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Research Paper

# Influence of Topographic Effect on Dynamic Behavior of Hill Slope Building

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**ABSTRACT**

This research was driven by observations made during the April 2015 Gorkha Earthquake, in which buildings located on the cliffs and hillslopes suffered significant damage. The primary goal of this research is to study the impact of topography on the dynamic behavior of buildings located on the slopes of hills, which are popular residential sites spread across Nepal. The numerical simulation of topographic effect was accomplished using Ground Response Analysis. 2D geological models were made, over which seismic simulation were done. The results are presented in the form of topographical amplification factor (TAF). The amplification factor calculated from ground response analysis were used in static and linear dynamic time history analysis of the buildings. The response of a two-storied structure is compared with and without considering the effect of topography. The outcome demonstrates that, owing to topographic impact, hill-slope structures built using contemporary seismic design codes are not sufficient to withstand the enhanced seismic forces.

## 1. Introduction

Nepal is a country known for its rich biodiversity. This rich biodiversity comes from the immense variation in geography. Geographically, the country is divided into three regions: The Terai region, the Hilly region and the Himalayan region. The altitude in the country ranges from 59 m in Terai low land to 8848 m at the top of Mt. Everest, which is located in the Himalayan region. Although this huge topographical variation makes this country an ideal inhabit for some of the rarest fauna and flora in the world, it has also posed a great deal of challenge for human habitation. High seismicity, high altitude settlement, scarcity of flat lands, etc. are some of the commonly faced problems. Due the scarcity of flat land, buildings in hilly and mountainous area are often constructed in sloped terrain. Buildings constructed on such sloped land are commonly referred to as “Hill Slope Buildings” and these buildings follow the general sloped terrain (**Fig.1**) The structural behavior of such buildings is quite different from those buildings constructed on flat land (Singh et al., 2011; Surana et al., 2018). The inevitable presence of irregularities, topographical and soil amplification of seismic motion and slope instability are some of the key issues which makes these building more vulnerable. Although numerous studies can be found regarding the behavior of hill slope buildings but none of them take into account the effect of topography. The present study analyses the structural behavior of buildings on hilly areas by incorporating the effect of topography using an amplification factor. Furthermore, coupling the effect of

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topography and irregularity, the vulnerability of building stock based on location is also studied.

## 2. Literature Review

The first observation regarding topographic amplification was probably made by Charles Darwin during his journey on the Royal Navy Warship H.M.S Beagle, popularly known as “The voyage of H.M.S beagle”. During the expedition observation of damages from Chilean earthquake was made. Darwin (1939) noted that “…..the effect of the vibration on the hard primary slate, which composes the foundation of the island, was still more curious the superficial parts of some narrow ridges were as completely shivered as if they had been blasted by gunpowder….”. A large number of contemporary studies on the effect of topography stem from this particular observation.

Boore (1972) studied the effect of simple topography on seismic horizontal shear waves. The study used finite difference method and found these (topographic) effects to be frequency dependent and the models exhibited an amplification factor of up to 1.75. The result of numerical analysis state that topography can cause significant amplification and can influence motion of surprisingly long wavelength. Similarly, Ashford (1997) studied the topographic effects on the seismic response of steep slopes by performing a frequency-domain parametric study using generalized consistent transmitting boundaries. The result demonstrated that the peak amplification of motion at the crest of the slope occurs at a normalized frequency H/λ= 0.2, where H is the slope height and λ is the wavelength.

Paolucci (2002) studied the amplification of earthquake ground motion by steep topographic irregularities using spectral element method to compute the amplification factor of several real steep mountains excited by SV (Shear vertical) waves and compared the 3D and 2D results with the provision of Eurocode 8. In the study, the fundamental frequency of vibration of selected topography was calculated using Rayleigh’s method which showed that the seismic amplification of topographic irregularity is dependent on the frequency content of input motion.

