Journal of Himalayan Earth Sciences 41 (2008) 33-43

# Predicting topographic aggravation of seismic ground shaking by applying geospatial tools

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## Abstract

The undisputable impact of topographic features on the uneven distribution of seismic ground shaking and associated devastation is well-observed and documented, but not applied at a regional scale. Seismic events located in rugged terrain, such as the Kashmir earthquake (2005) in the western Himalaya, exhibit amplified response on the inclined slopes and ridge crests, while de-amplified response at the hill toe. These observations are supplemented by numerical, analytical and experimental investigations. Current efforts on predicting topographic impact on seismic response are confined to synthetic terrain or isolated hills. The available regional models, like USGS ShakeMap, ignore the topographic effects on seismic response, limiting model applicability at local scale. Parametric studies analyzing impact of specific terrain feature and seismic characteristics on seismic ground shaking resulted in numerical models, predicting topographic aggravation of seismic response. This study aims to apply DEM derived topographic attributes and seismic parameters in numerical models to predict topographic aggravation of seismic response at a regional scale.

SRTM and ASTER DEMs are utilized to derive the required topographic attributes to investigate the impact of DEM resolution and data source on computed attributes. The uncertainty in the computed topographic attributes, due to DEM inherent random error, is quantified through Monte Carlo Simulations. The impact of slope angle, aspect, height, wavelength and damping on amplification and de-amplification of seismic response is analyzed in homogenous lithological and geotechnical scenario. The spatial variation of seismic wavelength is estimated empirically from instrumental ground shaking records. The remote sensing DEMs are found to be sensitive to steep slopes in terrain representation. The amplified seismic response is observed to be sensitive to the slope gradient among the analyzed parameters. The direction of incident seismic waves has significant impact on the occurrence and spatial distribution of seismic induced landslides.

## 1. Introduction

Natural disasters have caused, and are prone to cause, massive loss to human lives and economy around the world. The adverse affects of these disasters can be mitigated, through effective disaster management strategies, such as pre-disaster risk assessment and post-disaster response. Among natural disasters, earthquakes are proved to be the most devastating in causing human and economic loss, and widespread destruction. The situation is deteriorated by its temporal and spatial unpredictability. Ground shaking during an earthquake leads to damaging the infrastructure and triggering secondary hazards. The intensity and duration of seismic ground shaking at a particular location is determined by earthquake magnitude, location of the epicenter, medium traversed by seismic waves, local geology, topography and soil conditions (Kramer, 1996).

In general, rugged terrains, like the western Himalaya in northern Pakistan, and terrain features have a profound impact on the amplification or de-amplification of seismic response. Much research has been dedicated to analyze the impact of various terrain features on the uneven distribution of the seismic ground shaking and consequent building damages (Stamatopoulos et al., 2007). The numerical and analytical studies are consistent in finding amplified seismic shaking at the slope crests and de-amplification at the slope toes (Athanasopoulos et al., 1999; Bard, 1982; Chávez-García et al., 2000; Sanchez-sesma et al., 1982). These findings were supported by the experimental and instrumental seismic shaking records and post-earthquake observations records (Çelebi, 1987; Kawase and Aki, 1990; Siro, 1982). Parametric studies analyzing the impact of various terrain features and seismic properties on seismic response lead to formulate numerical models, predicting topographic aggravation of seismic response. The existing techniques on predicting topographic impact on seismic response are confined to synthetic environments or analyzing isolated hills. The numerical models, developed to predict the topographic impact on seismic response are not being applied in real case scenario and at a regional scale.

Satellite remote sensing acquired digital elevation models (DEM), available at various resolutions and accuracies, are a potential source of computing topographic features at regional scale to be utilized for topographic seismic modeling. The impact of the random errors and the resolution of DEMs on topographic attributes and predicted seismic response are explicitly dealt in this study. The spatial distribution of seismic wave's wavelength is estimated from the instrumental seismic shaking records. The relative height of the terrain features is calculated from the nearest surrounding drainage network. The amplified seismic response due to topographic location is expressed in topographic aggravation factor (TAF), throughout the study area. The sensitivity of the applied parameters, the impact of DEM resolution, and the random errors on derived TAF is also addressed.

Numerical models, which analyze the impact of terrain features and specific seismic incident characteristics, are applied in real case scenario of the 2005 Kashmir earthquake and at a regional scale (Fig. 1).

