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Impact of topographic parameters on seismic amplification applying Geospatial tools

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ABSTRACT: The impact of topography on the uneven distribution of seismic response is well observed synthetically, experimentally and visually during seismic events. Numerical and experimental investigations for predicting topographic effects on seismic shaking are limited to isolated and/or synthetic hills and ridges. Furthermore, most of these studies only focus on one of the many terrain parameters necessary for analyzing the impact of topographic features on amplification or de-amplification of seismic response. Seismic events located in rough terrain, like the Kashmir earthquake (2005) in the western Himalaya, exhibit intensified ground shaking and associated devastation at hill ridges and on inclined slopes. Regional seismic ground shaking maps developed through USGS-ShakeMap ignore this topographic impact. DEM derived topographic attributes and seismic event characteristics can be integrated, to predict the topographic seismic amplification.

Satellite sensor's acquired SRTM (90 m) and ASTER (30 m) DEMs are employed to compute terrain attributes, and also to investigate the impact of DEM random errors and resolution on the topographic attributes, and topographic seismic response. Data disparity of SRTM and ASTER DEMs, and derived topographic attributes, imply the sensitivity of satellite remote sensing DEMs, to rugged terrain and steep slopes. Impact of DEM random errors on derived topographic attributes is quantified through Monte Carlo Simulation that shows higher consistency of SRTM DEM to derived topographic attributes. Impact of slope angle, relative height, wavelength and damping on amplification and de-amplification of seismic response is analyzed, in homogeneous lithological and geotechnical environment. Seismic response is predicted to be sensitive to the slope geometry, among the analysed parameters. DEM resolution and random errors have meager impact on the predicted topographic seismic response.

1 INTRODUCTION

Natural disasters are dynamic and uncertain processes that can have adverse impact on, and a threat to, sustainable socio-economic development (Morales, 2002). Forecasting disasters in advance, assists to minimize the potential devastation, but unfortunately predicting earthquakes remains impossible with the current understanding and technology. Earthquakes have proved to be the most devastating natural disaster, with a high mortality rate and a wide spread destruction (Alexander, 1993). The strength and duration of seismic ground shaking, that plays a key role in seismic devastation, depends on the earthquake magnitude, location of epicenter, medium traversed by the seismic waves and the physical characteristics like geology, topography and soil conditions of the site (Kramer, 1996). In rough terrain, like the western Himalaya covering northern Pakistan, topography and soil thickness significantly controls, the intensity of seismic ground shaking. The existing models predicting seismic ground shaking at regional scale such as USGS-Shakemap and (INGV) are ignoring the topographic impact, while the seismic events are usually associated with mountainous regions, therefore limiting their reliability at local scale.

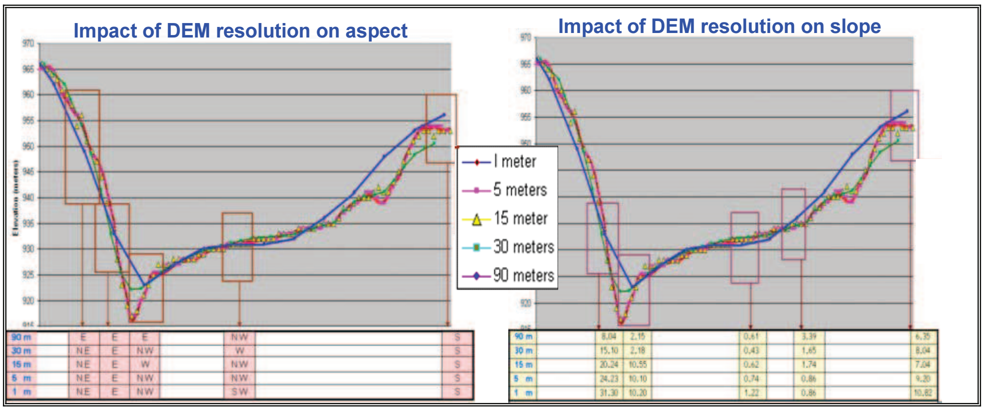

Figure 1. Impact of DEM resolutions on realistic representation of terrain features. At 1, 5, 15 m resolutions, smaller features and edges can be separately identified, while at 30 and 90 m resolution, the terrain appears smoothening and minor features are disappearing.

