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# TOPOGRAPHIC AMPLIFICATION OF GROUND MOTIONS: A CASE STUDY OF HONG KONG

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## BRIEF INRODUCTION

Amplification of seismic waves due to surface topography and subsurface soils has often been observed to cause intensive damage in past earthquakes. Due to its complexity, topography amplification has not yet been considered in most seismic design codes, with a few exceptions such as the Eurocode 8. Using a simplified classification of ridge geometry and slope angle, EU8 prescribes a topographic amplification factor which is frequency-independent and limited to a maximum increase of 40%. On the other hand, significantly larger topography amplification in order of 10 to 20 has been observed through instrumented data. As is against EU8, the topography amplification is also found to be frequency-dependent (Burjanek *et al.* 2014).

Hong Kong is a mountainous region where many buildings and infrastructures were built on hill tops and steep slopes due to paucity of land. The latest Chinese Seismic Code (China Code 2010) prescribes a peak ground acceleration of 0.12 g for the 475-year return period on “rock” outcrop. It is noted that the obtained design ground-motion are only applicable for a level ground. To date, scientifically based standard for seismic design of buildings on steep slopes is still not available. It is expected that the intensity of shaking could be much larger on hill slopes due to topographic amplification. In particular, the amplified spectral accelerations at long periods could have significant implication for designing and evaluating tall buildings on steep slopes.

## METHODOLOGY AND KEY RESULTS

Extensive numerical studies have been conducted to improve our understanding of topography amplification in the lack of well instrumented data (e.g. Sitar and Clough 1983, Ashford et al. 1997). In these analyses, simple 2D topography geometries are often used and the soil is assumed to be a uniform viscoelastic material. The numerical simulations usually result in an amplification factor less than 2, which tends to underestimate the field data.

Recently, Du *et al.* (2016) analyzed spectral amplification of ground motions on a 2D rock ridge (Figure 1). The rock is assumed to be elastic with a shear wave velocity Vs=1000 m/s, and the surface soil layer on top of the rock is assumed to be 0 to 10 m deep with Vs=200 m/s. The soil nonlinearity is modelled using the equivalent linear method. The result further confirmed that a low velocity zone near the slope surface can have a significant impact on the amplification of the spectral accelerations (SA). Apparently, such amplification is frequency dependent. Figure 2 compares the “topography amplification effects” (SA at the rock ridge top vs. SA at rock free field, without soils), “soil amplification effects” (SA at free field with soils vs. SA at free field without soils), as well as the “total amplification effects” (SA at ridge top with soils vs SA at free field without soils). The numerical analyses show that the “total amplification” can be approximated as the “topography amplification” factor multiplies the “soil amplification” factor. In Fig. 2, the estimated vibration period of the soil layer is highlighted using a black line. The fundamental period of the ridge is estimated to be 0.3 s. Amplification of the peak ground acceleration (PGA) varies from 1.5 to 2.5 depending on the thickness of the soil layer. When soil depth is 7.5 m, the period of the soil layer is close to that of the ridge (0.3 s), spectral amplification at that period reaches as large as 4, while amplification of the PGA is around 2 in that case.

