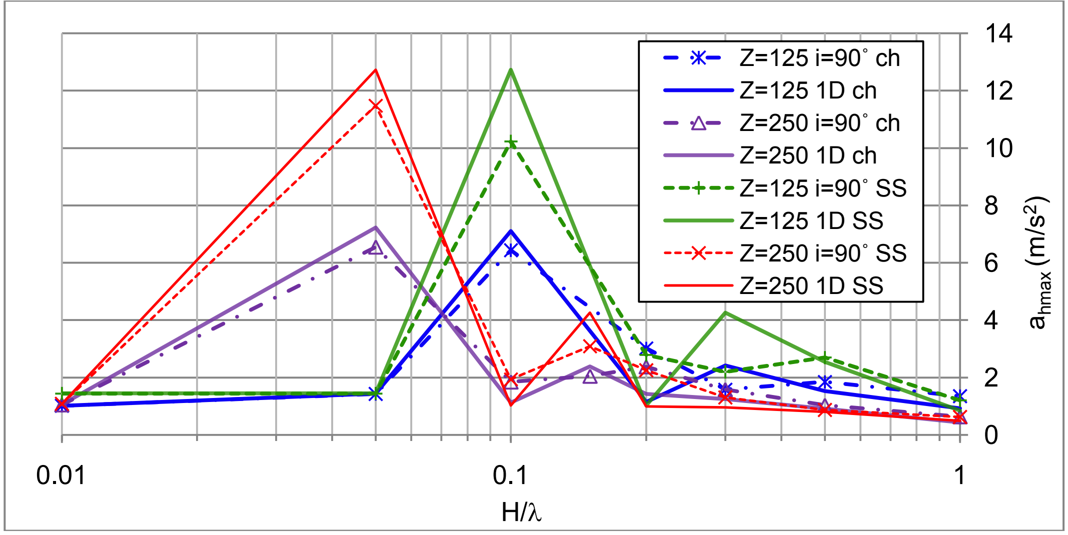

Figure 6. Horizontal acceleration (a_{hmax}) at crest of slope, and free field (1D) accelerations for vertical slopes (i=90)

By comparing the amplification values with H/λ for the two different bedrock depths considered, shown in Figures 7 and 8, it is seen that the pattern of normalised amplification varies between the two cases. This indicates that the soil layer effects affect topographic amplification, even though the soil layer effect is removed by normalising by the free field motion. The effect of soil layers is most evident at the soil layers natural period where attenuation is seen to occur, as indicated in Figures 7 and 8.

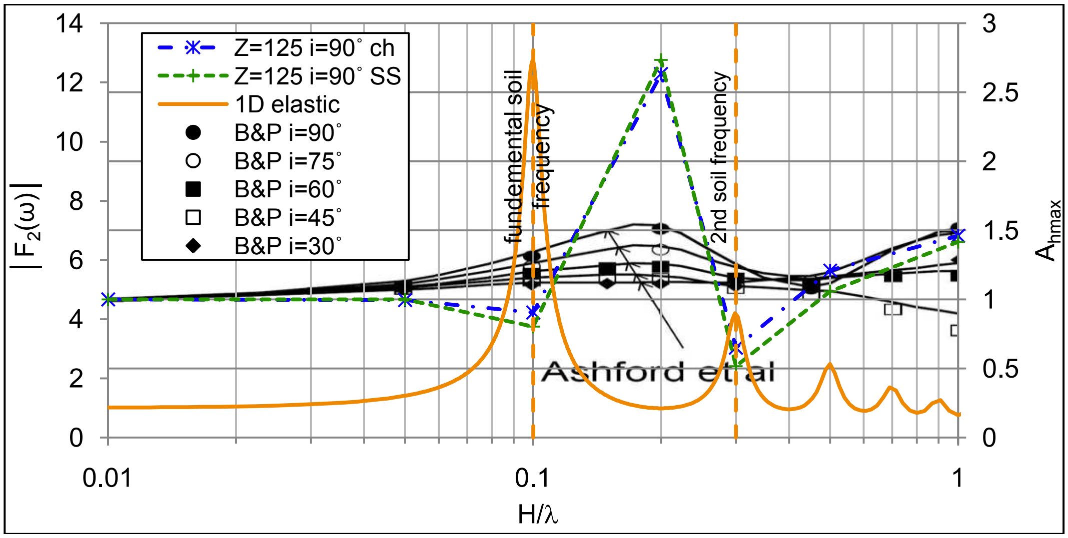

Figure 7: Horizontal amplification (A_{hmax}) at crest of slope and 1D elastic soil layer amplification (left hand scale) for Z = 125 m, with results of Ashford et al (1997) and Bouckovalas & Papadimitriou (2005) adapted from Bouckovalas & Papadimitriou (2005).