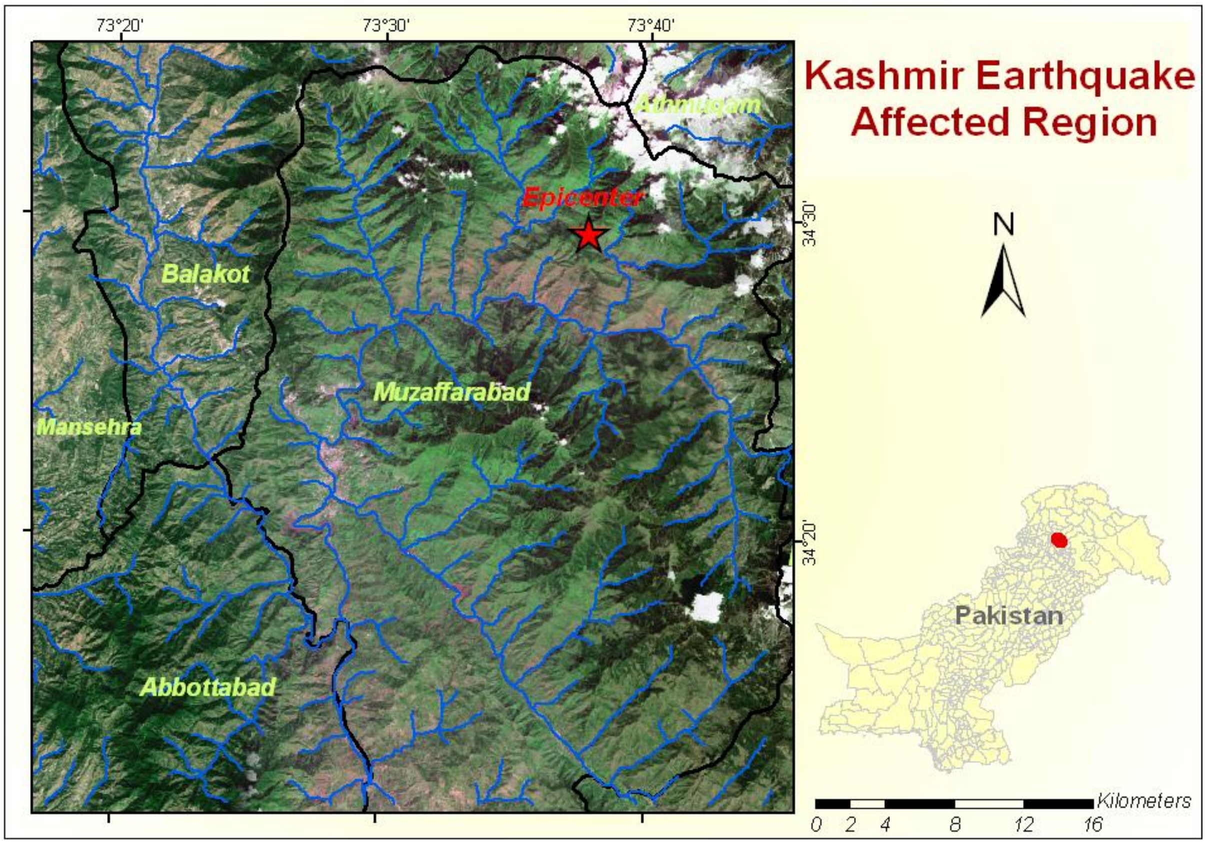


Fig. 1. Location map of study area (northern Pakistan).

## 2. Methodology

In hilly terrain such as the western Himalaya, the impact of terrain features on amplification and de-amplification of seismic response is being observed, reported, and supplemented by numerical, analytical and experimental techniques. Qualitatively, there is agreement between theory and observed topographic amplification, although not quantitatively. The predicted topographic impact from synthetic modeling practices leads to formulating a numerical relationship between terrain features, seismic characteristics and seismic response. Digital topographic information derived from DEMs of the study area can be a utilized as input to these numerical models for predicting and demarcating sites of critical topographic amplification, at regional scale.

This study is executed with the intention to integrate the decades-long efforts for analyzing impact of topographic features on seismic response, and geospatial tools such as GIS and remote sensing (Fig. 2). Earlier studies on the issue were extensively reviewed, to find a comprehensive numerical model, incorporating most of the crucial terrain features and the seismic properties, and predict topographic aggravation of seismic response. The numerical model by Bouckovalas and Papadimitriou (2005), predicting the topographic aggravation factor (TAF), is applied as the optimum choice. The model parameters consist of slope geometry, relative height of terrain feature, seismic wave's wavelength, damping and number of excitation cycles, in homogenous soil and lithology. TAF is categorized in horizontal and vertical TAF, and are defined in equation 1 and 2, respectively:

$$A_{h,\max} = a_h / a_{h,ff} \qquad \text{Equation 1: Horizontal TAF}$$

$$A_{v,\max} = a_v / a_{h,ff} \qquad \text{Equation 2: Vertical TAF}$$

Where

$a_h$ = Peak horizontal acceleration at any point

$a_v$ = Peak vertical acceleration at any point

$a_{h,ff}$ = Peak horizontal acceleration at free field

Parameter $a_{h,ff}$ is applied for normalization of both $a_h$ and $a_v$, since $a_{v,ff}$ = 0 for a vertically propagating shortwave (SV) (Bouckovalas and Papadimitriou, 2005). The applied model was developed by combining the results from previous topographic parametric studies and suggested the following numerical relations for horizontal and vertical TAF (equation 3 and 4, respectively):