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He concluded that resonance will occur if the wavelength of motion is slightly larger than the base of the mountain. He found the provisions of Eurocode 8 (1998) in terms of a factor F for scaling design spectra to be satisfactory in term.

Rizzitano et. al (2014) studied the coupling of topographic and stratigraphic effects on seismic response of slopes through 2D linear and equivalent linear analyses by performing 2D seismic response analyses of slopes subjected SV (Shear vertical) waves using FE code QUAKE/W. The analysis concluded that despite of extensive research on the topographic amplification the phenomenon is not well understood due to the complex geological variation making the quantification uncertain. In addition, topographic amplification has been shown to be dependent on the soil's non-linear nature.

A significant number of studies has been done regarding the behavior of hill slope buildings. Singh et. al (2011) studied the seismic behavior of buildings located on slopes by studying the dynamic behavior of hill buildings and compared them with the flat ground buildings. The study found that hill buildings have significantly different dynamic characteristics as compared to their flat terrain counterparts. Furthermore, it was concluded that the storeys immediately above the road level, in case of down-hill buildings, are particularly vulnerable to earthquake action.

Surana et. al (2018) performed fragility analysis on different configuration of hillside buildings using incremental dynamic analysis and found that split foundation and step back hillside building exhibit significant torsional effect at the storey just above the uppermost foundation level. Also, the research showed that high-rise split foundation and step back buildings show unacceptably high probability of collapse at maximum considered earthquake in zone V and for near-field site in zone IV. To summarize all the foregoing research, most of these studies suggest that the hill slopes buildings are more vulnerable than their flat terrain counterparts.

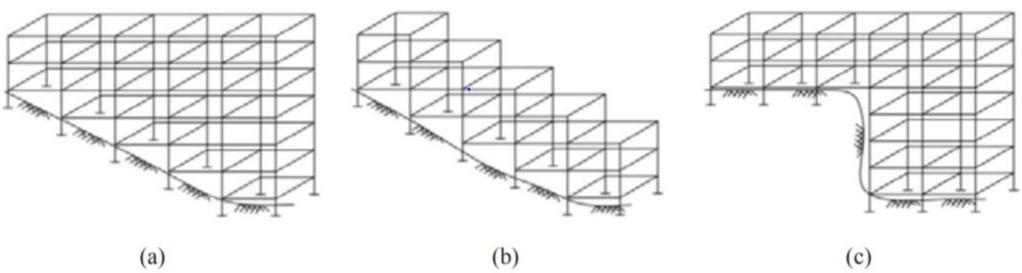


**Fig. 1.** Common Configuraiton of hill slope buildings. a) Step back building, b) Set back building, c) Split foundation building

## 3. Methodology

Three different sets of analyses were performed. Firstly, a preliminary ground response analysis was conducted for the purpose of model validation. Based on the preliminary analysis, ground response analysis using actual geomorphological data is performed. The peak ground acceleration values were obtained from this ground response analysis using which topographical amplification factors (TAF) were calculated for 10 different ground motions. Finally, using the calculated TAF static and linear dynamic structural analysis is performed to get the building response in the form of maximum displacement and storey drifts.

### *3.1 Preliminary Analysis*

The FEM model for ground response analysis is shown below. The analysis is performed in Geo Studio software. The model is trapezoidal hill having a base width of 400 m and top width of 200 mm (**Fig. 2**). The height of slope is taken as 100 m and depth of bedrock is taken as 450 m. The side boundary has been moved considerably further (L=1500 m, refer **Fig. 2**) to avoid the interference due to reflected seismic waves. The boundary condition at the base is assumed to be fixed along both direction and the BCs along the sides is to assumed to be fixed along vertical direction (**Fig. 2**). The shear wave velocity is taken as 200 m/s as suggested by Gautam (2016) for Kathmandu valley and the density of soil is assumed to be 20 kN/m$^3$ considering a medium dense soil for the study.

For the purpose of preliminary analysis, sinusoidal waves have been applied as input motion. Sinusoidal waves of frequency range varying from 0.05 Hz, 0.2 Hz, 0.5 HZ, 0.8 Hz, 2 Hz and 5 Hz has been used for simulation.