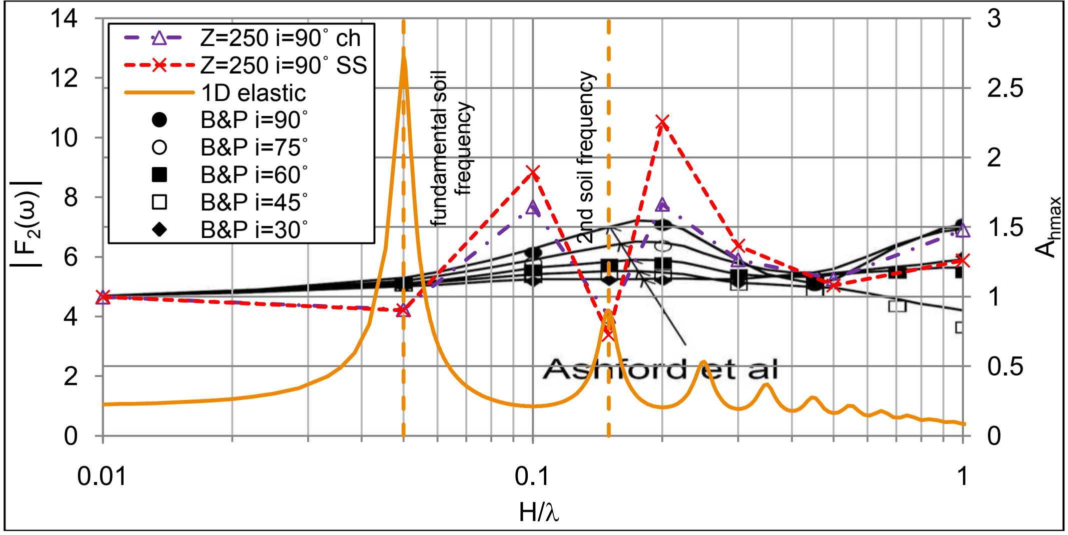

Figure 8: Horizontal amplification (A_{hmax}) at crest of slope and 1D elastic soil layer amplification (left hand scale) for Z = 250 m, with results of Ashford et al (1997) and Bouckovalas & Papadimitriou (2005) adapted from Bouckovalas & Papadimitriou (2005).

Where there is little / no amplification due to soil layer effects, it is seen that topographic amplification is greater for the case of soil layer overlaying bedrock (topographic and soil layer amplification), than for the case of homogeneous half space topographic amplification alone (topographic amplification only). This is seen comparing the amplification from the studies of Bouckovalas and Papadimitriou (2005) and Ashford et al (1997) of homogeneous slopes, with the results of this study, particularly at H/λ of 0.1 for Z=250m and H/λ of 0.2 for Z=125m which are between the natural frequencies of these layers.

This increase in topographic and soil layer amplification over topographic amplification, occurring between the soil layers natural frequencies, only appears to happen across the range of frequencies for which considerable soil layer amplification occurs. Figures 7 & 8 plot the theoretical amplification for an 1D elastic soil layer, as given by Equation 2. It is seen that beyond H/λ ≈ 0.5, as theoretical 1D elastic amplification becomes small, as higher soil layer natural frequencies are reached, topographic and soil layer amplification (seen in the results of this study) and topographic amplification only (seen in the results of Ashford et al and Bouckovalas & Papadimitriou) start to converge.

$$|F_2(\omega)| = \frac{1}{\sqrt{cos^2 kH + sinh^2 \xi kH}} \qquad (2)$$

It should be noted that the above comparisons with the results of Ashford et al (1997) and Bouckovalas and Papadimitriou (2005) are indicative only, as no verification between the FE method used in this analysis and the results of their analyses has been carried out.

As discussed above, the presence of a soil layer complicates the topographic response compared to the case of a homogeneous half space. The complicated interaction between the two effects suggests that they should not be treated independently. This is in contrast to the conclusions of the study by Ashford et al (1997), where they determined that the two effects could be handled separately.

Comparison to EC8 recommendations.

This study found that topographic amplification varies with H/λ, and hence with input frequency. Therefore the EC8 recommendation that the S_T should be applied as a scalar across all frequencies is not considered accurate. Also, as discussed above, it has been found that topographic effects and soil layer effects are not independent, and that the two effects interact. Hence the application of topographic amplification separately to soil layer effects is similarly not considered accurate. The interaction of the two effects, and the highly variable amplifications do not give a clear slope height and slope angle criteria for when topographic effects should be considered, from the cases considered in this study.