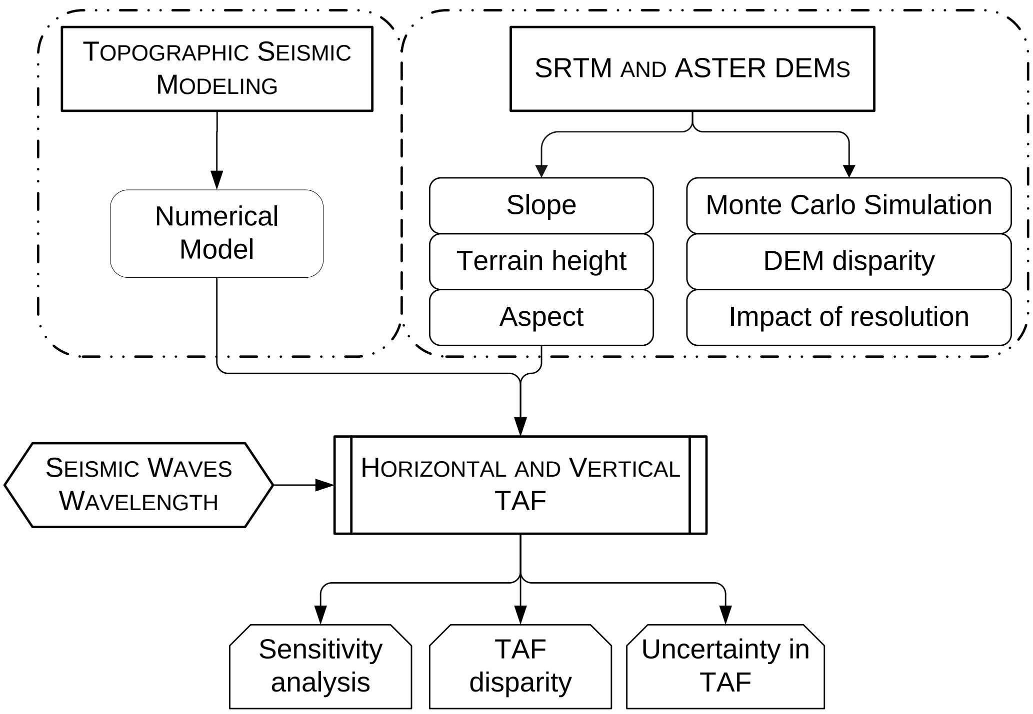


Fig. 2. Flow chart of methodology adopted for the study.

$$A_{h,\max} = 1 + \frac{0.225\left(\frac{H}{\lambda}\right)^{0.4}\left[\frac{I^2+2I^6}{I^3+0.02}\right]}{1+0.9\xi}$$

Equation 1: Prediction of horizontal TAF

$$A_{v,\max} = \frac{0.75\left(\frac{H}{\lambda}\right)^{0.8}\left(I^{0.5}+1.5I^{5}\right)}{1+0.15\xi^{0.5}}$$

Equation 2: Prediction of vertical TAF

Where
H = Relative height from the assumed base level
I = Slope
$\lambda$ = Wavelength of incident seismic waves
$\xi$ = Material damping
$A_{h,max}$= Horizontal TAF
$A_{v,max}$= Vertical TAF

H, I, $\lambda$ are applied as variable and computed at a regional scale, while $\xi$ is assumed to be homogeneous throughout the study area.

To derive the aforementioned topographic parameters at regional scale, DEMs from Shuttle Radar Topography Mission (SRTM) at 90m, and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) at 30m, were utilized. The Monte Carlo Simulation (MCS) technique is applied to quantify the uncertainty in the computed digital topographic attributes, which can be inherent errors in the SRTM and ASTER DEMs. The consistency of SRTM and ASTER DEMs in the rough terrain of the western Himalaya is explored through disparity of DEMs and the derived topographic attributes. The impact of topographic attributes resolution on the predicted TAF is also investigated.

Topographic seismic modeling requires relative height of terrain feature from some assumed base level. In the present paper, the drainage network is assumed as base level, and the height of terrain feature is estimated from the nearest surrounding network. To implement the theory, local minima are manually selected at the streams confluences and heads, and in the river base. The elevation at these local minima are interpolated to generate the base level surface, which is then subtracted from the original DEM to acquire surface presenting height of the terrain features from the surrounding drainage network.

The spatial distribution of incident seismic wavelength during the 2005 Kashmir earthquake is estimated from instrumental ground shaking records (courtesy of PAEC), by integrating the peak time of seismic shaking and the shear wave velocity (equation 5). The derived wavelength is compared with its spatial distance from the Kashmir earthquake epicenter, and the decay of seismic waves wavelength per meter from epicenter is derived, which is multiplied with the euclidance distance to compute the spatial distribution of seismic waves wavelength.

Equation 3: Estimation wavelength (Nave, 2000)

$$\lambda = vT$$

Where
$\lambda$= Wavelength
v=Shear wave velocity
T = Predominant time of peak acceleration

The generated topographic and seismic parameters were integrated in the numerical models to predict horizontal and vertical TAF, at a regional scale. Sensitivity analysis is performed by observing the impact of each parameter on the computed TAF. The disparity of TAF, computed from DEM derived model parameters, is performed to estimate the impact of DEM resolution on the derived TAF. Uncertainty in TAF is quantified synthetically, due to uncertainty in the utilized topographic parameters.

