**Is There a Safe Spot?
Modeling Seismic Amplification
with Spectral Element Method and
DEM based Topography**

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ITC

FACULTY OF GEO-INFORMATION SCIENCE AND EARTH OBSERVATION

**IS THERE A SAFE SPOT?
MODELING SEISMIC AMPLIFICATION WITH
SPECTRAL ELEMENT METHOD AND DEM BASED
TOPOGRAPHY**

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Summary

The earth's topography reflects seismic energy which can lead to scattering or focusing of seismic waves, and thereby amplifies or de-amplifies the seismic response. Estimation of such site effects on ground shaking is often done using 1D or 2D numerical codes. These studies are usually limited to small spatial area (single basin or ridge). However, because of the large extent of a seismically active area, with at least the same area affected by an earthquake, regional evaluation of site effects on seismic response is required that is also applicable at local scale. Existing regional studies on seismic induced ground shaking and expected damage (like USGS-ShakeMap and PAGER in near-real time for effective response activities) are derived at coarse resolutions of around 1 km², hence giving much generalization in results. Furthermore, quite a few of these approaches adopt proxies for estimating the seismic effect instead of applying realistic wave propagation models.

This study aims to cover the gap between these two extremes of scale and investigate impact of topography on a regional scale using the spectral element method (SEM) technique; thereby adopting a realistic full-elastic waveform modeling approach. SEM is a technique that can be used for simulating 3D seismic wave propagation to estimate ground shaking. It incorporates a 3D physical model, with a particular focus on the simulation of the interaction of seismic waves with a free-surface topography through a full elastic waveform simulation including all possible waves, based on realistic source characteristics of an earthquake. The Digital Elevation Model (DEM) and spectral element mesh resolutions play an important role in influencing estimation of ground shaking when performing SEM simulation. DEM resolution influences the accuracy and detail with which the Earth's surface can be represented and hence affects seismic simulation studies. Apart from the spatial resolution of a DEM, the mesh resolution, adopted in the creation of a 3D spectral element meshing, also changes the detailedness of surface topography. Furthermore, with the use of high resolution data, the computation cost increases and may not be processed without supercomputing. There-

fore, we evaluate how low the resolution of DEM and mesh can become before the results are significantly affected. We simulated models with different combinations of DEM and mesh resolutions. The peak ground displacement obtained from these simulations was compared with the peak ground displacement of the model having the finest mesh and DEM resolution. Our results show that any mesh or DEM resolution of 540 meters or coarser would give unrealistic results.

The 2005 Kashmir earthquake was one of the most devastating natural disaster in northern Pakistan, resulting in heavy loss of life and infrastructure. Muzaffarabad city (Kashmir region, north Pakistan) and its surrounding areas were severely affected. Previous studies showed manifestations of topographic effects on seismic amplification and infrastructural damage. This study investigates the influence of topography on seismic amplification during the 2005 Kashmir earthquake. The 2005 Kashmir earthquake is simulated in 3D with SEM in the area of Muzaffarabad and adjacent areas. The study shows that the ridges in the area experience an amplified seismic response while the valley shows overall a de-amplified seismic response. There is a clear relation between seismic amplification and the occurrence of landslides. Slopes facing away from the source receive an amplified seismic response resulting in an increased landslide occurrence rate than slopes facing away from the earthquake source. Furthermore, 98 % of the highly damaged areas are located in the topographically amplified seismic response zone.

Major efforts are being put into minimizing the impact of earthquakes since the prediction of the exact time and location of an earthquake is still not possible. The SEM modelling is applied in a kind of probabilistic approach to map the potential hazard due to earthquakes, including the topographic effect. The area of focus is also here on the Kashmir region, which lies on a converging plate boundary between the Indian and Eurasian plate. Predictions are that this region is prone to future large earthquakes because of the continuous build up of tension on these boundaries. We simulate 25 scenario earthquakes on main faults in the region based on earthquake characteristics of the 2005 Kashmir earthquake. We estimate the expected ground shaking, including topographic amplification effects from potential future earthquakes in the region. These 25 scenarios are used to build a seismic hazard map for the study area that can be used by concerned organization for disaster management practices.

