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# TOPOGRAPHIC EFFECTS IN A CENTRIFUGE MODEL EXPERIMENT

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## ABSTRACT

It is widely recognized that the amplitude and frequency content of strong ground motion can vary across slopes, ridges, and canyons. This phenomenon, known as topographic effects, may result in damage concentrations near the crests of slopes. This article discusses topographic effects observed during a centrifuge model test of an embankment and compares these with the findings of numerical studies by others. The centrifuge model was intended to simulate a 10.5 m high prototype sand embankment ($D_r$ =50%) overlying a 4.5 m foundation layer consisting of dense sand ($D_r$ =80%). The side slopes of the model were inclined at 30 degrees (left slope) and 25 degrees (right slope), and both the embankment and the foundation layer were unsaturated. Overall dynamic response of the embankment was largely governed by site effects, particularly at its resonate frequency of approximately 5.5 Hz. Topographic effects playing a much less significant role; nevertheless, significant amplification did occur at normalized frequencies (slope height/wavelength) of approximately 0.2 to 0.4. In general, there was significant spatial variation in the amplitude and frequency content across the embankment. Topographic effects were most pronounced for the tests involving low amplitude input motions.

Keywords: Topographic amplification, site effects, centrifuge model

## INTRODUCTION

It is widely recognized that the amplitude and frequency content of strong ground motion can vary across slopes, ridges, and canyons. This phenomenon, known as topographic effects, can result in damage concentrations near the crests of slopes [e.g. Hartzell at al. (1994), Pedersen et al. (1994), Shakal et al. (1988, 1994), and Spudich et. al. (1996)]. There are relatively few field recordings of this phenomena, and as such, researchers have traditionally relied upon numerical simulation techniques such as finite element and finite difference analyses to study topographic effects [e.g. Sitar and Clough (1983), Ashford and Sitar (1994, 1997), Ashford et. al. (1997), Gazetas (2001), Assimaki et al. (2004), Assimaki and Gazetas (2004), Bouckovalas and Papadimitriou (2004, 2005)]. However, an alternative simulation technique, centrifuge physical modeling, is a powerful and largely overlooked approach for studying the influence of topography on ground motion. This article discusses topographic effects observed during a centrifuge model test of an embankment and compares these with the findings of numerical studies by others.

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## PREVIOUS STUDIES

Most previous studies of topographic amplification have utilized numerical simulations to quantify the spatial variation in strong ground motion amplitude and frequency content across slopes and ridges [e.g. Bouckovalas and Papadimitriou (2004, 2005), Assimaki et al. (2004), Assimaki and Gazetas (2004), Gazetas (2001), Ashford and Sitar (1997), Ashford et. al. (1997)]. Ashford et al. (1997) performed a frequency-domain parametric study using generalized consistent transmitting boundaries to evaluate the significance of topographic effects on the seismic response of slopes inclined between 30 and 90 degrees. The results showed that the peak amplification of motion at the crest of a slope occurs at a normalized frequency $H/\lambda = 0.2$, where $H$ is the slope height and $\lambda$ is the wavelength of the motion. They suggested that at low values of $H/\lambda$ , topography has little effect on overall response. Ashford et al. (1997) also considered the relative importance of slope inclination and concluded that topographic effects were more pronounced for slopes in excess of 60 degrees.

Gazetas (2001) performed one- and two-dimensional wave propagation analysis for the Ano Lisa and Adames sites during 1999 Athens earthquake. He proposed a new measure of topographic amplification in frequency domain and termed it "topographic aggravation factor (TAF)," defined as the ratio of the Fourier amplitude spectra at the slope crest to that at the free field ground surface. The study showed that the TAF spectrum largely depend on the spectral content of the excitation. Asimaki and Gazetas (2004) performed two-dimensional finite element and spectral-element analyses for various input motions. They found that nature and direction of waves, slope inclination and frequency of excitation all affect the topographic amplification of ground motion.

Several recent studies have used physical modeling to investigate topographic effects. Madbushi et al. (2002) carried out centrifuge tests to investigate the seismic stability of the steep slopes of granular soil. Acceleration-time histories recorded within the slope showed significant apparent acceleration amplification (from combined site and topographic effects) of the base motion. Similarly, Yu and Lee (2002) conducted centrifuge model studies to investigate topographic amplification in soft ground. The models were comprised of Singapore marine clay, a kaolin-rich soft clay with small shell fragments. Their study concluded that for a given soft clay thickness, the amplification of earthquake shaking decreases with increasing earthquake intensity. Both of these physical model studies indicated that overall amplification of ground motion decreases with earthquake intensity.