However, if the general trend in topographic amplification is considered, ignoring the attenuation values obtained at the soils natural frequency and low amplifications obtained at low H/λ values ($H/\lambda=0.05$), the magnitude of topographic amplification seen in this study can be compared against the values recommended in EC8. As this study investigated ground surface accelerations, with no analysis of acceleration response spectra, comparison can only be made for the peak ground acceleration, which is also used in determining the seismic inertia force in pseudo static seismic slope stability analysis.

From the results of the analysis for the Chang's motion, it was found that the average horizontal amplification for slopes >30° was 1.50 (ranging from 0.73 to 2.63), and for slopes ≤ 30° the average was 1.37 (ranging from 1.11 to 1.86). These values suggest that the EC8 S_T values are of the right magnitude for scaling horizontal ground accelerations, for slopes with the additional presence of soil layer effects. For vertical amplification, for slopes >30° the average was 1.30 (ranging from 0.38 to 2.90), and for slopes ≤ 30° the average was 0.73 (ranging from 0.13 to 1.61). These values give ratios of vertical amplification to horizontal amplification of 0.87 for slopes > 30˚, and 0.58 for slopes ≤ 30˚. This suggests that the values for determining vertical design ground accelerations from horizontal design ground accelerations given in EC8 would give vertical design ground accelerations of an appropriate magnitude. The additional increase for a 'loose surface layer' has not been considered in this comparison as it is interpreted as not being applicable for the case of a slope in a deep soil layer. Further investigation is required to assess the EC8 recommended S_T values for scaling the elastic response spectra.

Although the EC8 criteria result in vertical accelerations of an appropriate magnitude, it is considered vertical accelerations generated by topographic effects are not effectively addressed in the code. Also it is considered EC8 does not give clear guidance on the area over which topographic effects should be considered. Further discussion of these shortcomings of the code recommendations, and discussion of topographic amplification criteria for the homogeneous slopes can be found in Bouckovalas and Papadimitriou (2005).

CONCLUSION

This study examined topographic seismic amplification phenomena related to the case of a slope formed within a soil layer of set thickness. Parametric analyses were carried out for two different motions, two soil layer depths and for various slope angles. The nature of topographic amplification in the presence of soil layer effects and the interaction of topographic effects and soil layer effects was investigated in particular.

The parametric analysis showed a number of topographic effects that are in agreement with previous studies. In particular it was shown that:

- the acceleration response of points on the surface of topography is modified from the free-field response,
- "parasitic" vertical motion is generated,
- zones of both amplification and attenuation occur on the topography surface,
- the topographic effect is seen to vary along the ground surface reducing with distance from the crest of the slope.

Examining the acceleration response in the presence of both topographic effects and soil layer effects, it has been found that the contribution from the soil layer effects is greater than the component due to topographic amplification. Comparing the actual magnitude of the response at the crest of the slope in the presence of both topographic and soil layer effects, to the magnitude of the free-field motion, it is seen that the additional effect of topography is relatively small.

It has been observed that there is a complex interaction between soil layer effects and topographic effects which leads to highly variable topographic amplification values. Variation of the soil layers' natural frequency causes differences in topographic amplification with H/λ, in some cases resulting in attenuation occurring at the crest of the slope. The interaction of topography and soil layering, suggests that these two effects cannot be separated and considered independently.

By comparison to the previous studies of Ashford et al (1997) and Bouckovalas and Papadimitriou (2005) where no soil layer effects were considered, it is seen that topographic amplification is greater for the case of slopes formed within a soil layer of set thickness than for the case of slopes in a homogeneous half-space. The results show that this occurs only for frequencies in between the natural soil layer frequencies, as for the latter the soil layer amplification is dominant. Outside of the range of frequencies for which considerable soil layer amplification occurs, this increase in topographic amplification is seen to reduce, with topographic amplification in the presence of a soil layer approaching topographic amplification of the homogeneous case.

Assessment of the EC8 recommendations for topographic amplification, based on the results of this study, suggests that the adoption of a single scalar value for all frequencies is not accurate, due to the complexities of the interaction between soil layer and topographic effects. Similarly the simplified slope height and slope angle criteria do not give accurate guidance for when to allow for topographic effects. However the values of the topographic factor, S_T, given in the code are of a suitable magnitude, based on the cases considered in this study for scaling ground accelerations.

It should be noted that this study considered a very simplified case. A number of studies have shown that topographic amplification is affected by many other factors, particularly wave field properties, and the 3D geometry of the topography, which were not considered in this paper. These factors cause real topographic effects to be much more complicated and variable than the simplified cases considered here.

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