Samenvatting

De topografie van de aarde reflecteert seismische energie, wat zorgt voor verspreiding of concentratie van seismische golven, wat resulteert in versterking of verzwakking van het seismische signaal. Het schatten van zulke nevenactiviteiten van grondtrillingen is vaak gedaan aan de hand van numerieke modellen in één of twee dimensies. Zulke studies zijn gelimiteerd tot kleine gebieden op de schaal van een geologisch bekken of bergkam. Vanwege de grote omvang van een seismisch actief gebied, met minstens hetzelfde gebied getroffen door een aardbeving, inschattingen van de lokale effecten op de seismische reactie is noodzakelijk, die ook toepasbaar is op de lokale schaal. Huidige regionale studies over de door seismiek beïnvloedde grond trilling en de daarbij verwachte schade (zoals USGS-ShakeMap en Pager die 'real-time' effecten van het seismische signaal voorspellen) zijn verkregen op een lage resolutie van circa 1 km², waardoor de resultaten worden gegeneraliseerd. Verder doen een aantal van deze benaderingen inschattingen van seismische effecten in plaats van het toepassen van realistische golf verspreidingsmodellen.

Deze studie heeft het doel om het gat in kennis tussen de twee extremen in schaal en het bestuderen van de invloed van topografie op regionale schaal in te vullen door gebruik te maken van een spectrale element methode (SEM) techniek waarbij een realistische volledige golfvorm modellering toegepast wordt. SEM is een techniek dat kan worden gebruikt het in 3D simuleren van de seismische golf verspreiding, om een inschatting van golftrillingen te kunnen maken. Het combineert een 3D fysisch model, met een specifieke focus op de simulatie van de interactie van seismische golven met een topografie in een gebied door middel van een volledige elastische golfvorm simulatie met alle mogelijke golven, gebaseerd op een realistische bron die karakteristiek is voor een aardbeving. De resolutie van het digitaal hoogte model en het spectrale element model spelen een belangrijke rol voor het inschatten van golftrillingen wanneer een SEM simulatie wordt uitgevoerd. De resolutie van het hoogte model beïnvloedt de nauwkeurigheid en de detail

waarmee het oppervlak van de aarde kan worden vertegenwoordigd en daardoor beïnvloedt het de seismische simulatie. Naast de resolutie van het hoogte model, is ook de model resolutie van invloed op de details van de oppervlakte topografie. Door het gebruik van hoge resolutie data worden de computer berekeningen zwaarder, waardoor het gebruik van een supercomputer mogelijk noodzakelijk is. Daarom evalueren we hier hoe laag de resolutie van het hoogte model en de het ondergrond model kunnen zijn voordat er een significant verschil waarneembaar is. Simulaties worden uitgevoerd met verschillende resoluties van het ondergrond en het hoogte model. De maximale oppervlak verplaatsing volgens de simulaties zijn vergeleken met de maximale verplaatsing volgens het model met de hoogste resolutie van het ondergrond en het hoogte model. De resultaten laten zien dat bij een resolutie van het ondergrond of hoogte model van 540 meter de resultaten onrealistisch worden.

De Kashmir aardbeving van 2005 was een van de meest vernietigende natuurrampen in noord-Pakistan, die zorgde voor vele doden en zware schade aan de infrastructuur. De stad Muzaffarabad (regio Kashmir, noord-Pakistan) en omstreken raakte zwaar beschadigd. Eerdere studies toonde de invloed van topografie op de seismische amplificatie, en de schade op infrastructuur. In dit onderzoek wordt de 2005 Kashmir aardbeving gesimuleerd in 3D, door middel van SEM, in de omgeving van Muzaffarabad. Onderzoek wijst uit dat de seismische reacties wordt versterkt in bergkammen terwijl de seismische reactie in de valleien wordt verzwakt. Er is een duidelijk verband te zien tussen de toename van seismische reactie en het voor komen van aardverschuivingen. Hellingen in tegenovergestelde richting van de bron ervaren een versterking van de seismische reactie wat zorgt voor een toename in aardverschuivingen ten opzichte van de hellingen met de helling richting naar de bron van de aardbeving. Verder is 98 % van de zwaar getroffen gebieden in het gebied met een versterkte seismische reactie.