## CENTRIFUGE EXPERIMENT

### Model

The centrifuge test was performed as part of a larger study that examined the seismic stability of embankments and slopes (Nasim 2005). The centrifuge model was intended to simulate a 10.5 m high prototype sand embankment ($D_r$=50%) overlying a 4.5 m foundation layer consisting of dense sand ($D_r$=80%). The side slopes of the model were inclined at 30 degrees (left slope) and 25 degrees (right slope), and both the embankment and the foundation layer were unsaturated. Dimensions and properties of the model are reported at the prototype scale in the remaining of this article. Figure 1 shows a cross section of the centrifuge model along with the instrumentation (accelerometers) referenced in this article (the locations of other non-referenced instrumentation, which included displacement transducers and accelerometers, are omitted from the figure for clarity). The model was constructed using Nevada sand No.120, a rounded to sub-rounded fine sand. Data pertaining to the monotonic and cyclic response characteristics of this soil is provided by Arulmoli et al (1992). The specific gravity of the sand was 2.68, while its maximum and minimum void ratios were $e_{\max}$=0.894 and $e_{\min}$=0.516, respectively.

The experiments were conducted at Rensselaer Polytechnic Institute (RPI), located in Troy, New York, USA. The RPI geotechnical centrifuge is a model Acutronic 665-1 device with 3-m radius and

150-g ton capacity. An electro hydrodynamic shaker installed on the centrifuge platform produces in-flight earthquake shaking at the base of the soil. The nominal operating frequency range is 20 Hz to 600 Hz with the maximum stroke (i.e. peak-to-peak displacement of the slip-table) of 3.2 cm. The model was built in a rigid-wall model container with inner dimensions of 0.88 m (length), 0.37 m (width), and 0.36 m (height). A transparent side window allowed the model to be observed during testing using an in-flight video recording system. Sand paper was affixed to the inner base surface of the container to provide a high degree of interface friction between the box and the soil base.

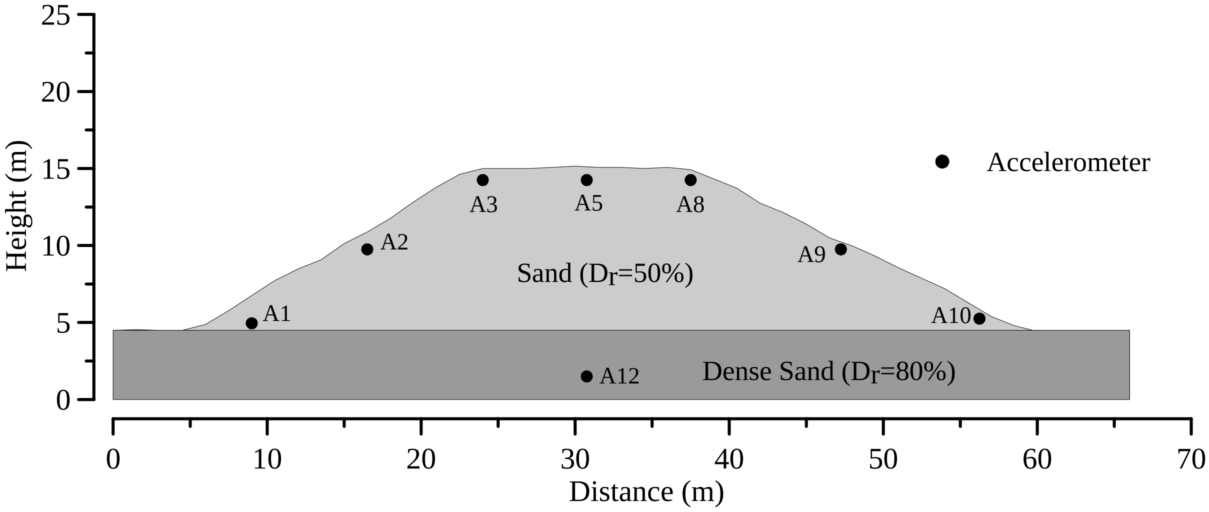


**Figure 1. Centrifuge model geometry and instrumentation plan in prototype scale**

The model was subjected to a suite of ground motions including both synthetic (0.4-4 Hz range frequency sweeps) and a recorded earthquake motion scaled to different amplitudes. The ground motion was recorded at the Redwood City ground motion station during the 1989 Loma Prieta earthquake. The model was subjected to 14 motions of progressively increasing amplitude. Table 1 summarizes the ground motions used in the centrifuge test series.