## 3. Results

### *3.1 Digital topographic features for predicting topographic seismic response*

Predicting the undisputable impact of topographic features on seismic response, SRTM and ASTER DEMs and computed digital topographic features were utilized to compute the parameters necessary for the topographic seismic modeling. The accuracy of the DEMs is assessed through their disparity in the terrain representation. Slope and aspect show that on average there is discrepancy of 32 m in elevation, 0.36º in slope and 1.79º in aspect representation. The spatial distribution of high discrepancies shows concentration (Fig. 3) in steep slopes, which reflects the spatial autocorrelation of the errors and sensitivity of DEMs to steep slopes. Terrain features smaller than the DEM resolutions are considerably smoothened and cannot be identified distinctly. DEM resolution has significant impact on slope and aspect in rugged terrain, while consistency is observed in flat and steep sites.

DEMs are prone to un-adjustable errors, which are assumed to be distributed randomly and normally throughout the study area. The uncertainty injected by random errors is quantified through the MCS by many (Heuvelink et al., 1990; Lanter and Veregin, 1992; Oksanen and Sarjakoski, 2005; Wechsler and Kroll, 2006). The statistical analyses of the ensemble generated from MCS predict the SRTM DEM to be more consistent in terrain representation than the ASTER DEM. The coarse resolution of the SRTM DEM also nullifies the impact of random errors on topographic attributes. The quantified uncertainty of slope and aspect (Table 1) gives the possible deviation from computed values to achieve the absolute values.

The spatial distribution of slope and aspect uncertainty shows that slope computation is sensitive to steep areas, while aspect computation is sensitive to the flat region (Fig. 4), in agreement with Carter (1992) and Florinsky (1998).

### *3.2 Relative height of terrain features and seismic waves wavelength*

Topographic seismic modeling considers the height of terrain features from some assumed base level, instead of elevation. Selecting the optimum base level from various applied techniques, and following the predecessor researchers, the nearest drainage network is assumed as a base level. The height derived from analyzing SRTM DEM presents a more elevated terrain than ASTER DEM.

Table 1. Uncertainty in slope and aspect computation from SRTM DEM.

| DEMs | Topographic attributes | Minimum | Mean | Standard deviation | Maximum |
|---|---|---|---|---|---|
| **SRTM** | Slope (degrees) | 0.03 | 0.93 | 0.17 | 1.67 |
| | Aspect (degrees) | 0.2 | 22.69 | 38.68 | 179.61 |
| **ASTER** | Slope (degrees) | 0.005 | 2.853 | 0.595 | 6.001 |
| | Aspect (degrees) | 0 | 41.41 | 45.94 | 179.68 |

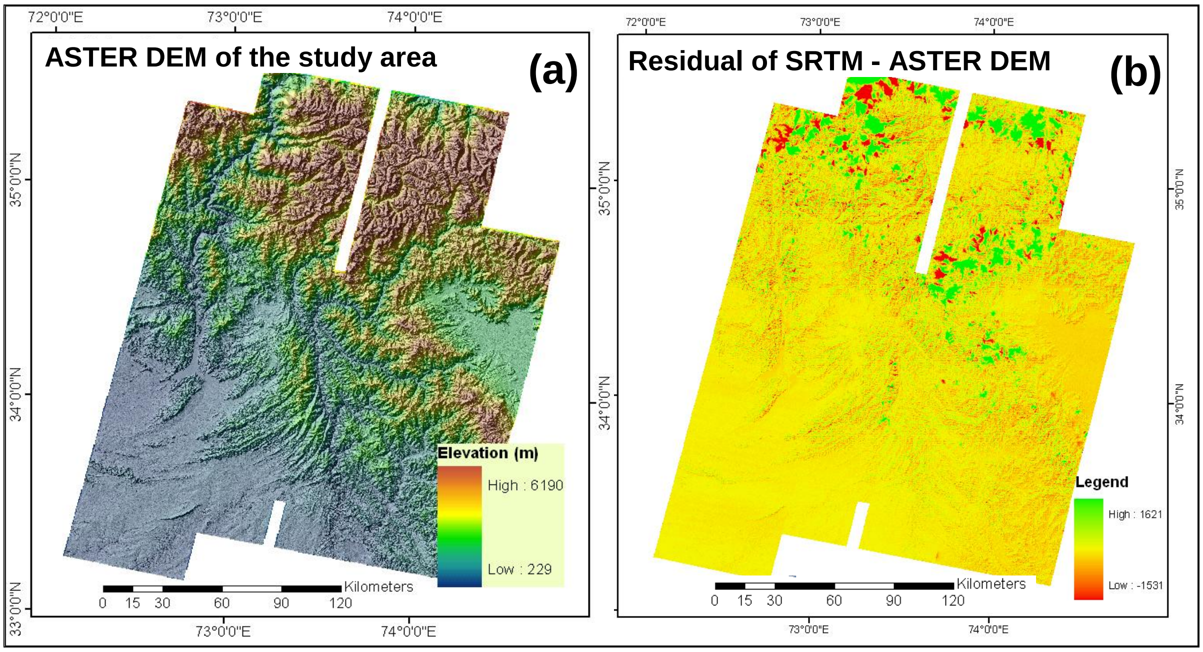


Fig. 3. (a) ASTER DEM of the study area, (b) SRTM and ASTER DEMs disparity.