Als laatste hebben we gekeken naar seismisch risico analyse. Het meeste werk in dit veld is gedaan in het minimaliseren van de impact van aardbevingen omdat de voorspelling van de tijd en locatie van een aardbeving is nog steeds nog niet mogelijk. Het SEM model is toegepast in een soort van waarschijnlijkheid benadering om de mogelijke schade door aardbeving in kaart te brengen, inclusief de topografische invloed. Het onderzoeksgebied is ook hier de Kashmir regio, op de convergerende plaat overgang tussen de Indische en Eurazische plaat. Voorspellingen zijn dat de regio getroffen zal worden door toekomstige grote aardbevingen omdat de spanning op deze plaatgrens blijft toenemen. We simuleren 25 scenario aardbevingen op de voornaamste breuken in de regio gebaseerd op aardbeving eigenschappen van de 2005 Kashmir aardbeving. Wij schatten de verwachte grond trillingen

in, inclusief de topografische versterkende effecten van de potentiële komende aardbevingen. Deze 25 scenario's zijn gebruikt om een seismische rampen kaart te maken voor het beschreven studiegebied die kan worden gebruikt voor betrokken organisaties voor risico management toepassingen.

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General Introduction

1

Earthquakes are disasters that cause ground shaking on the earth surface, which in turn leads to loss of life and infrastructure. Since the prediction of exact time and location of earthquakes is not possible, therefore major efforts are made for minimizing its damaging effects. In depth studies, on factors responsible for ground shaking have led to demarcation of hazardous regions, formulation of mitigation and preparedness strategies. The 2005 Kashmir earthquake was one the devastating natural disaster resulting in heavy loss of life and infrastructure. The area of Kashmir lies on a converging plate boundary of the Indian plate and the Eurasian plate. It is why this area is exposed to more earthquakes in the future. In this study, with the help of modern numerical simulation we simulate the 2005 Kashmir earthquake to analyse its induced ground shaking. Furthermore, we create scenario earthquakes of similar characteristic for the same area at potential locations to estimate expected ground shaking emerging from future earthquakes in the region.

1.1 Seismic Induced Ground Shaking

Ground shaking is caused by seismic waves generated as a result of an earthquake. The intensity of ground shaking is not only directly responsible for damages, but also indirectly by triggering secondary hazards such as landslides, tsunami, flooding, fire, liquefaction and ground deformation. The intensity of ground shaking is mainly described by frequency, duration and amplitude (Kramer, 1996). The to and fro motion of ground during an earthquake is referred as 'frequency'. Waves travel through the structure and the building begins to vibrate at various frequencies. A structure is most sensitive to ground shaking with frequencies near its natural resonant frequency. In general, both amplitudes and frequency content of seismic waves decrease with increase of distance from hypocenter. Hence, the probability of dam-

age intensity decreases with increase of distance from the hypocenter, unless local site effect amplify this generic pattern. The time period of sustained ground shaking is referred to as 'duration' of ground motion. The duration of earthquake has strong influence on ground shaking. High damage is expected if the duration of ground shaking is high, and *vice versa*. The 'amplitude' of ground shaking is represented in three ways; the peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD). PGA, PGV and PGD are the maximum ground amplitudes recorded in terms of acceleration, velocity and displacement, respectively, at a location during a particular earthquake. Generally, high amplitudes of PGA, PGV and PGD are responsible for high damage.