Extensive numerical, analytical and experimental techniques have been applied to investigate and predict the impact of various terrain features on amplification or deamplification of seismic response. These studies are in agreement in predicting amplification of seismic response at the slope crest, and deamplification at the slope toe (Ashford et al., 1997a; Ashford et al., 1997b; Athanasopoulos et al., 1999; Bard, 1982; Bouckovalas et al., 2005; Chávez-García et al., 2000; Sanchez-sesma et al., 1982; Stamatopoulos et al., 2007). Parametric studies analysing the impact of various topographic features on seismic response, leads to deriving numerical models, that predict topographic aggravation of seismic response. Main limitation of these studies is that they are limited to a synthetic environment and/or isolated hills, not applied at regional scale.

Investigating topographic impact at regional scale, the Satellite Remote Sensing (SRS) acquired Digital Elevation Model (DEM) and their derived terrain information, can potentially be utilized, to predict topographic amplification of seismic response, in real case scenario of rough terrain. With development in remote sensing technology and techniques, SRS acquired DEMs are available at range of resolutions, accuracy and at global coverage. Resolution of DEM significantly affects the realistic representation of the terrain and derived topographic attributes (Fig. 1).

Shuttle Radar Topography Mission (SRTM) DEM at 90 m grid size and Advance Spaceborne Thermal Emission and Reflective Radiometer (ASTER) DEM at 30 m grid size are utilized, to compute the required topographic attributes (slope, aspect, relative height, curvature) for seismic amplification modeling. Consistency of SRTM and ASTER DEMs is investigated, and impact of their respective random errors and resolution on derived topographic attributes is also estimated. The derived topographic attributes were incorporated in synthetically developed numerical model, to predict the topographic aggravation of seismic response. Impact of DEM resolution and data source on predicted topographic amplification is also quantified. The study area is located around the cities of Balakot and Muzaffarabad, located in north Pakistan, that were severely devastated during the 8th October 2005 Kashmir earthquake (Fig. 2).

2 METHODOLOGY

This study investigates the applicability, and the impact of DEM random errors and resolution on the predicting topographic amplification of seismic response (Fig. 3). SRS recorded SRTM and ASTER DEMs of study area were acquired from USGS and ERSDAC respectively, with the assumption that blunders and the systematic errors in the DEMs are already adjusted. Due to unavailability of reference data for DEM accuracy assessment, consistency of the utilized SRTM and

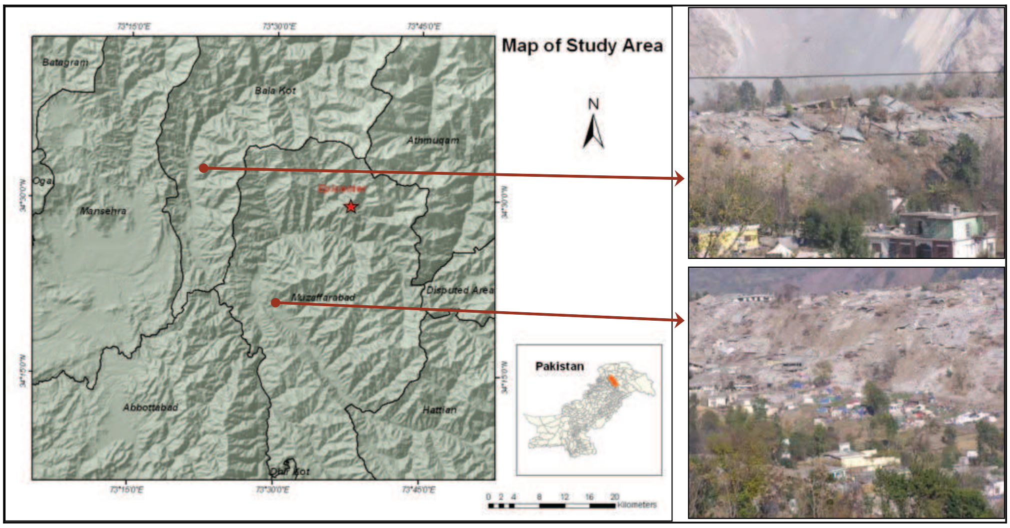

Figure 2. Location map of study area, source and surrounding of 2005 Kashmir earthquake.