**Table 1. Details of ground motions used in the centrifuge test**

| No | Motion Type | Amplitude (g) | Predominant Frequency (Hz) | Arias Intensity $I_a$ (m/sec) | Significant Duration[2] $D_{5\text{-}95}$ (sec) | Mean Frequency[1] (Hz) |
|---|---|---|---|---|---|---|
| 1 | Sine sweep | 0.017 | 0.4 - 4 | 0.009 | 22.02 | 1.99 |
| 2 | Sine sweep | 0.004 | 0.4 - 4 | 0.001 | 43.80 | 2.66 |
| 3 | Sine sweep | 0.058 | 0.4 - 4 | 0.120 | 17.60 | 1.98 |
| 4 | Redwood City | 0.096 | 1.27 | 0.281 | 14.775 | 1.15 |
| 5 | Redwood City | 0.213 | 1.27 | 1.869 | 26.85 | 1.568 |
| 6 | Redwood City | 0.246 | 1.27 | 2.586 | 27.45 | 2.05 |
| 7 | Sine sweep | 0.287 | 0.4 - 4 | 3.458 | 21.70 | 6.00 |
| 8 | Sine sweep | 0.375 | 0.4 - 4 | 3.986 | 21.65 | 7.01 |
| 9 | Sine sweep | 0.375 | 0.4 - 4 | 3.986 | 21.65 | 7.01 |
| 10 | Sine sweep | 0.441 | 0.4 - 4 | 4.35 | 21.52 | 7.57 |
| 11 | Redwood City | 0.279 | 1.27 | 3.316 | 28.47 | 2.95 |
| 12 | Redwood City | 0.261 | 1.27 | 3.232 | 28.07 | 2.62 |
| 13 | Redwood City | 0.425 | 1.27 | 3.790 | 28.60 | 3.70 |
| 14 | Redwood City | 0.366 | 1.27 | 4.051 | 28.85 | 3.96 |

Notes:

1. Mean frequency was calculated after Rathje et al. (1998)
2. Significant duration was calculated after Trifunac and Brady (1975)

## RESULTS

Although it was subjected to a series of moderate to high intensity earthquakes, the model experienced relatively little permanent deformation during the test series (Nasim 2005). The limited deformation that occurred resulted from densification of the sand rather then shearing.

Accelerations were recorded at a 3000 Hz sampling frequency during the tests. The acceleration time histories recorded during input motions were baseline corrected using a $4^{th}$ order Butterworth filter with a corner frequency of 0.075 Hz.

Near-surface ground motions were compared in the frequency domain using a scheme similar to that developed by Ashford and Sitar (2002) to study amplification of peak ground acceleration. Specifically, three types of amplifications were defined:

*"Topographic amplification,"* defined as the amplification of the free-field motion at the crest:

$$A_t(p) = \frac{Sa(p)_{crest} - Sa(p)_{emb}}{Sa(p)_{emb}} \tag{1}$$

*"Site amplification,"* defined as the amplification of the soil column at the middle location of the model relative to that at the base of the model:

$$A_s(p) = \frac{Sa(p)_{emb} - Sa(p)_{base}}{Sa(p)_{base}} \tag{2}$$

*"Apparent amplification,"* defined as the amplification of the motion between the base and the crest of the model:

$$A_a(p) = \frac{Sa(p)_{crest} - Sa(p)_{base}}{Sa(p)_{base}} \tag{3}$$

In these equations:

$Sa(p)_{emb}$ = Acceleration response spectra ordinate for accelerometer located at the midpoint of the upper part of the embankment (similar is some respects to the "free field" used in Ashford and Sitar's (2002) amplification definition) [corresponds to accelerometer A5 in the model]

$Sa(p)_{crest}$ = Acceleration response spectra ordinate for accelerometer located at the slope crest [corresponds to accelerometer A3 or A8 in the model]

$Sa(p)_{base}$ = Acceleration response spectra ordinate for base motion [corresponds to accelerometer A12 in the model]

Treating topographic and site amplification separately allows estimation of their individual contributions to total ground motion amplifications (Ashford and Sitar, 2002) In the absence of true, one-dimensional "free field" recordings, the motion recorded at the middle top portion of the embankment (A5) was used for this purpose in the equations above. It is important to recognize that although taken as a field free recording, the recording at A5 will included some effects of the embankment geometry.

The following section considers the dynamic response of the model during a single test, after which trends in the larger database of tests is discussed.

**Observed amplifications during Test 1**

Test 1 involved a low amplitude sine sweep input motion (Table 1) that did not cause any measurable permanent deformation of the model. Figure 2 shows contours for peak horizontal ground acceleration (PGA) developed from a dense accelerometer array located within the model. The peak ground acceleration at the crest of 30 degree (left) slope and middle of the embankment was approximately 0.04g, while the PGA at the crest of the 25 degree (right) slope was a slightly lower 0.035g. The figure shows that PGA values at crest of 30 degree slope and the middle top of the model are almost equal and thus indicating that there is virtually no topographic amplification of this parameter.