1.1.1 Factors Influencing Earthquake Induced Ground Shaking

There are three major factors that affect ground shaking at a site (Figure 1.1) (Kramer, 1996).

1. Source effects: Source effects include magnitude and hypocenter of earthquake. Close proximity of a site to the hypocenter and high magnitude earthquake result in intensified ground shaking for a longer duration. Moreover, the nature (thrust/reverse, normal and strike slip) and dimensions of faulting can also effect the seismic induced ground shaking. The source parameters are readily available from United States Geological Survey (USGS), or local seismological organizations.
2. Medium effects: Medium effects includes the medium of seismic wave propagation path from source to site. Depending on the density of the material through which the seismic wave propagates, influence the wave velocity and attenuation. Material such as regolith are responsible for amplified ground shaking. The velocity of seismic wave decreases when it enters the regolith from bedrock, and produced amplified shaking following the law of conservation of energy (Robinson et al., 2006). The medium effects are evaluated through region specific attenuation models.
3. Site effects: Site effects include geologic and topographic characteristics at the site (Kramer, 1996). Site effects are responsible for spatial variation of ground shaking. The shear wave velocity is influenced by local geological conditions (Wills and Clahan, 2006). Due to difference of shear wave velocity in different geological media, it determines the impedance contrast between underlying bedrock and unconsolidated surface material. This work specifically deals with the impact of topography on seismic ground shaking, which is discussed in detail in next section.

1.1.2 Impact of Earth's Topography

The topography is one of the contributing site factor to the causing (de-)amplification of seismic induced ground shaking at a site (Ashford et al., 1997). The topography acts as a reflecting surface for upcoming seismic waves (Lee et al., 2009a,b). The rugged nature of topography leads to scattering or focusing of propagating waves, thereby amplify or de-amplify ground shaking at site (Lee et al., 2009a,b; Hough et al., 2010; Shafique and van der Meijde, 2015). Studies, for example, Hartzell et al. (1994); Spudich et al. (1996) in California; Lee et al. (2009a,b) in Taiwan; Hough et al. (2010) in Haiti and Kumagai et al. (2011) in Ecuador found that topography amplifies the ground shaking at mountain tops and ridges, while it de-amplifies in valleys. Furthermore, the directions of incident seismic waves also have an impact on (de-)amplification of ground shaking (Pedersen et al., 1994; Ashford and Sitar, 1997; Shafique et al., 2008; Meunier et al., 2008; Qi et al., 2010; Xu et al., 2013). Similar observations were also reported in Singh et al. (1988); Pischiutta et al. (2010); Snelson et al. (2007). The analysis of the Tarzana Hill recordings from the 1987 Whittier Narrows and the 1994 Northridge earthquakes by Graizer (2009) showed that the observed amplification was due to the combined effects of topography and layering that resulted in trapping energy within a low velocity layer near the surface. Assimaki and Gazetas (2004); Assimaki et al. (2005a,b) studied the 1999 Athens earthquake in Greece and showed that the observed amplification of seismic motion in the vicinity of a cliff crest could only be predicted by simultaneously accounting for the topographic geometry, stratigraphy, and nonlinearity. Recent earthquakes, such as, 2005 Kashmir earthquake (Shafique et al., 2008), 2008 Wenchuan earthquake (Xu et al., 2013), 2010 Haiti earthquake (Hough et al., 2010) and 2015 Nepal earthquake (Wang et al., 2016; Kargel et al., 2016) showed manifestation of topographic amplification. Incorporating the topographic impact on seismic response is thus important for seismic hazard assessment, mitigation and seismic shaking prediction (Wu et al., 2008; Bauer et al., 2001; Shafique et al., 2011a).

Further reviews on observations on seismic amplification can be found in Massa et al. (2010); Buech et al. (2010).