The soil parameters were adopted from the commonl y accepted value in the current literature (**Table 1**). The analysis has been formed in Geo-Studio Software Quake/W. The results are expressed in the form of TAF ratio, TAF variation along the hill cross-section.

### *3.2 Ground Response Analysis*

The geomorphological data were collected from geotechnical report obtained from Tech Studio of Engineering, Nepal (April, 2019). The site is located in Larke region, which lies in Sindhupalchowk district of Nepal. The selected hill has a base width of 2008 m and a total height of 800 m. The top soil is a sandy soil, the bed rock consists of layers of mica schist and quartzite with occasional layers of gneiss. Bed rock depth varies from 0.55 m to 15.2 m

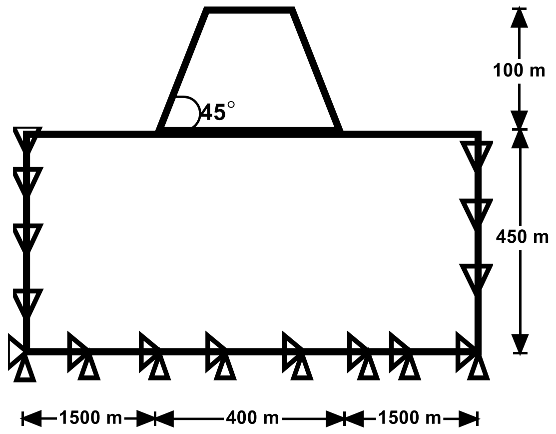


**Fig. 2.** FEM model for preliminary analysis

**Table 1**. Input parameter for preliminary analysis

| S.N | Input Parameter | Details | Remarks |
|---|---|---|---|
| 1 | Density of soil | 20 kN/m$^3$ | |
| 2 | Shear wave velocity | 200 m/s | |
| 3 | Poisson's ratio | 0.333 | |
| 4 | Soil behavior | Linear elastic | |
| 5 | Analysis type | Time history | |
| 6 | Mesh size | Wavelength/15 | Modha et. al (2018) |

Although, the depth of top soil is varying but a constant depth of 10 m is assumed for the purpose of analysis for ease in modelling. The density of top sand soil is taken as 20 kN/m$^3$ and a shear modulus of 6.523 GPa is used. For the bedrock, density and shear modulus values were taken as 26 kN/m$^3$ and 10.38 GPa respectively. These values were obtained from the empirical relation between Q values and modulus of elasticity of rock mass (Barton). The L and D values of the model was so selected that the base and sides doesn't cause interference with the reflected seismic waves. A value of L/H = 30 and D/H proposed by Rizzitano (2014) gave acceptable results in preliminary analysis. So for the values of L and D are kept as 24000 m and 4000 m respectively based on above relation. The mesh size is so selected that the numerical distortion of frequency content in simulation is avoided. Kuhlemeyer and Lysmer (1973) proposed that the maxim um size of the element mesh should be restricted to 1/8$^{th}$ to 1/12$^{th}$ of the wavelength. In addition, Semblat and Brioist (2000) suggested using the value between 1/10th to 1/20$^{th}$ of the wavelength. Different mesh size from 1/10$^{th}$ to 1/20$^{th}$ of wavelength were used in preliminary analysis from which value of 1/15th of wavelength was found to give satisfactory result. So, a mesh size of 1/15th of wavelength was adopted.

Equivalent linear dynamic ground response analysis was performed using 10 different earthquakes. The earthquake records were taken from PEER ground motion database. It has been well established that the ground response of a particular morphology is dependent on the frequency content of input motion (Boore,1972; Paolucci, 2002), so the amplification factor here obtained are valid for only the selected earthquake. Hence, same suites of earthquake motion are applied for both ground response analysis and structural analysis. The earthquake records selected are Indian seismic design code IS 1893:2016 response spectra compatible. Other parameters such as active fault type, building fundamental period etc. are also considered for selection of earthquake. Fault types are taken into account by considering most active fault types in Nepal (Kumahara, Chamlagain and Upreti, 2016) and the fundamental period of building has been calculated to obtain the period of interest (**Table 2**). A 2D equivalent linear ground response analysis is then performed and the PGA are recorded at five different points along the hill (**Fig. 3**). The result from the ground response analysis are expressed in the form of topographical amplification factor.