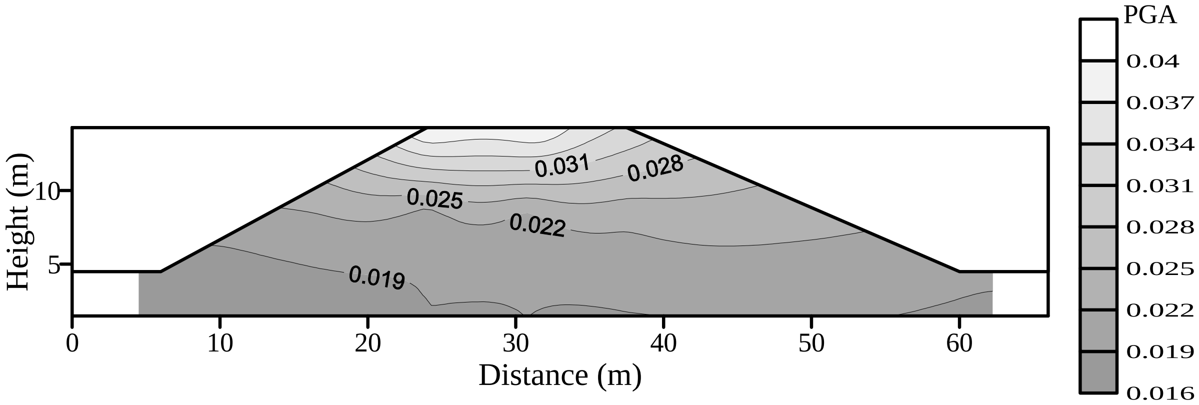


**Figure 2. Peak ground acceleration (PGA) contours during first test motion (sine sweep 0.4 - 4 Hz) with amplitude of 0.017g**

Figure 3 presents the acceleration response spectra for each of the surface accelerometers. Figure 3 shows that the accelerometers along the top of the embankment top (A3, A5 and A8) have relatively high spectral accelerations, the largest being A3 located at the crest of 30 degree slope. The higher response at this location, the steeper of the two slopes, is a consequence of surface topography. Figure 3 also shows that the response spectra of motions recorded along the 30 and 25 degree slopes progressively increase with elevation. Also note the high degree of spatial variation in the frequency characteristics of the motion across the model. Accelerometers at the crest (A3 and A8) show a peak response at 4.5 Hz as compared with 6.0 Hz along the top middle of the embankment (i.e. A5).