1.2 Importance of Topography in Study Area

The study area of Muzaffarabad is located in a rough terrain. The seismic energy during an earthquake can get trapped in the topographic irregularities and can result in amplification and prolonged duration of ground shaking. The phenomena has been widely observed in similar

settings at other locations (Hough et al., 2010; Pavlenko and Wen, 2008; Pratt et al., 2003). Similar topographic impact on seismic response has also been observed during several landslides and damage related studies after the 2005 Kashmir earthquake (Shafique et al., 2008, 2011b). Shafique et al. (2008) upon comparing 2005 Kashmir earthquake induced landslides with the aspect map of the study area, found that direction of seismic waves to the slopes might have been a reason for intense landsliding. Their observations show that about 80% of the landslides are facing away from the epicenter. Shafique et al. (2011b), in their study of investigating the impact of regolith thickness on earthquake induced building damages, found that at several places despite less thickness there is high damage. A possible reason for intensified damage was attributed to the topographic impact on seismic response, as these places were located on ridges.

1.3 Estimation of Seismic Induced Ground Shaking

As discussed earlier, the seismic induced ground shaking is influenced by source, path and site effects. Therefore quantitative estimation of ground shaking at a given site involves dealing with the source of seismic waves, their paths to the site, and the effects of site conditions (Figure 1.1) (Kramer, 1996). Ground shaking estimation is dependent on availability of detailed geological and geophysical information about locations, geometries, and rupture characteristics of earthquake causative faults (O'Connell and Ake, 2007). The methods for estimating seismic induced ground shaking can be broadly divided into three categories (Poursartip et al., 2017):

1. *observations* from earthquakes and *field experiments* (e.g. observations in 1971 San Fernando Valley earthquake Boore (1972); the aftershocks study of 1971 San Fernando earthquake (Davis and West, 1973); the 1987 Whittier Narrows earthquake (Kawase and Aki, 1990); the 2002 Molise earthquake in Italy (Massa et al., 2010); and the 2010 Haiti earthquake (Hough et al., 2010));
2. studies based on *analytical and semi-analytical solutions* for simple topographic geometries, such as a triangular wedge or a semi-circular valley (e.g. Sánchez-Sesma and Campillo (1993); Bouchon et al. (1996)); and
3. studies based on *numerical simulations* (e.g. finite difference method application by Bohlen and Wittkamp (2016); Pal and Ghorai (2016); Etemadsaeed et al. (2016) and others; finite element method by Faccioli et al. (1997); Komatitsch and Vilotte (1998); Lee et al.

Figure 1.1 Illustration of factors responsible for the seismic induced ground shaking.

(2008) and others. This study is based on numerical simulations, which are discussed in detail in Chapter 3.

Each technique has its advantage and disadvantage associated with it. The choice of selection depends on the desired precision and availability of data (Sánchez-Sesma et al., 2004).

1.4 Problem Statement

Evaluating the impact of site on earthquake induced ground shaking using 1D or 2D numerical codes is usually limited to small spatial scale (single basin or ridge) (e.g. Sánchez-Sesma and Campillo, 1993; Bouchon et al., 1996). These studies are more often conducted through synthetic laboratory experiments or in case related to actual site, of a small spatial scale. However, because of the large extent of the seismically active, and affected areas, regional scale evaluation of site effects on seismic response is required that is also applicable at local scale. On the other hand, seismic induced ground shaking and expected damage maps derived from, respectively, USGS-ShakeMap and PAGER in near-real time for effective response activities, are at coarse resolution of 1 km², hence giving much generalization in results at a local scale (Jaiswal et al., 2011).

3D numerical simulations (such as spectral element method, explained with detail in Chapter 3) can be used to simulate global, regional and local seismic wave for estimation of ground shaking. These methods require designing of computational model (mesh), composed of mesh elements. The resolution of mesh is variable and define details of the model. On the other hand, topographic surface in such models is created from digital elevation model (DEM), which also comes in variable resolutions. High resolution mesh and DEM can increase the accuracy but in turns require high computational power for simulation. Therefore, detailed studies for larger area may not be possible due to lack of computational resources in general. This problem is addressed in detail in Chapter 4.