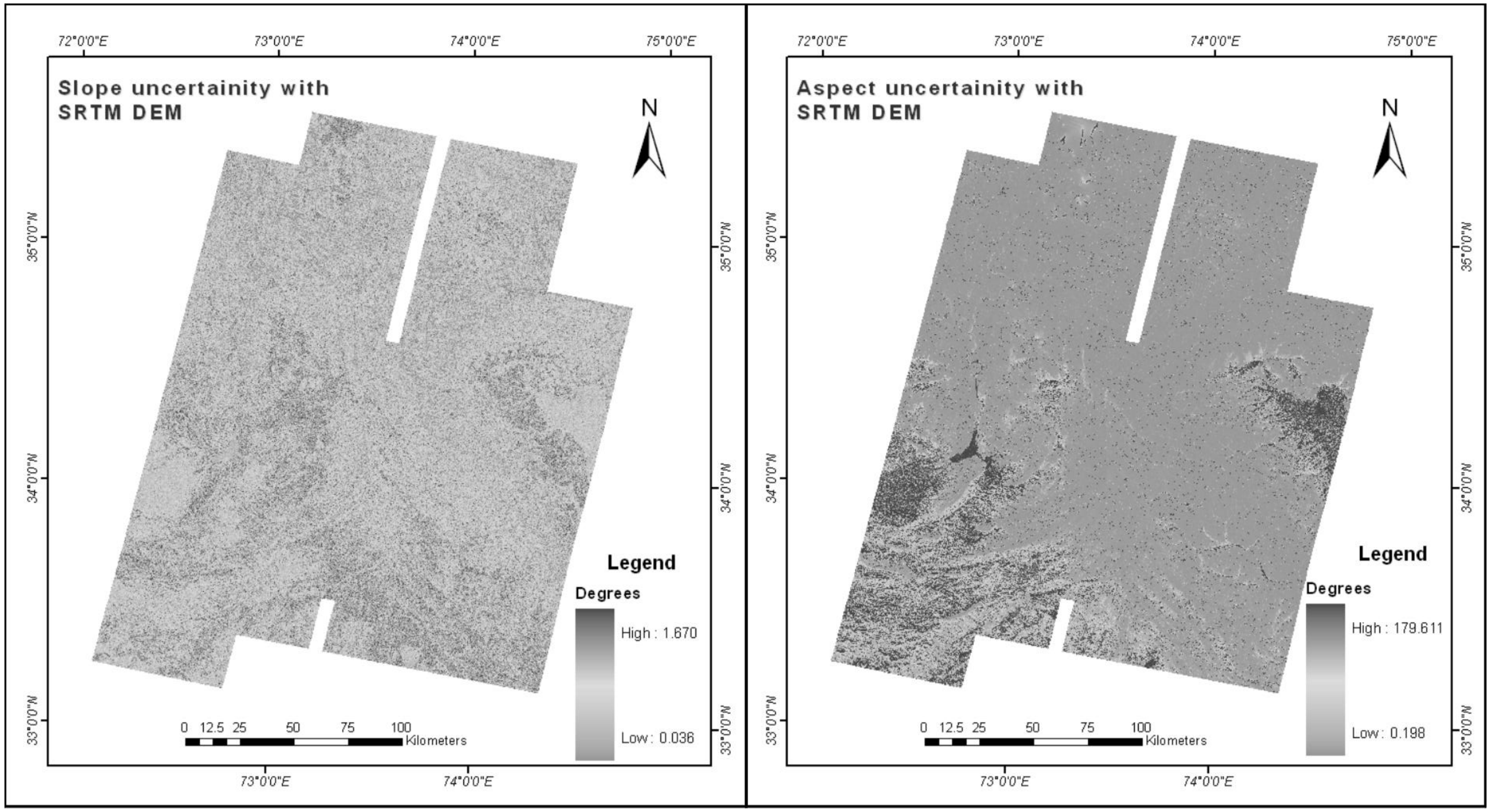


Fig. 4. Uncertainty of slope and aspect computed from SRTM DEM in geographic space.

Spatial distribution of the 2005 Kashmir earthquake induced seismic waves wavelength estimated using equation 5, incorporating the Kashmir earthquake instrumental ground shaking records and the shear wave velocity reported by Mandal et al. (2007), as 3.2 km/s for the study area. Wavelength at each recording station was calculated and is compared with their spatial distance from the epicenter. Wavelength of the seismic waves is widening as moving away from epicenter, on average there is addition of 0.055m to wavelength/m from epicenter. The euclidance distance from epicenter is multiplied with 0.055m to estimate the spatial distribution of seismic waves wavelength, which is increasing as spreading from epicenter (Fig. 5).

Since wavelength is inversely proportional to the frequency content of seismic waves, and the frequency and energy content of seismic waves is losing with distance, which eventually reduces the devastation (Fig. 5). Estimated wavelength is also affected by the DEM resolution, as area covered by 9 pixels of ASTER DEM are covered by a single pixel of SRTM DEM, hence it leads to averaging of wavelength locally, and also lower mean of wavelength regionally.

*3.3 Topographic aggravation of seismic response*

The estimated relative height and wavelength in preceding sections were applied in the numerical models of equations 3 and 4 to predict the topographic aggravation of seismic response during the 2005 Kashmir earthquake employing model parameters computed from SRTM and ASTER DEMs, classified in horizontal and vertical TAF.