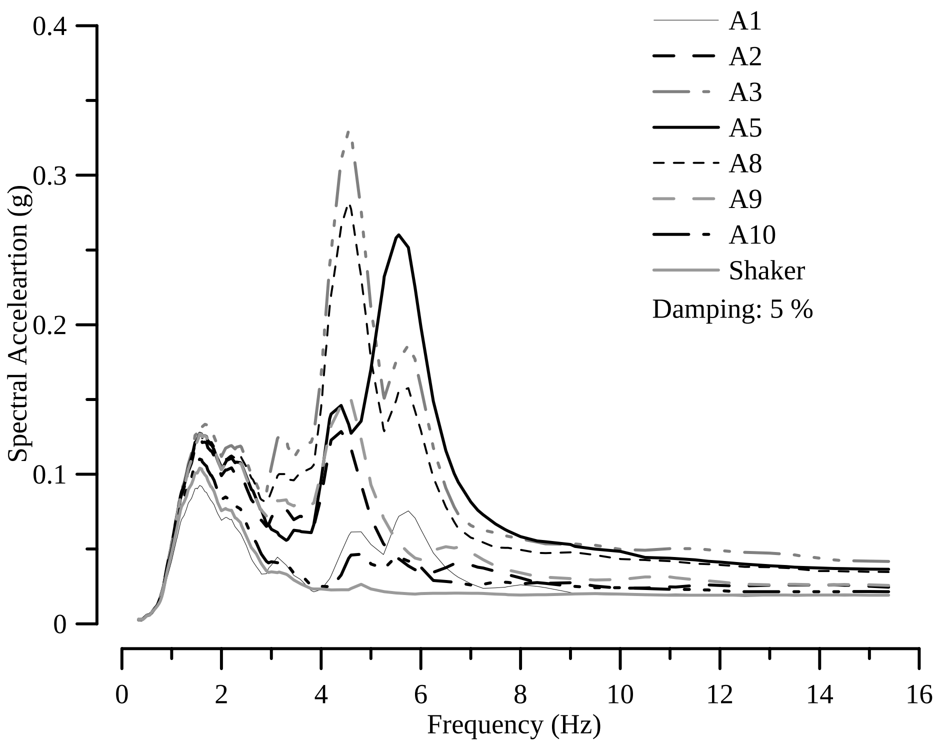


**Figure 3. Spectral accelerations of surface accelerometers during input motion 1**

Figure 4 presents the calculated apparent, site and topographic amplifications as defined by Equations 1 through 3 for both side slopes The results are presented as a function of frequency (at the prototype scale) and normalized frequency, defined as slope height/wavelength.  This is comparable to the normalized frequency scale used in previous studies of topographic amplification by Ashford et. al. (1997).  Overall, it is clear that overall response of the embankment is largely governed by its site effects, with topographic effects playing a much less significant role.  Peak response in the middle-top portion (A5) of the embankment occurs at about 5.5 Hz., which corresponds to the natural frequency of the embankment (Nasim 2005).  Topographic effects are shown to be significant over normalized frequencies in the range of 0.2 to 0.4. This corroborates well with the Ashford et. al. (1997) who found that peak topographic response occurs at a normalized frequency of 0.2.  Finally, note that topographic effects are slightly more pronounced for the steeper for the two slopes.

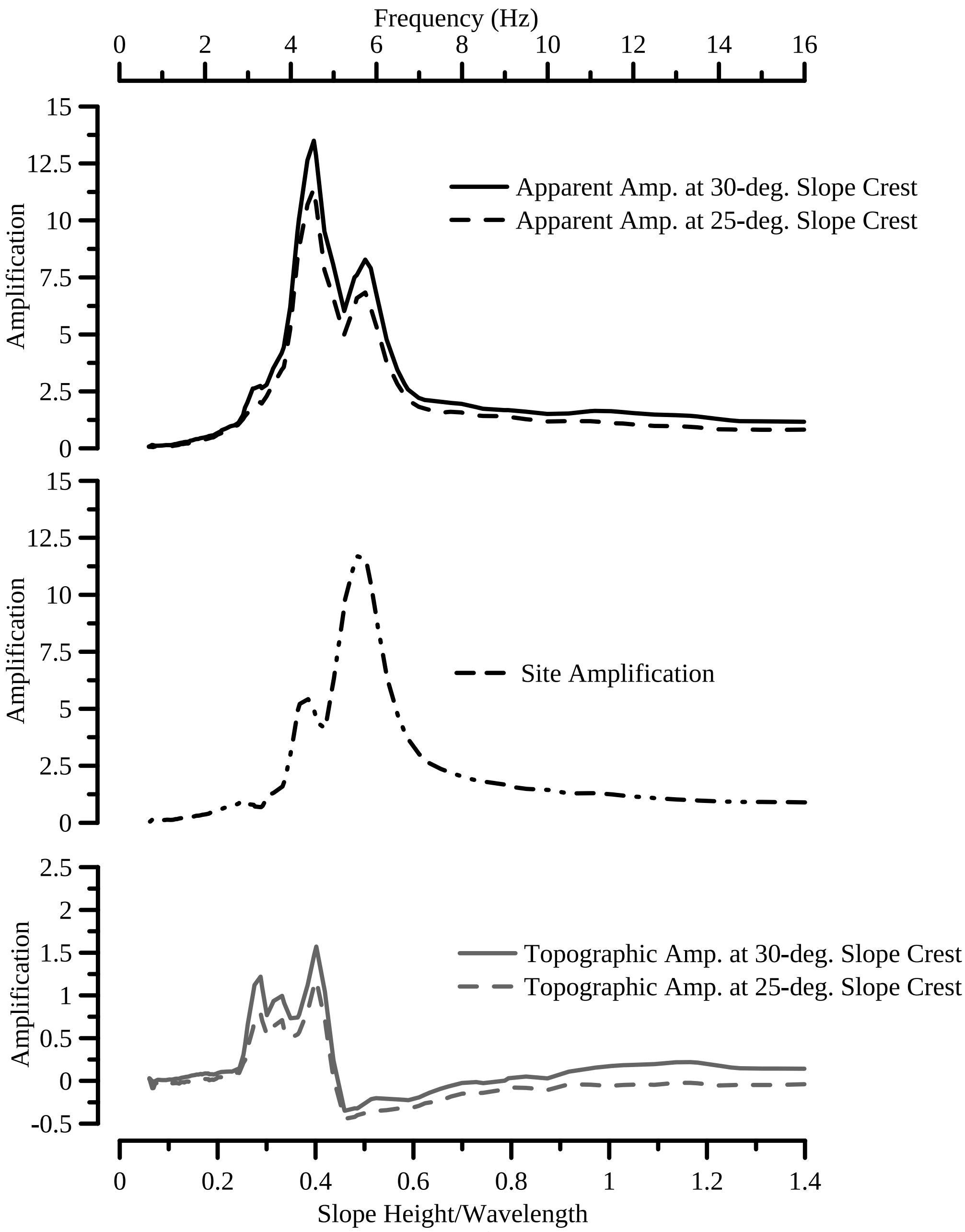


**Figure 4. Observed amplifications during 1st input motion on 30 and 25 degree slopes of centrifuge model (Amplifications were based on Eq. 1-3)**

**Topographic amplification during over full test series**

It is interesting to consider topographic amplification over the full test series, which consisted of input motions having different amplitude and frequency characteristics (Table 1).  For brevity, only the steeper of the two slopes (30 degrees) will be discussed, though it is noted that similar trends were found for both slopes.