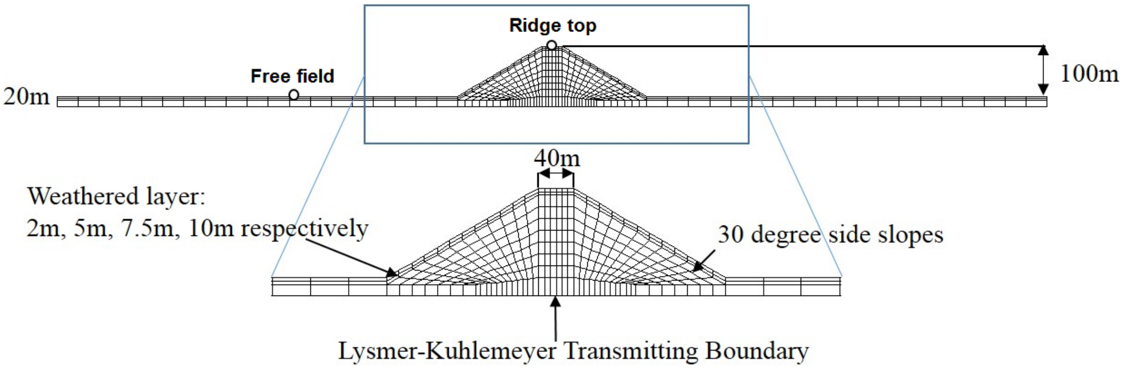


Figure 1: 2D numerical simulation considered weathered soil layers

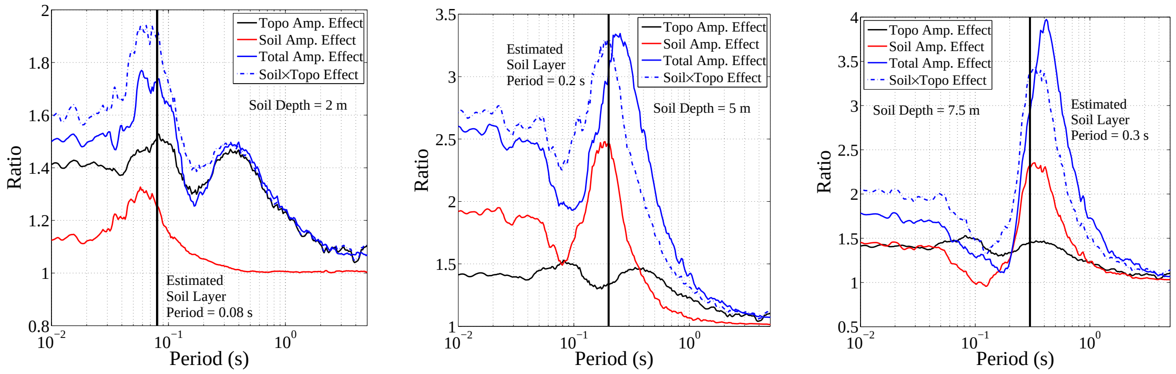


Figure 2: Spectral amplification ratio for cases with different soil depths

Compared with the above simple 2D example, numerical simulations incorporating realistic 3D topography and subsurface soil conditions is more attractive. However, 3D site response analysis is rarely done in the geotechnical community. There are several challenges to be addressed: (1) since 3D topography is complex, it is important to parameterize the ground-motion amplification using simple topographic measures. (2) It is important to find well-instrumented field data to validate and calibrate the numerical modeling; (3) Subsurface soil distribution can be highly heterogeneous and variable. Yet, we typically have little information on the subsurface stratigraphy of a region. It is challenging to adequately quantify the uncertainties associated with the numerical modeling.

In this project, we study ground-motion amplification on 3D topography based on 3D Spectral Element Method (SEM), using Hong Kong as a local testbed site. The SEM is a high-order finite element method that uses a special nodal basis. The SEM method is superior to the commonly used finite-difference method in many ways. The SEM uses a pseudo-spectral method to achieve high accuracy in modeling wave propagation. If a polynomial degree of 4 is used in interpolation, one SEM element per wavelength has been found to be very accurate. In other words, if the element size is 5 m and shear wave velocity is 200 m/s, the highest frequency that SEM can simulate will be up to 40 Hz. As a comparison, the finite difference method will be very expensive since a great number of grid points will be needed to achieve the same accuracy. The SEM can be easily implemented in parallel computing because its mass matrix is diagonal (Komatitsch and Vilotte 1998). Because of these advantages, the SEM has been recently widely used in global and regional scale wave simulation with a simulation domain up to hundreds of kilometers (He *et al.* 2015).

Figure 3 illustrated a constructed 3D SEM model of the western part of Hong Kong Island. The dimension of the computational domain is 8 km × 9 km. In general, the rocks in Hong Kong Island consist of volcanics intruded by granite. The volcanic and granitic rocks are subjected to extensive weathering. The hill slopes are generally covered by colluvium (0-15 m thick) on the surface, underlain by weathered rocks varying significantly from 10 m to 50 m, but can be up to 90 m locally. The highest point, Victoria Peak, is 554 m above the sea level.