### *3.3 Structural Analysis*

For the purpose of structural analyses, a two-storied building was used. Two different building models configurations, namely sloped building (SB) and free field (FL) buildings were considered. Sloped building refers to a building having foundations at different levels which are normally built along the slope of hilly areas. Free field buildings are the ones built on flat land which have the foundation at same level. A typological survey is performed based on which a generic plan is developed based on the type of buildings found on hills of Nepal. The most common type of hill building configuration found was the step back building (**Fig. 1**). For both step back and free field structure, a common building plan with the dimension of 11.13 m (x) by 8.18 m (y) is adopted. Step back models are used for analysis in crest region whereas for riff and free field flat land buildings are used. In order to make the results comparable, the seismic weight, building height of both sloped and flat land building are kept the same. The buildings are first analyzed and designed using equivalent linear static method of analysis as per Indian building design code IS 1893:2016. Before commencing the time history analysis, ground motion data obtained from the PEER ground motion database needs to matched to the local site condition. Henceforth, a time domain matching is performed in ETABS 2017 before performing the time history analysis.

**Table 2**. Earthquake records for analysis

| S.N | Earthquake | Magnitude | Fault type |
|---|---|---|---|
| 1 | Coalinga | 6.26 | Reverse |
| 2 | Dinar | 6.4 | Normal |
| 3 | El centro | 6.95 | Strike-slip |
| 4 | Gazli | 6.8 | Reverse |
| 5 | Kobe | 6.9 | Strike-slip |
| 6 | Kocaeili | 7.51 | Strike-slip |
| 7 | Loma Prieta | 6.93 | Reverse |
| 8 | Managua | 6.24 | Strike-slip |
| 9 | Northridge | 6.69 | Reverse |
| 10 | Parkfield | 6 | Strike-slip |

Then, linear time history analysis is performed for altogether two building base models using the calculated topographical amplification factor. The building response are compared in terms of story drift at riff and at crest. For that purpose, the building is first analyzed without considering the topographic effect. After that the analysis is re-run applying the TAF.

## 4. Results and Discussions

### *4.1 Preliminary Analysis*

The FEM analysis was performed for six different input motions. The resonant frequency was close to 0.5 Hz. It can be seen for frequency of 0.5 Hz whole of the hill portion is amplified (**Fig. 6**). Similar amplification was observed for frequency of 0.2 Hz and 0.8 Hz which are within 15% of the fundamental frequency. For frequency below and above 15% of fundamental frequency amplification and de-amplification were observed. This validated that the amplification is caused mainly due to resonance of whole relief (Paolucci, 2002). Furthermore, the maximum amplification value was 2.58 which was obtained at crest point located at 300 m and 500m from the origin (**Fig. 6**) for the frequency of 0.5 Hz (**Fig. 6**). Also a TAF value of 2.08 was obtained at crest point for the same frequency. Similar observations can be made for the frequency of 0.2 Hz. For the frequency of 0.5Hz, however de-amplification was observed at one of the crest point located at 500m from the origin.

*4.2 Ground Response Analysis*

PGA values are obtained at five different locations along the hill geometry (**Fig. 4** and **Fig. 8**). Out of the five location the crest and riff portion has the highest model for nine of the earthquakes indicating higher amplification of along these regions.The highest PGA value recorded was 0.994 g at riff for Northridge earthquake and lowest PGA value recorded was 0.163 g for Loma Prieta earthquake. It was observed in most of cases similar PGA values were recorded at both crest and riff. Further, along the crest and trough, the PGA values are lower than that at free field. But in case El centro and Northridge earthquake, higher PGA values were also observed. The PGA distribution along the hill geometry is shown in **Fig. 8**. The highest PGA of input motion was 1.31 g for Park EQ, but the PGA value at crest and riff were 0.567 g and 0.574 g respectively for this motion. However, the Northridge EQs input PGA was only 0.441 g but the PGA values at crest and riff were 0.991 g and 0.994 g respectively.