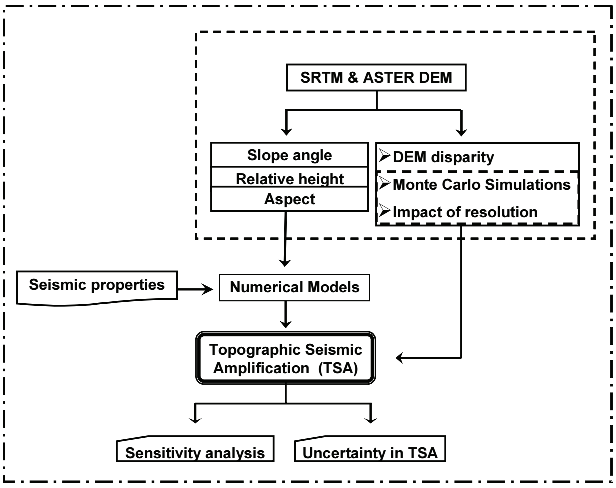

Figure 3. Flow chart of methodology adopted for the study.

ASTER DEMs is investigated through the disparity calculation, of the elevation data and their derived slope and aspect. The impact of DEM resolution on the terrain representation and computed topographic attributes is portrayed through comparing the terrain profile generated from the DEMs of various resolutions.

In contrast to elevation recorded by SRTM and ASTER DEMs, topographic seismic modeling requires relative height of terrain features from the assumed base level. Following the predecessors research such as Bouckovalas et al. (2005), Assimaki et al. (2004), Ashford et al. (1997a) and Pedersen et al. (1994), the nearest drainage network is assumed as base level, for the surrounding terrain features. To implement the theory, local minima are manually selected at the streams confluence and heads, and in the river base. Local minimal spots were assign elevation from the respective DEM, and interpolated to derive a continuous surface, as the assumed base level for the

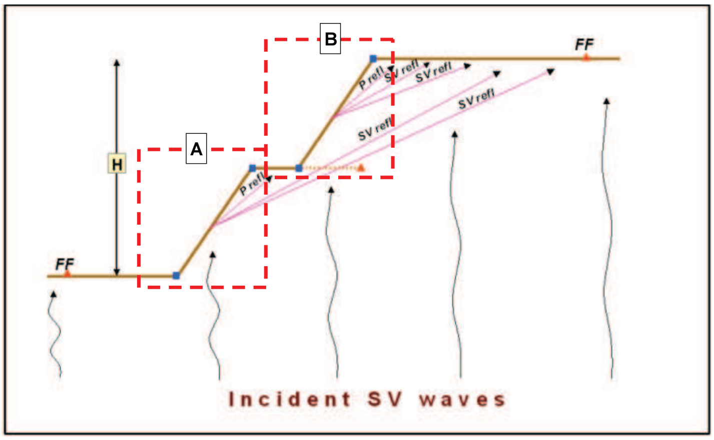

Figure 4. Applicability limitation of synthetic model to real world.

study area. The generated base level surface is subtracted from the original DEM, resulting in surface exhibiting height of terrain from the nearest drainage network.

DEMs acquired directly through the satellite sensors are prone to blunders, systematic and random errors. The blunders and systematic errors were assumed to be adjusted in the utilized DEMs, the presence of un-adjustable random errors injects uncertainty in the derived topographic attributes. Monte Carlo Simulations (MCS) technique is applied to quantify the uncertainty in the slope and aspect computation from SRTM and ASTER DEMs, in the rough terrain of northern Pakistan. MCS is commonly used by many researchers to evaluate errors in GIS data, and specifically to address DEM uncertainty (Heuvelink et al., 1990; Lanter et al., 1992; Oksanen et al., 2005; Wechsler et al., 2006). Elevation values are added to the model in the provided uncertainty (e.g. RMSE), randomly and normally distributed throughout the model to derive the topographic attributes. The 100 simulation are arbitrarily selected, and analysed to quantify the uncertainty in the computed slope and aspect.