The assumed SV as incident seismic waves in the model has the capacity to cause horizontal shaking, if unaffected by the medium. When these SV waves interfere with the terrain features, they are reflected and refracted, and converted to SV reflected, P reflected, and Rayleigh waves, with vertical shaking component. The vertical shaking observed in the model is due to these reflected waves, while the site beyond the approach of the reflected waves is demonstrated as the free field, believed to be protected from aggravated seismic response. Since Rayleigh waves are surface waves, they cause amplified shaking and, consequently, building damages.

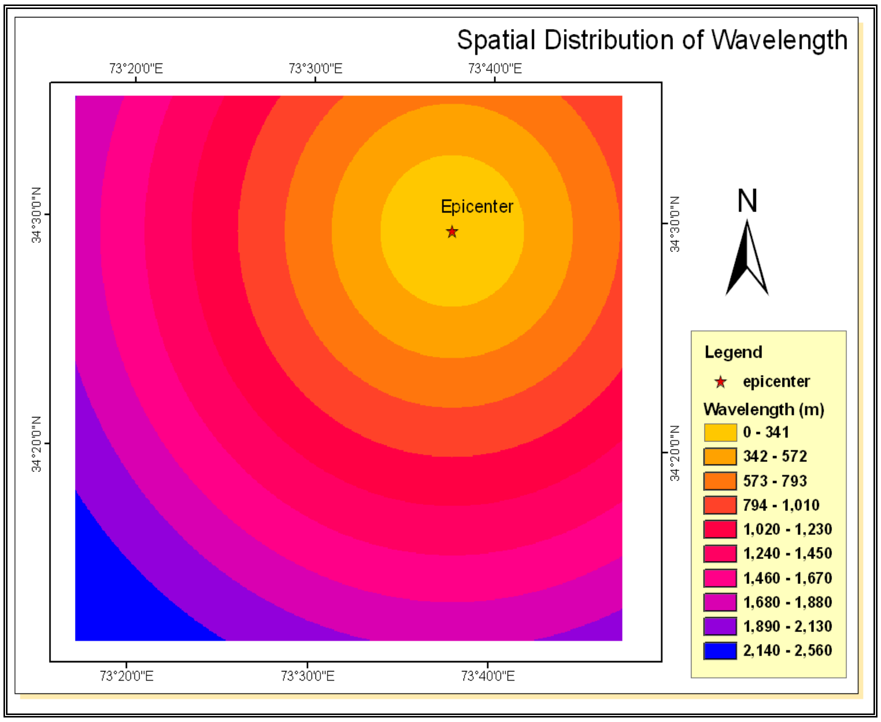


Fig. 5. Distribution of seismic waves wavelength during the 2005 Kashmir earthquake.

Horizontal ($A_h$) and Vertical ($A_v$) TAF are computed from utilizing the models in equations 3 and 4, respectively. The derived TAF predicts that the vicinities of the epicenter are aggravated due to the high frequency and energy content of incident seismic waves (Fig. 6 and 7). Steep and elevated terrain is observed with amplified seismic response. In the assumed environment, H/λ ratio is sensitive to the vertical shaking. SRTM DEM with smoothed slope, height and wavelength values, reflect rapid decay of TAF with distance from the epicenter, compared to the ASTER DEM.

### *3.4. Sensitivity analysis*

Sensitivity analysis is performed through a base terrain profile, which is modified parametrically, and the respective $A_h$ and $A_v$ are computed, to investigate the impact of predicted seismic response (Table 2). The utilized topographic and seismic parameters on sensitivity analysis conclude the slope angle as a sensitive parameter for the aggravation of seismic response followed by the terrain height.

### *3.5 Impact of DEM resolution and inherent errors on TAF*

Disparity of TAF computed from SRTM and ASTER reflect less impact of DEM resolution on the predicted horizontal and vertical TAF (Table 3). High disparity of the predicted horizontal and vertical TAF is concentrated at steep slopes, strengthening the theory of the sensitivity of the steep areas to DEMs. The impact of quantified uncertainty in the topographic attributes computed from SRTM and ASTER DEM is analyzed to quantify their impact on the predicted TAF. Uncertainty in the slope affects Av to a greater extent than Ah (Table 4).

Due to the high uncertainty in the ASTER DEM derived slope, it shows greater uncertainty in predicted topographic effects than in the SRTM DEM.