This might be because the cliff is relatively close to the riff. Thus, the amplification of a particular hill geometry depends upon the frequency content of input motion rather than the PGA values. TAF values were calculated and shown in **Fig. 8**. The highest TAF were obtained as 2.24 and 2.25 at riff for Northridge EQ. Expect for Park, a minimum of 10% amplification is observed in case of all earthquakes. Thus, there is inevitable amplification along and near the crest and riff of a sloped hill.

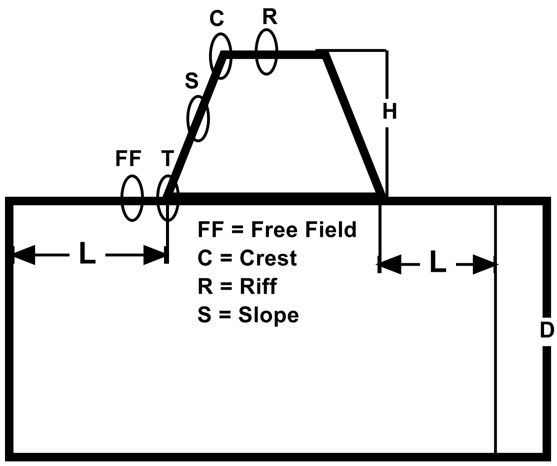


**Fig. 3.** FEM model for ground response analysis

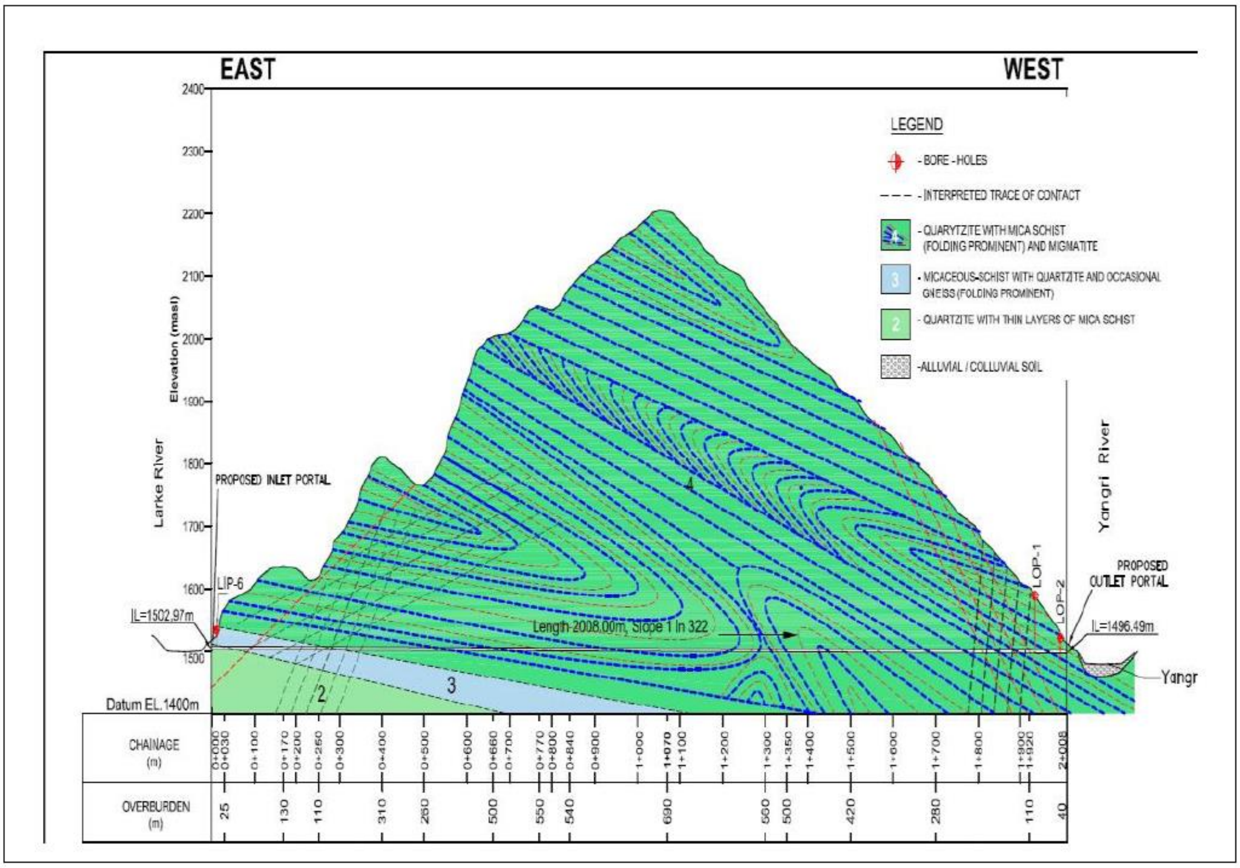


**Fig. 4.** Geological cross-section of selected site

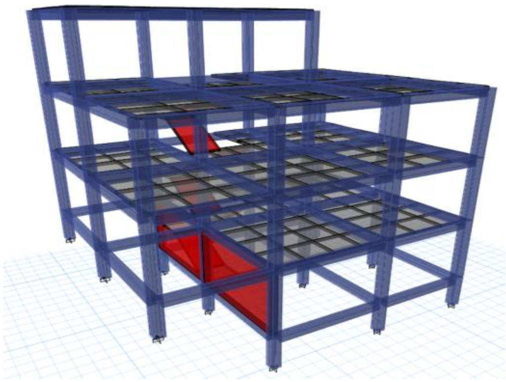

**Fig. 5.** Typical 3D FEM model for structural analysis

### *4.2 Structural Analysis*

The amplification factors are applied as a linear scaling factors so the base shear are scaled. For equivalent linear elastic analysis, the unscaled static base shear value is 267.67 kN along both X and Y direction. The base shear value at crest along is 374.25 kN and 388.45 kN along X and Y direction respectively applying a 40% amplification. Four of the column two below the ground storey, which are short columns and two at the ground storey fail.

The results of dynamic time history analysis are presented for cliff and riff. For the two-storied reinforced concrete frame, two separate analyses were done, one without applying the topographic amplification factor and the same model is re-run applying the amplification factor. The results are compared in terms of maximum storey drifts. In case of cliff, the drift value increases by almost 3 times when topographic effect is considered (**Figs. 9** and **10**). The maximum drift is 0.0032 in case of Northridge earthquake when topographic effect is considered, while the drift value is only 0.0011 when amplification factors are not applied. Similar increase in drift in observed along Y-direction with the maximum value as 0.0031 in case of Northridge earthquake. The drift value without applying amplification factor is only 0.00115. The minimum increase in drift value is about 26% and 40% for Kocaeili earthquake along X and Y direction respectively. Although the maximum and minimum amplification factor considered are 2.25 and 1.15, the drift values are increasing in greater proportion suggesting a non-linear relationship between story drift and topographic amplification factor.