Extensive literature is reviewed to search for a numerical model predicting impact of topographic features and seismic wave's properties on seismic response. Bouckovalas et al. (2006) developed and verified numerical model predicting topographic aggravation factor (TAF) taking into consideration slope geometry, height of terrain feature, seismic wave's wavelength and material damping, assuming SV as a incident seismic waves in homogenous soil and lithological environment.

$$A_{h,\max} = a_h / a_{h,ff} \tag{1}$$

Equation 1. Numerical representation of horizontal TAF (Bouckovalas et al., 2006).

where a_h = Peak horizontal acceleration at any point, $a_{h,ff}$ = Peak horizontal acceleration at free field.

The a_h depends on relative height of terrain, slope inclination, wavelength of approaching seismic waves and material damping (Bouckovalas et al., 2006). The applied TAF predicting numerical model is felt to be most comprehensive in incorporating the crucial topographic and seismic parameters, compared to other available models.

The aforementioned numerical model was developed by using the synthetic terrain profile (Fig. 4), ranging from slope toe to crest. Applying this model on the DEM attributes will assume each DEM pixel (Fig. 4, A & B) as separate terrain profile, which limits the applicability of numerical model at regional scale.

Table 1. Disparity of SRTM-ASTER DEMs and derived attributes

Category	Disparity (SRTM-ASTER)		
	Minimum	Mean	Maximum
Elevation (m)	–1531	32.80	1621
Slope (degrees)	–82.32	–0.36	74.54
Aspect (degrees)	–360.14	1.79	360.89
Relative height (m)	–451.77	25.84	1012.22

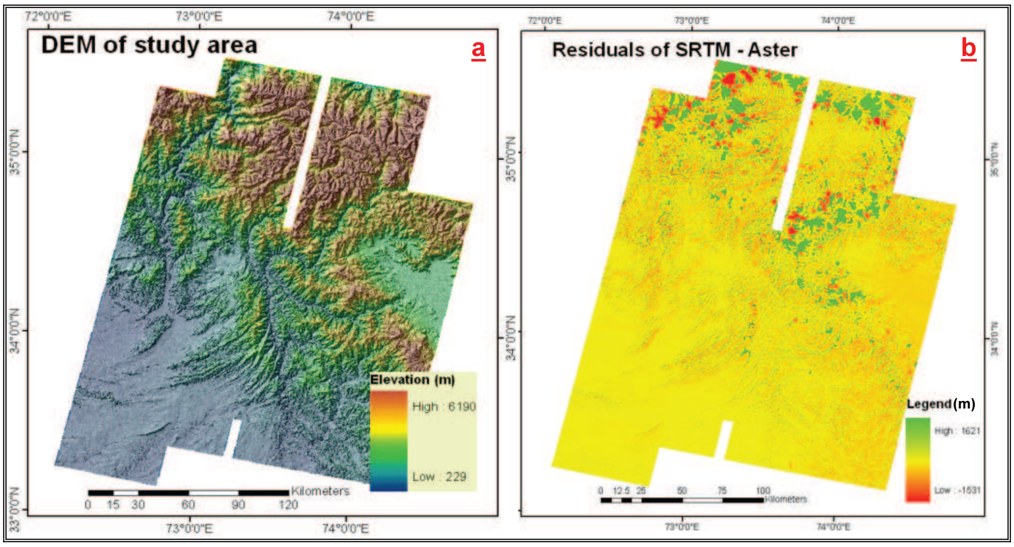

Figure 5. (a) ASTER DEM of the study area, (b) SRTM and ASTER DEMs disparity.

The derived digital topographic parameters and assumed seismic characteristics are integrated in a numerical model, to predict the topographic amplification of seismic response. Sensitivity of the model parameters to seismic response is determined through sensitivity analysis. Uncertainty in the predicted TAF, due to uncertainty in the applied topographic attributes, is quantified, and the impact of DEM resolution is also investigated.

3 RESULTS

3.1 *Disparity of SRTM and ASTER DEMs*

The disparity of SRTM and ASTER DEMs, predict consistency in recoding elevation and topographic attributes on flat terrain, while large discrepancies are clustered in rugged terrain (Fig. 5, b). On average there are minor differences in slope and aspect estimation at same location from SRTM and ASTER DEMs (Table 1).