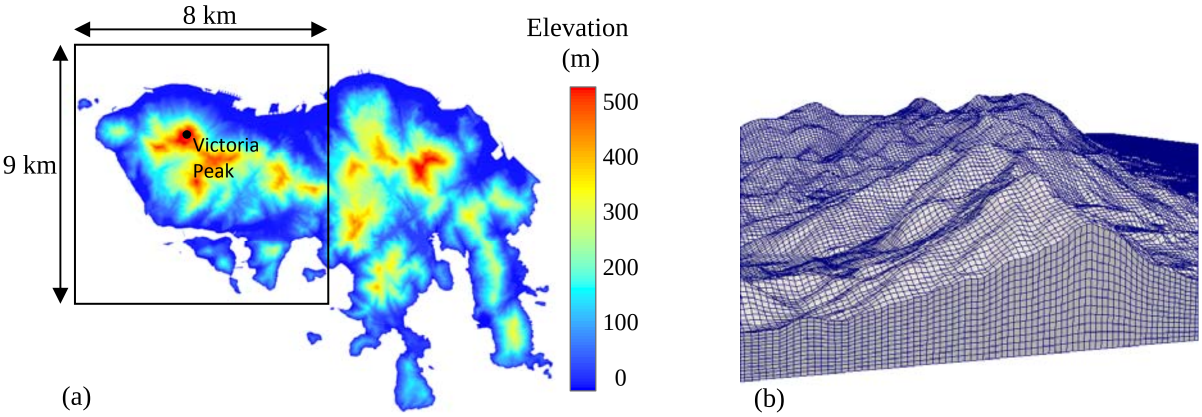
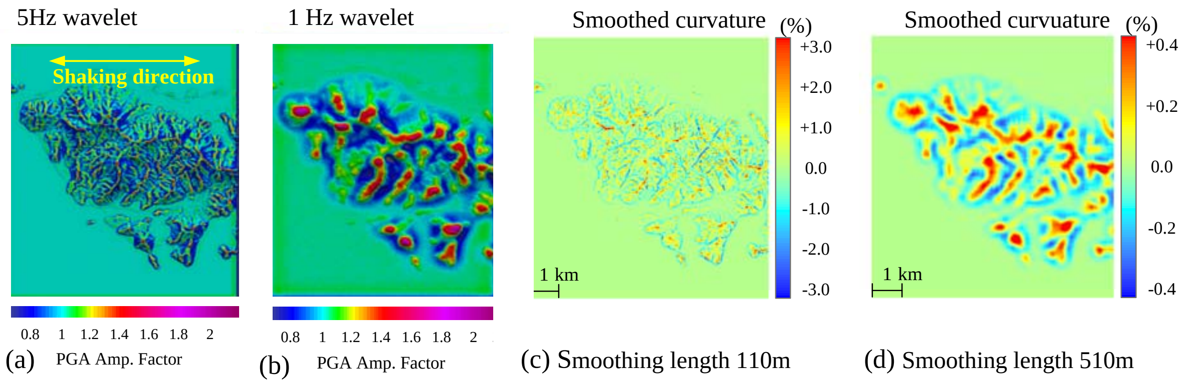


Figure 3: (a) Hong Kong Island elevation map and study region, (b) 3D SEM mesh illustration

High resolution Digital Elevation Model (DEM) is used to extract elevation data in numerical simulations and topographic curvature calculation. The resolution of the elevation model is fine enough to cover the very detailed topographic features. Uniform ground excitation is input at the base of the model. Lysmer-Kuhlemeyer transmitting boundary is implemented to mimic the infinite half space at the bottom, and absorbing boundaries are used on the sides to avoid wave reflection from the boundary. The mesh resolution can accurately capture wave motions well above 10 Hz. Material in the simulation is assumed to be uniform and linearly elastic with Vs=1000 m/s, so only the topography effects is studied at the present stage.

First, Ricker wavelet is used as acceleration input in the simulation, with predominate frequency of the wavelet varying from 0.5 Hz to 5 Hz. The amplification factor is defined as the PGA recorded on the slope surface divided by the PGA recorded on the level ground, as shown in Figure 4.



(a) PGA Amp. Factor (b) PGA Amp. Factor (c) Smoothing length 110m (d) Smoothing length 510m

Figure 4: PGA amplification factor maps excited by (a) 5 Hz wavelet; (b) 1 Hz wavelet; (c) and (d): smoothed curvatures using different smoothing lengths

Figs. 4 (a)(b) show amplification factor maps under 5 Hz and 1 Hz wavelet excitation, where the maximum amplicaiton factor is 2.1 and 1.9, respectively. It is obvious that the amplification/de-amplification is closely related to very localized topographic features under the high frequency (5Hz) excitation. Figs. 4(c)(d) compares topographic curvatures smoothed using neighborhood data within different smoothing lengths. Apparently, more localized topography (convex/concave) details can be captured if a shorter smoothing length is used.