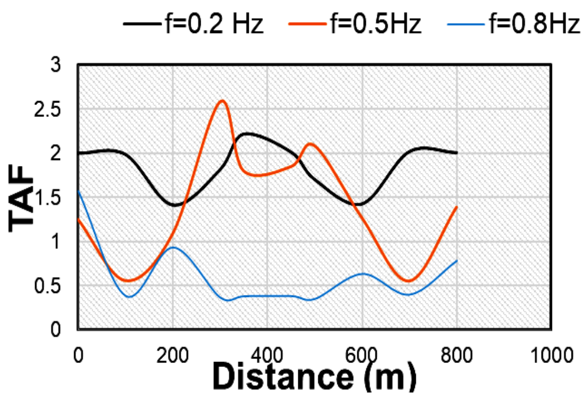


**Fig. 6.** PGA variation within 15% of natural frequency

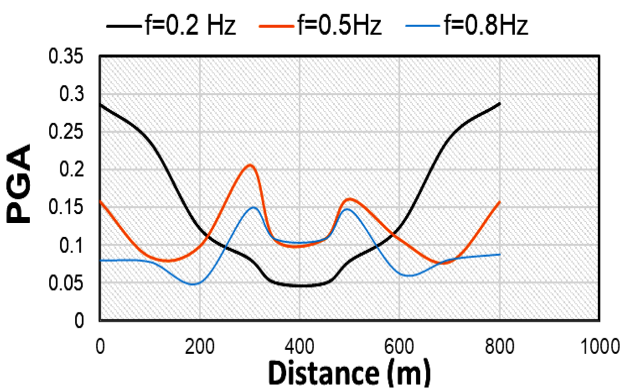


**Fig. 7.** TAF variation within 15% of natural frequency

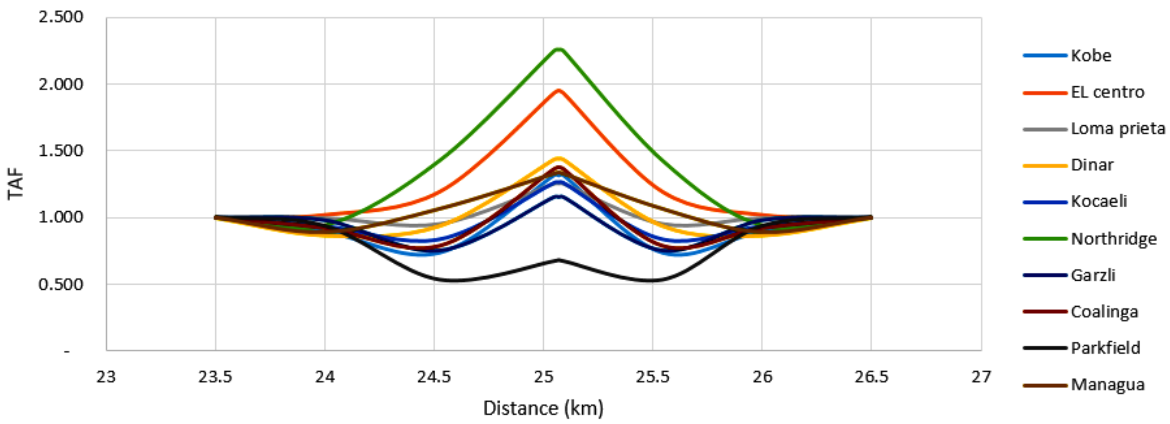


**Fig. 8.** TAF variation across the hill geometry

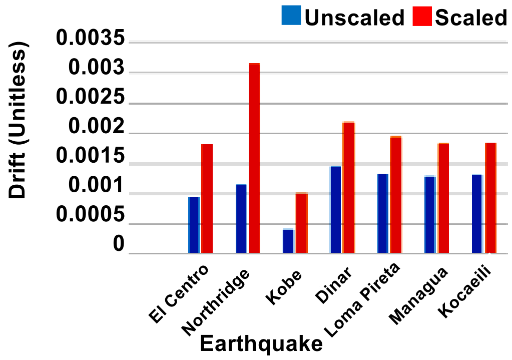


**Fig. 9.** Drift values along X direction at crest

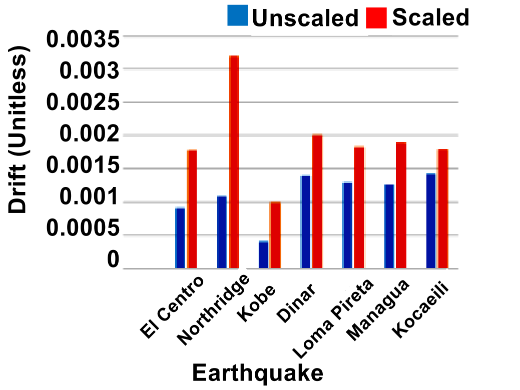


**Fig. 10.** Drift values along Y direction at crest

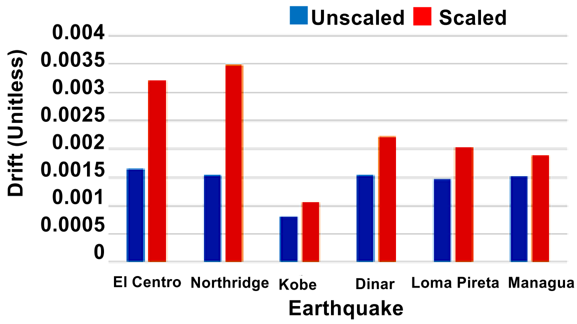


**Fig. 11.** Drift values along X direction at riff

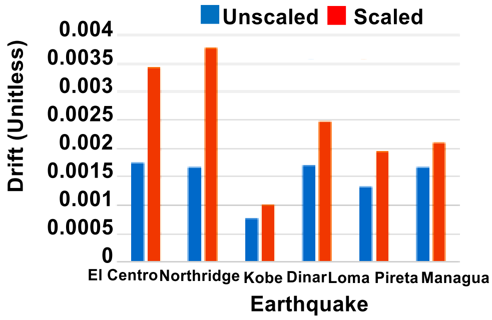


**Fig. 12.** Drift values along Y direction at riff

In case of riff (**Figs. 11** and **12**), the drift value is increased from 25% to 126% when amplification factors are applied. Higher increase in drift ratio were observed for El centro and Northridge earthquake. The maximum value of storey drift is 0.0037 for Northridge earthquake applied along Y direction, while the drift value is only 0.0016 when amplification factor is not considered. The corresponding drift value for Northridge earthquake along X direction are 0.0034 and 0.0015. The minimum drift value observed in for Managua earthquake which is about 0.001893 along X direction when considering the topographic effect. The increase in drift is by 25%. Along Y direction, the increase in drift is almost similar, the respective drift values are 0.00211 and 0.001674. Lower values of drifts were observed for Kobe and Dinar earthquakes because of lower amplification at these points.