Table 2. Sensitivity analysis of terrain parameters to TAF.

| **Model Parameter** | | **Predicted results** | | **Sensitivity analysis** | | | |
|---|---|---|---|---|---|---|---|
| | | **TAF parameter** | **Base model** | **Slope 60º** | **Height 400m** | **Wavel 200m** | **Damp 10%** |
| Slope<br>Height | 30º<br>200 m | $A_{h,max}$ | 1.10 | 1.17 | 1.14 | 1.08 | 1.06 |
| Wavel<br>Damp | 100 m<br>5% | $A_{v,max}$ | 0.76 | 2.85 | 1.33 | 0.44 | 0.69 |

Wavel = Wavelength
Damp = Damping

Table 3. Disparity of TAF computed from SRTM and ASTER DEMs.

| | **SRTM DEM** | | **ASTER DEM** | | **Disparity** | | |
|---|---|---|---|---|---|---|---|
| | **Min** | **Max** | **Min** | **Max** | **Min** | **Mean** | **Max** |
| Ah ,max | 1 | 1.43 | 1 | 1.66 | -0.260 | 0.003 | 0.227 |
| Av ,max | 0 | 12.04 | 0 | 23.71 | -14.992 | 0.030 | 6.521 |

Table 4. Impact of DEM random errors on predicted TAF.

| **DEM** | **TAF** | **Uncertainty** |
|---|---|---|
| ASTER | $A_{h,max}$ | 0.002 |
| | $A_{v,max}$ | 0.123 |
| SRTM | $A_{h,max}$ | 0.001 |
| | $A_{v,max}$ | 0.040 |

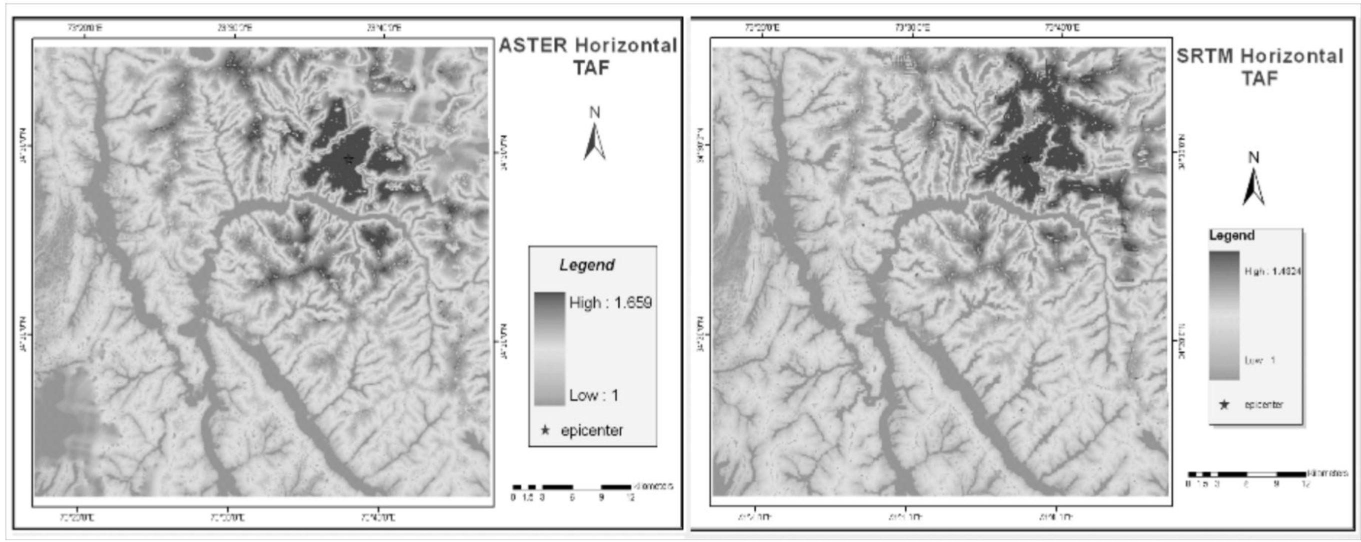


Fig. 6. Horizontal TAF computed from ASTER and SRTM DEM derived model parameters.