Figure 5, reflect clear signs of spatial autocorrelation of residuals, which strengthens the theory of sensitivity of SRS DEMs to rugged terrain.

The relative height of the terrain features estimated from the surrounding drainage network shows that SRTM DEM besides course resolution, present the relative height of terrain feature elevated than ASTER (Table 1). While in geographic space the disparity of SRTM and ASTER DEMs derived relative heights are in agreement with the Fig. 5, presenting higher discrepancy concentrated on steep slopes.

Table 2. Uncertainity in slope and aspect derieved from SRTM and ASTER DEMs

DEMs	Topographic attributes	Minimum	Mean	Standard deviation	Maximum
SRTM	Slope (degrees)	0.03	0.93	0.17	1.67
	Slope (Percentage)	0.01	1.63	0.30	2.92
	Aspect (Degrees)	0.2	22.69	38.68	179.61
ASTER	Slope (degrees)	0.005	2.85	0.59	6.01
	Slope (Percentage)	0.008	4.98	1.038	10.51
	Aspect(Degrees)	0	41.41	45.94	179.68

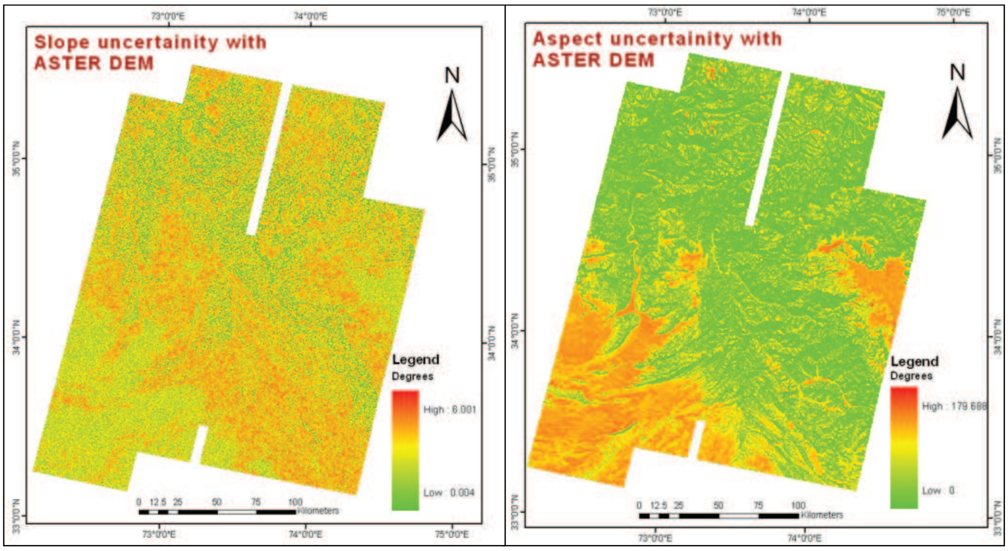

Figure 6. Uncertainty of slope and aspect computed from ASTER DEM in geographic space.

3.2 *Impact of DEM resolution and random errors on topographic attributes*

Impact of DEM resolution on the terrain representation and derived topographic attributes is presented in Fig. 1, which shows that as the resolution gets coarser, the features smaller than the DEM grid size are disappearing, due to smoothening effect, and the slope angle also starts reducing. Aspect is affected significantly with varying DEM resolution, particularly in narrow valleys. Figure 1, reflects the sensitivity of aspect estimation to the rugged terrain, while consistency is observed on steep slopes. While slope computation is sensitive to rugged terrain and to steep slopes, while consistent in flat terrain.

The impact of random errors on derived topographic attributes is determined, and uncertainty is quantified through Monte Carlo Simulations (MCS). Statistical analysis of the MCS predicts SRTM DEM more consistent in slope and aspect computation, compared to ASTER DEM. Coarse resolution of SRTM DEM also nullifies the impact of random error on computed slope and aspect, to some extent. Although the applied RMSE of ASTER DEM is just 4 m higher than SRTM DEM, but comparatively fine resolution, magnify the uncertainty in the computed topographic attributes. MCS derived values in Table 2, quantify the possible deviation or the uncertainties in the computed slope and aspect values from the reality.