## 5. Conclusions

The ground response analysis results indicate that in every case regardless of the earthquake motion selected, there is an amplification at crest and riff. The amount of amplification is dependent mainly on frequency content of selected ground motion if other parameters such as slope angle, height of hill, base width are kept constant.

Buildings placed in proximity of crest are step- back buildings, which inevitably possess structural irregularities. Despite the fact that the amplification factor at a riff is slightly higher than that at a crest, step-back buildings have been observed to be more vulnerable than buildings placed on a riff, due to the combined effect of both building irregularity and topographic effects in the former. These buildings due to the combined effect of both building irregularity and topographic effect are found to more vulnerable than the building placed on riff despite the fact that amplification factor at riff is slightly higher than that at crest.

Although there is an increasing evidence regarding the effect local morphology on ground response, its effect is always neglected in seismic design of structures. Furthermore, except at riff most of the structure built on hill terrain are of irregular nature which are more vulnerable to damage than structures built of flat terrain. So, the provision of topographic effects needs to be included in modern seismic design codes of structures.

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### Symbols and abbreviations

| | |
|---|---|
| TAF | Topographic Amplification Factor |
| PGA | Peak Ground Acceleration |
| BC | Boundary Condition |
| SV | Shear Vertical |
| EQ | Earthquake |
| FEM | Finite Element Method |
| GRA | Ground Response Analysis |