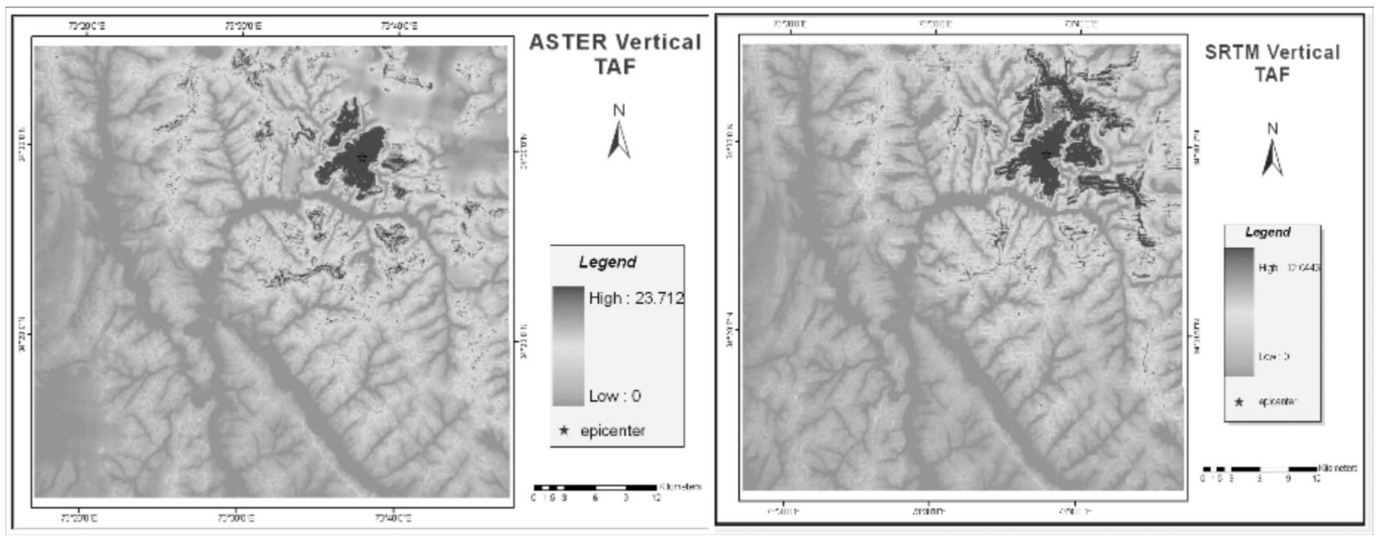


Fig. 7. Vertical TAF computed from ASTER and SRTM DEM derived model parameters

### 3.6 *Impact of direction if incident waves on seismic induced landslides*

Directions of incident seismic waves have profound impact on seismic-induced landslides and the amplified seismic response (Ashford and Sitar., 1997; Ashford et al., 1997; Pedersen et al., 1994). The Kashmir earthquake induced landslides map (courtesy of HIC-Pakistan) is compared with the aspect map of the study area (Fig. 8). The aspect of the landslides is concentrated at the terrain opposite to the direction of incident seismic waves. About 80% of the landslides are facing between west and south direction in response to incident waves from the northeast (Fig. 8).

## 4. Discussion and Conclusions

Numerically developed models were utilized and integrated with the SRS DEM attributes to predict the topographic aggravation of seismic response during the 2005 Kashmir earthquake. Accuracy and resolution of the ASTER and SRTM DEMs are adequate to predict pragmatic topographic aggravation of seismic response at a regional scale, although not at local scale. SRTM and ASTER DEMs were observed to be sensitive to the rough terrain. The SRTM DEM, with coarse resolution, is more consistent in slope and aspect computation than ASTER. The SRTM DEM was sensitive to slope computation, especially in steep terrain and for narrow features, particularly when the terrain features were smaller than the DEM grid size.

The applied model predicts high aggravation of sites close to the epicenter, due to higher frequency and energy content of the incident seismic waves. Seismic response fluctuation is sensitive to slope geometry and height of the terrain features. Inclined terrain features significantly affect the diffraction and reflection of incident seismic waves, amplifying or de-amplifying the seismic response. The direct seismic waves have higher amplitude than the reflected waves, resulting in the terrain having an aspect opposite to the direction of incident seismic waves, which is true for 80% of the Kashmir earthquake induced landslides. Impact of DEM random errors and resolution has less impact on the predicated topographic seismic response.

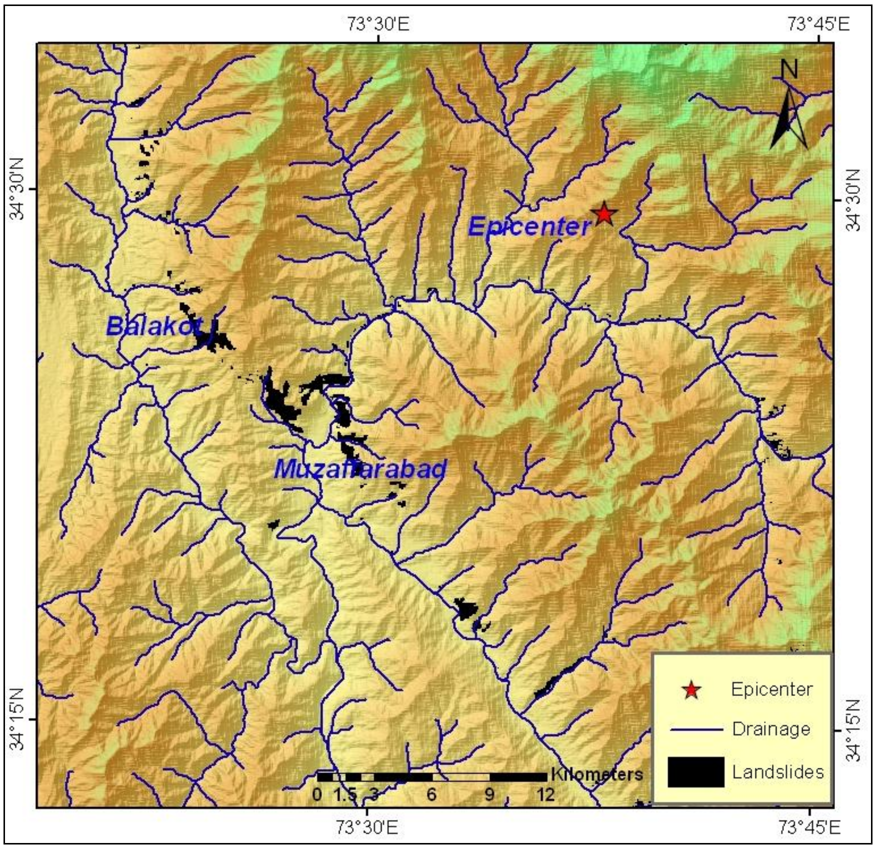


Fig. 8. Impact of direction of incident waves on seismic-induced landslides.

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