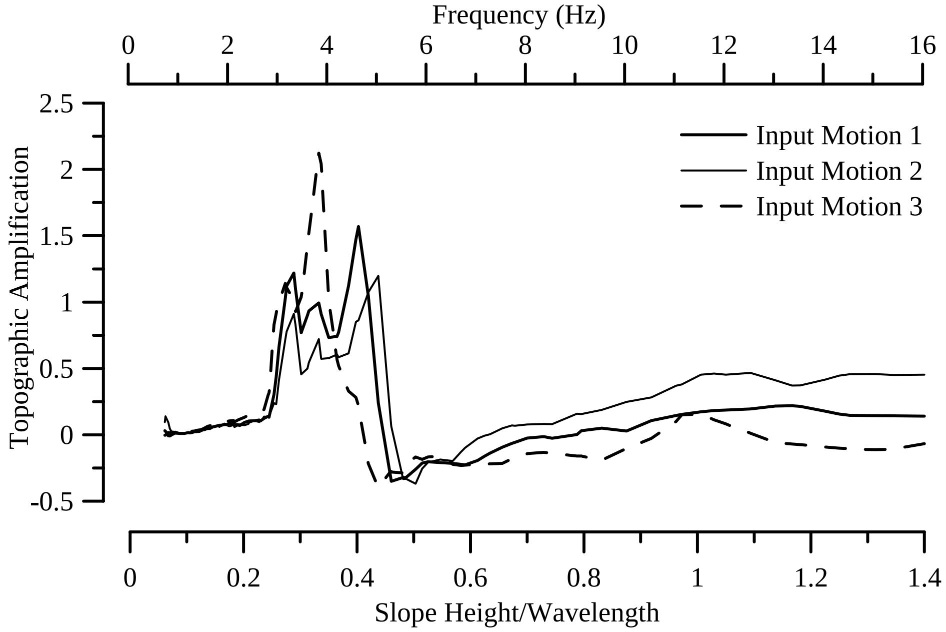


**Figure 5. Observed topographic amplifications during input motions 1-3 on 30 degree slope (at accelerometer A3) of centrifuge model (Amplifications were based on Eq. 1-3)**

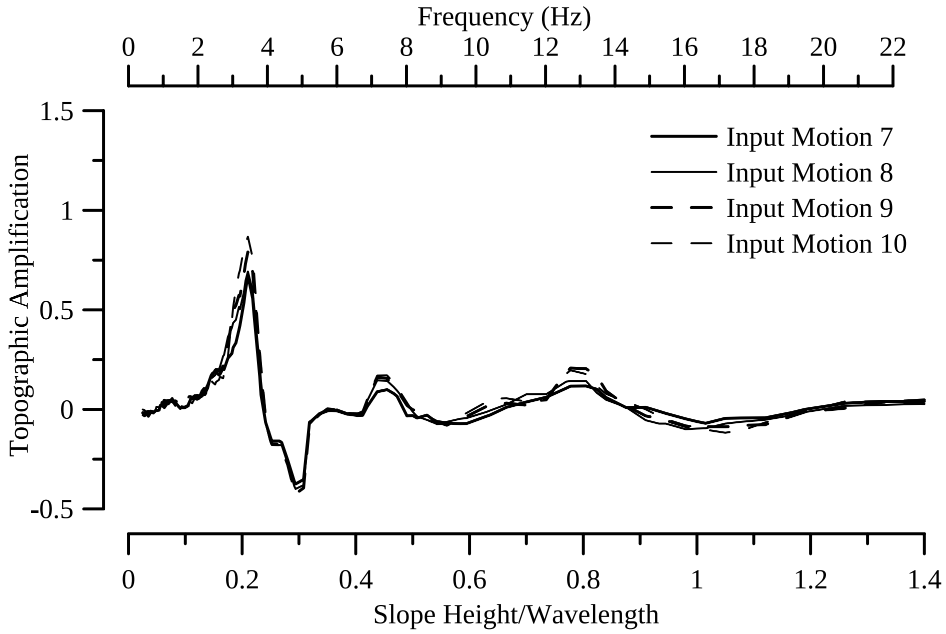


**Figure 6. Observed topographic amplifications during input motions 7-10 on 30 degree slope (at accelerometer A3) of centrifuge model (Amplifications were based on Eq. 1-3)**