The spatial distribution of slope and aspect uncertainty in Fig. 6 reflects the slope computation is more sensitive to steep slopes, while the aspect computation is sensitive to flat areas, which are in agreement with the Carter (1992) and Florinsky (1998).

Table 3. Sensitivity of terrain parameters to TAF

Model Parameter		Predicted results		Sensitivity analysis			
		TAF parameter	Base-model	Slope 60°	Height 400m	Wavel 200m	Damp 10%
Slope	30°	$A_{h,max}$	1.10	1.17	1.14	1.08	1.06
Height	200 m						
Wavel	100 m						
Damp	5%						

Wavel = Wavelength
Damp = Damping

Table 4. Disparity of TAF computed from SRTM and ASTER DEMs

	SRTM DEM		ASTER DEM		Disparity		
	Min	Max	Min	Max	Min	Mean	Max
$A_{h,max}$	1	1.43	1	1.66	–0.260	0.003	0.227

Table 5. Uncertainty in TAF predicted from ASTER and SRTM DEM

ASTER DEM	$A_{h,max}$	Slope (30°)	Slope (32.853°)	Slope (27.147°)	Uncertainty
		1.104	1.103	1.105	0.002
SRTM DEM			Slope (30.935°)	Slope (29.065°)	Uncertainty
			1.104	1.104	0.001

3.3 *Topographic aggravation of seismic response*

The numerical model (Eq. 1) is applied to predict the impact of topographic features on aggravation of seismic response. The model is applied to synthetic terrain profiles, due to its limitation of applicability, in real environment and at regional scale. The impact of model parameters on derived TAF is determined through base terrain of varying input parameters. The model parameters are doubled gradually, and TAF is computed to explore the sensitivity of each parameter to TAF (Table 3). The sensitivity analysis implies the slope angle as a sensitive parameter for the aggravation of seismic response.

3.4 *Impact of DEM resolution and random errors on TAF*

Disparity of TAF computed from SRTM and ASTER reflect meager impact of DEM resolution, on the predicted horizontal TAF (Table 4).

The uncertainty in the computed TAF, due to random errors in ASTER and SRTM DEMs is quantified in Table 5. Due to the high uncertainty in the ASTER DEM derived slope, it shows greater uncertainty in predicted topographic effects than from SRTM DEM.

4 DISCUSSIONS AND CONCLUSIONS

The extensive previous efforts on predicting the topographic impact on the variation of seismic response, lead to formulation of numerical models incorporating the topographic features and seismic properties. This study integrates DEM derived topographic features such as slope and relative height, and seismic wave characteristics in a numerical model, to predict topographic amplification or deamplification of seismic response.

Satellite remote sensing DEMs, like SRTM and ASTER DEMs and their derived topographic attributes are observed to be sensitive to steep slopes in terrain representation. The SRTM DEM, with coarse resolution, is predicted more consistent in slope and aspect computation than ASTER DEM. SRTM DEM is observed in representing terrain elevated than the ASTER DEM. The slope computation from SRTM and ASTER DEMs is prone to exaggerated errors on steep slopes, while the aspect computation is sensitive to flat areas. The coarse resolution DEMs were sensitive to the slope computation, especially in steep terrain and for narrow features, particularly when the terrain features were smaller than the DEM grid size.

DEM derived topographic attributes with quantified uncertainty, assumed wavelength of incident seismic waves and material damping are incorporated in numerical model, predict slope angle sensitivity to the predicted TAF. The Slope geometry controls the clustering of reflected seismic waves from terrain features, while height controls the number of incident seismic waves. SRTM and ASTER DEMs random errors and resolution, predict meager impact on the derived TAF.

REFERENCES

Alexander, D. (1993) “Natural Disasters”. USL Press, United Kingdom.

Ashford, S.A. and N. Sitar. (1997a) “Analysis of Topographic Amplification of Inclined Shear Waves in a Steep Coastal Bluff”. Bulletin of the Seismological Society of America, 87, 692-700.