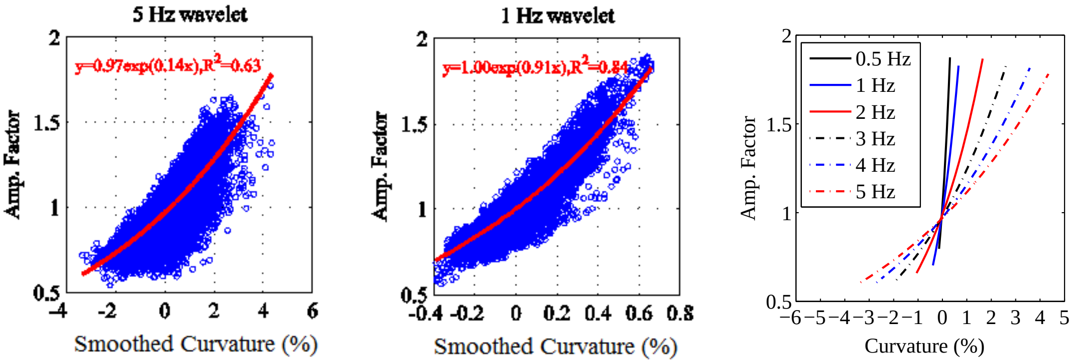


Figure 5: Correlation between amplification factor and smoothed curvature (smoothing length=*L*/2)

Similar patterns in Fig. 4 suggest a parameteric relationship between the ground-motion amplification and smoothed curvatures. It is found that the amplification factor (AF) can be best correlated with the smoothed curvature ($c_S$), if half of the input wavelength is used as the smoothing length. The relationship can be cast into an exponential form:

$$AF\left(L,c_s\right)=\exp\left[a\left(L\right)\times c_s\times 100\right] \tag{1}$$

where $a\left(L\right)=9.90\times10^{-4}L-0.083$ and $L$ is the wavelength (in meter, $L=V_S/f$). $c_S$ is the curvature smoothed using *L*/2. Eq. (4) manifests that the frequency-dependent amplification is related to a scale-dependent topographic feature.