Figure 5 and 6 presents topographic amplification during the low (input PGA < 0.02g) and high amplitude (input 0.025g < PGA < 0.45 g) sine sweep input motions, respectively. The frequency sweep motions consisted of a four second ramping windows at the beginning and at the end of the full amplitude motion. The input frequency linearly increased from 0.4 to 4 Hz during the 30 second duration of the motions. Comparing these figures, two observations can be made: (1) topographic amplification is significant in the normalized frequency range of 0.25–0.40 for the low amplitude motion (Fig. 5), and at a normalized frequency of 0.2 for the larger amplitude input motion [Fig. 6], (2) comparatively more topographic amplification occurs for the low versus the high amplitude test motions. Also note in these figures that de-amplification occurs at a normalized frequencies in the range of 0.3 to 0.45, which corresponds to the approximate fundamental frequency of the embankment.

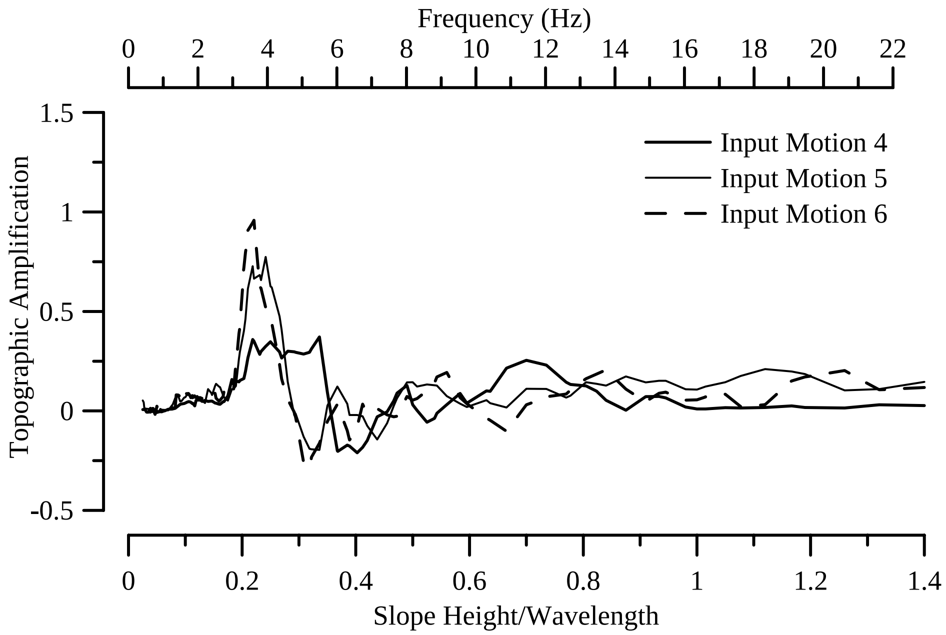


**Figure 7. Observed topographic amplifications during input motions 4-6 on 30 degree slope (at accelerometer A3) of centrifuge model (Amplifications were based on Eq. 1-3)**

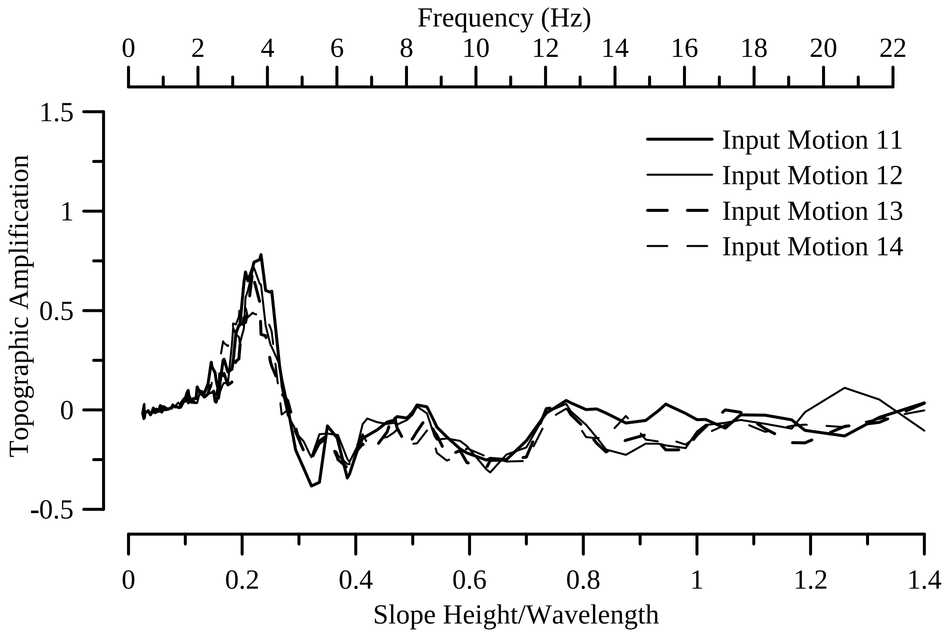


**Figure 8. Observed topographic amplifications during input motions 11-14 on 30 degree slope (at accelerometer A3) of centrifuge model (Amplifications were based on Eq. 1-3)**