Ashford, S.A., N. Sitar, J. Lysmer and N. Deng. (1997b) “Topographic Effects on the Seismic Response of Steep Slopes”. Bulletin of the Seismological Society of America, 87, 701-709.

Assimaki, D. and G. Gazetas. (2004) “Soil and Topographic Amplification on Canyon Banks and the 1999 Athens Earthquake”. Journal of Earthquake Engineering, Imperial College Press, 8, 1-43.

Athanasopoulos, G.A., P.C. Pelekis and E.A. Leonidou. (1999) “Effects of surface topography on seismic ground response in the Egion (Greece) 15 June 1995 earthquake”. Soil Dynamics and Earthquake Engineering, 18, 135-149.

Bard, P.Y. (1982) “Diffracted waves and displacement field over two-dimensional elevated topographies”. Geophysical Journal International, 71, 731-760.

Bouckovalas, G. and A.G. Papadimitriou. (2006) “Aggravation of seismic ground motion due to slope topography”, First European Conference on Earthquake Engineering and Seismology, Geneva-Switzerland, 1-10.

Bouckovalas, G.D. and A.G. Papadimitriou. (2005) “Numerical evaluation of slope topography effects on seismic ground motion”. Soil Dynamics and Earthquake Engineering, 25, 547-558.

Carter, J.R. (1992) “The effect of data precision on the calculation of slope and aspct using gridded DEMs”. Cartographica, 29, 22-34.

Chávez-García, F.J., D. Raptakis, K. Makra and K. Pitilakis. (2000) “Site effects at Euroseistest—II. Results from 2D numerical modeling and comparison with observations”. Soil Dynamics and Earthquake Engineering, 19, 23-39.

Dunning, S.A., W.A. Mitchella, N.J. Rossera and D.N. Petleya. (2007) “The Hattian Bala rock avalanche and associated landslides triggered by the Kashmir Earthquake of 8 October 2005”. Engineering Geology, 93, 130-144.

Florinsky, I.V. (1998) “Accuracy of local topographic variables derived from digital elevation models”. International Journal of Geographical Information Science, 12, 47-61.

Heuvelink, G.B.M., P.A. Burrough and H. Leenaers. (1990) “Error propagation in spatial modelling with GIS.” Proceedings of the First European Conference on Geographical Information Systems EGIS’ 90, Amsterdam, The Netherlands, 453-462.

INGV. (2006) “Istituto Nazionale di Geofisica e Vulcanologia, DPC – S4 Project”. Website: http://earthquake.rm.ingv.it/index.php, Accessed: Accessed 15 November 2007.

Kramer, S.L. (1996) “Geotechnical Earthquake Engineering”. Prentice Hall International Series, New Jersey, 653 pp.

Lanter, D. and H. Veregin. (1992) “A research based paradigm for propagating error in layer-based GIS”. Photogrammetric Engineering & Remote Sensing, 58, 825-833.

Morales, A.L.M. (2002) “Urban Disaster Management, A case study of Earthquake Risk Assessment in Cartago, Costa Rica”. PhD-Thesis, Utretch University, The Netherlands. 235 pp.

Oksanen, J. and T. Sarjakoski. (2005) “Error propagation of DEM-based surface derivatives”. Computers & Geosciences, 31, 1015-1027.

Pedersen, H.A., F.J. Sanchez-Sesma and M. CampiIlo. (1994) “Three-Dimensional Scattering by Two-Dimensional Topographies”. Bulletin of the Seismological Society of America, 84, 1169-1183.

Sanchez-sesma, F.J., I. Herrera and J. Aviles. (1982) “A boundary method for elastic wave diffraction: Application to scattering of SH waves by surface irregularities". Bulletin of the Seismological Society of America, 72, 473-490.

Stamatopoulos, C.A., M. Bassanou, A.J. Brennan and G. Madabhushi. (2007) “Mitigation of the seismic motion near the edge of cliff-type topographies”. Soil Dynamics and Earthquake Engineering, In Press, Corrected Proof.

Wechsler, S.P. and C.N. Kroll. (2006) “Quantifying DEM Uncertainty and its Effect on Topographic Parameters”. Photogrammetric Engineering & Remote Sensing, 72, 1081-1090.