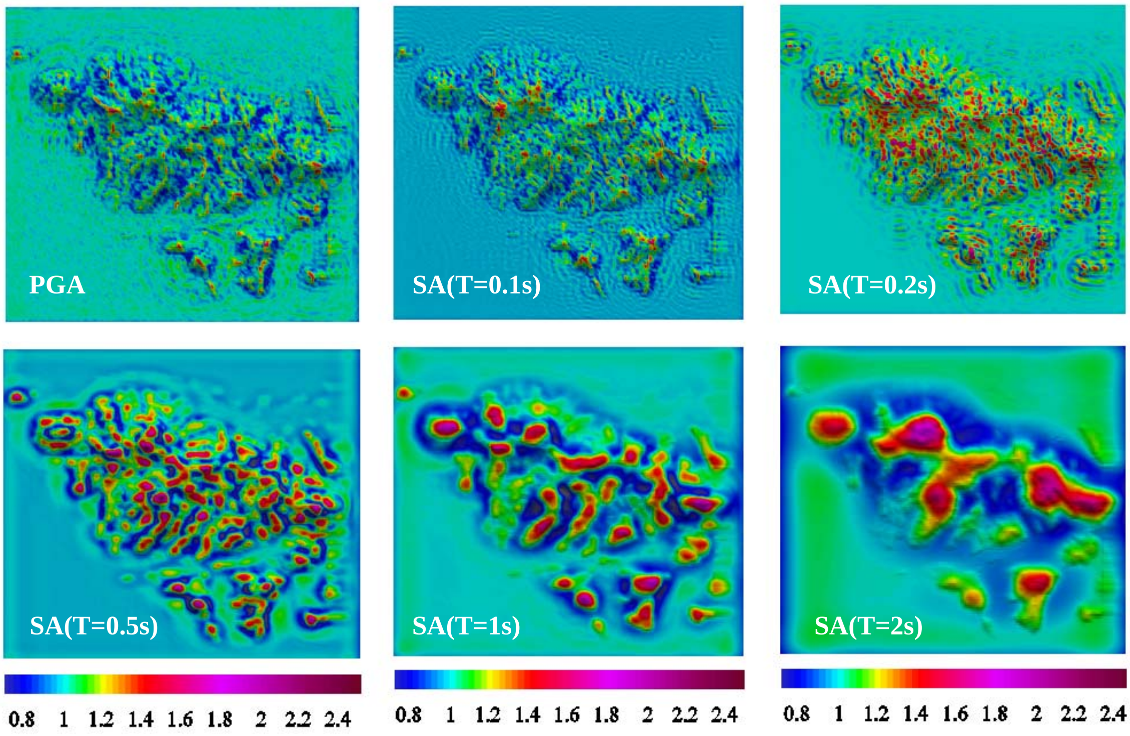


Figure 6: Topography amplification of spectral accelerations at different periods

3D SEM analyses were also conducted using recorded ground motions linearly scaled to fit to the 2475-year-return-period Uniform Hazard Spectrum for Hong Kong (input PGA=0.2 g). Fig. 6 shows the topography amplification of spectral accelerations at different periods (PGA, T=0.1s, 0.2s, 0.5s, 1s, 2s). The amplification pattern is similar to Fig. 4. Maximum amplication factors are 2.2 (PGA, T=0.1 s) to 2.5 (T=0.2 s, 0.5s), 2 (T=1 s) and 1.85 (T=2s).

## CONCLUSIONS

We conduct a region-scale 3D numerical simulation to quantify frequency-dependent topographic amplification with a reference to the design ground motions in Hong Kong. The analyses revealed that topography amplification of ground motions is frequency dependent. It can be parameterized using a scale-dependent topographic feature (the smoothed curvature). Amplification of high frequency wave is correlated with curvature smoothed over a small length scale. On the other hand, amplification of long-period waves is correlated with large-scale topography features. The maximum topography amplification generally ranges from 1.8 to 2.5 in the protruded areas, which is larger than EU8 specification. De-amplification of the high-frequency wave is observed in the locally concaved areas even at high elevations.

Inevitably, the numerical simulation will highly depend on the resolution of topography and the subsurface data available**.** At the present, we are collecting and reviewing borehole information to understand the near-surface geology of the study areas. Emphasis will be placed on investigating the extent of soil cover and weathered rock profiles on the hill top and hill slope, which may have great impact on site amplification as implied by the 2D analyses on simple geometry. Extensive parametric study needs to be performed to quantify the uncertainty of the numerical simulations through varying stratification and properties of soil/rock units.

## ACKNOWLEDGEMENTS

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## REFERENCES

Ashford, S.A., Sitar, N., Lysmer, J. and Deng, N. (1997). “Topographic effects on the seismic response of steep slopes”. *Bulletin of the seismological society of America* 87(3),701-709.

Burjanek, J., Edwards, B., Fah, D. (2014). “Empirical evidence of local seismic effects at sites with pronounced topography: a systematic approach.” *Geophysical Journal International*, 014.

China Code (2010). “Code for seismic design of buildings”, GB50011-2010, Ministry of Construction, P.R. China.

Du, C.Y., Wang, G., Koo, R.C.H., and Kwan, J.S.H. (2016). “Topography effects on design response spectrum”, The 7th Guangdong-Hong Kong-Macau Seminars on Earthquake Science and Technology, 7-8 April 2016, Hong Kong (in Chinese).

He, C.H., Wang, J.T., Zhang, C.H., and Jin, F. (2015). “Simulation of broadband seismic ground motions at dam canyons by using a deterministic numerical approach.” *Soil Dynamics and Earthquake Engineering* 76. pp.136-144.

Komatitsch, D. and Vilotte, J.P. (1998). “The spectral element method: An efficient tool to simulate the seismic response of 2D and 3D geological structures.” *Bulletin of the seismological society of America* 88(2). pp.368-392.

Sitar, N., Clough, G.W. (1983). “Seismic response of steep slopes in cemented soils.” *Journal of Geotechnical Engineering* 109, No. 2, pp. 210-227.