Figure 7 and 8 show topographic amplification during the tests conducted using the Loma Prieta input motions. Figure 7 corresponds to the low amplitude motions (input PGA = 0.10 g to 0.25 g), or input motions 4-6, while Figure 8 shows the high amplitude motions (input PGA = 0.28 g to 0.42 g), or input motions 11-14. The results show remarkable consistency in the peak topographic normalized frequency (0.2) regardless of the input motion amplitude. The levels of amplification mirror the results shown in Figures 5 and 6, with higher amplitude input motions yielding lower degrees of topographic amplification.

## DISCUSSION AND CONCLUSIONS

Figure 9 summarizes topographic amplification for all motions over the full test series. Peak topographic response ranges over normalized frequencies of 0.2 to 0.4, while peak response is largely centered at approximately 0.2 for the larger amplitude test motions. It is important to note that soil non-linearity effects become significant for the large amplitude motions, and hence, the offset in peak frequency response between the high and low amplitude tests may be the result of frequency normalization based on low strain modulus properties of the soil. If lower, strain-compatible shear wave velocities were adopted, the peak frequency would shift to a slightly higher normalized frequency. Nevertheless, the relative consistency in the frequency content of the peak topographic response is remarkable. Moreover, it provides support for the work of Ashford et. al. (1997), which found that peak topographic response occurs at a normalized frequency of 0.2. The results also mirror generally similar trends noted by Stewart (2005) for a full scale cut slope. The reduction in topographic amplification that occurs a normalized frequency of approximately 0.45 coincides with the embankment's fundamental frequency and is therefore a likely consequence of site rather topographic effects, though it is worth noting that Ashford et al. (1997) show some minor topographic de-amplification at this normalized frequency.

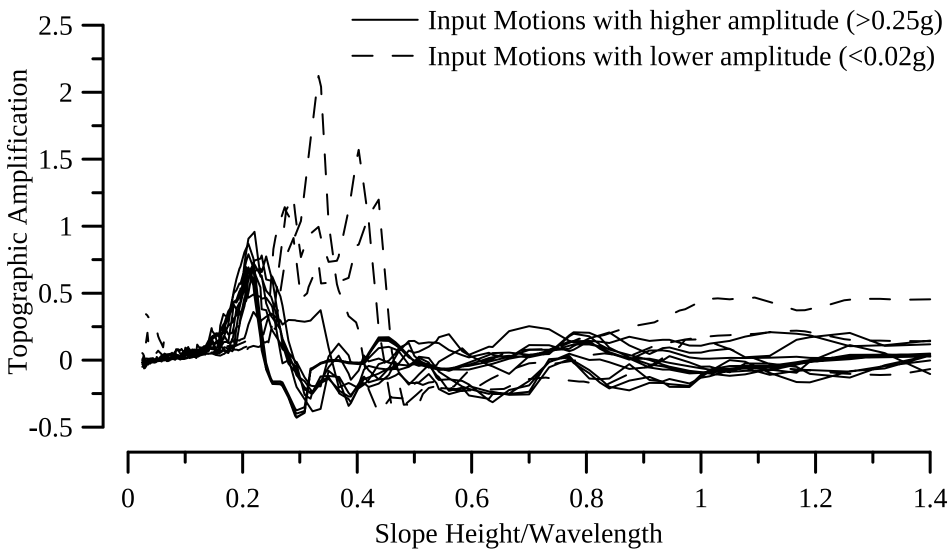


**Figure 9. Observed topographic amplifications during full series of input motions (at accelerometer A3) of centrifuge model (Amplifications were based on Eq. 1-3)**

Overall dynamic response of the embankment was largely governed by site effects, particularly at its resonate frequency of approximately 5.5 Hz. Topographic effects playing a much less significant role; nevertheless, significant amplification did occur at normalized frequencies of approximately 0.2 to 0.4. In general, there was significant spatial variation in the amplitude and frequency content across the embankment. Topographic effects were most pronounced for the tests involving low amplitude input motions. Finally, this article demonstrates the viability of using physical modeling to study site and topographic effects in earth structures and systems.

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