Pakistan is located in one of the highly seismically active regions of the world. It has been hit by a number of large earthquakes. One of the recent examples is the 2005 Kashmir earthquake. Like other developing countries, Pakistan also lack a good network of seismic stations to record instrument based ground shaking. Therefore, it is important to evaluate the impact of site conditions on ground shaking using numerical techniques (addressed in Chapter 5) . Since the threat of earthquakes remains for the future, there is a need for models that could estimate the ground shaking for any possible earthquake (addressed in Chapter 6).

1.5 Aim

The aim of this research is to evaluate the impact of data resolution in spectral element method at regional scale to assess and estimate the impact of topography on seismic induced ground shaking and ultimately develop a seismic hazard map.

1.6 Objectives

1. To evaluate the impact of DEM and mesh resolution for estimation of seismic induced ground shaking at a regional scale using spectral element method.
2. To evaluate the impact of topography on 2005 Kashmir earthquake induced ground shaking at suitable resolution obtained from objective 1.
3. To develop a seismic hazard map for the study area.

1.7 Thesis Structure

Chapter 1 gives an insight to the thesis. It introduces seismic induced ground shaking and explains the factors responsible, and estimation techniques for ground shaking. This chapter also discusses problems associated with ground shaking estimation and enumerates the objectives of this thesis for their solution.

Chapter 2 describes the regional seismotectonic setting and geological history of the study area. It explains the characteristics of 2005 Kashmir earthquake, its causative fault, and the aftermath in the context of infrastructural damage and landslides. The role of topography in the light of previous work is also highlighted.

Chapter 3 gives an insight to the numerical simulations used for estimation of seismic induced ground shaking. It explains the methodology of SPECFEM3D, a spectral element based software.

Chapter 4 analyzes the impact of mesh and DEM resolutions on estimation of seismic induced ground shaking. It aims to find the coarsest mesh and/or DEM resolution that can be used in a 3D numerical simulation without compromising on accuracy.

Chapter 5 adopts the conclusions from Chapter 4 and investigates the effect of regional topography on seismic amplification. The simulation is carried out for Muzaffarabad and its surrounding areas using centroid moment tensor (CMT) solution of 2005 Kashmir earthquake. A comparison of these results is made with damage and landslides occurred during the 2005 Kashmir earthquake.

Chapter 6 shows a probabilistic seismic hazard map for the study area based on SEM. Using the CMT solution of the 2005 Kashmir earthquake as a source, 25 simulations are carried out at intervals of approximately 6 km distance along regional faults. This is to estimate possible amplitudes in future earthquakes and the possible impact on the region.

Chapter 7 provides a synthesis and discusses the implication of results for mitigation of seismic impact and effective response. Recommendations for future work are also given.

Study Area and Kashmir Earthquake

2.1 Regional Geotectonic Setup

The Indo-Pak sub-continent is encircled by the Indian Ocean to the south and the Himalayas to the north (Figure 2.1). It is sculpt as a result of Sea-floor spreading, continental drift and collision tectonics (Johnson et al., 1976). The accretion at the collision zone resulted in formation of the Himalayas which are 2500 km long and form the Indo-Pakistan plate margin with Eurasia (Le Fort, 1975).

The subcontinent got separated from the Gondwanaland about 130 M.a ago (Johnson et al., 1976). During this period, the Tethys Ocean between India and Asia started to close, and the Indus Flysch and basic volcanics belt came into being at the southern margin of the Asian Plate. The subduction of oceanic crust caused anatexis leading to the intrusion of the Ladakh- or Trans-Himalayan plutons and the intermediate to acid volcanism north thereof (Powell and Conaghan, 1975; Frank et al., 1977; Andrews-Speed and Brookfield, 1982). Estimations based on magnetic anomalies show that between 130 M.a and 80 M.a, the Indo-Pakistan sub-continent moved northward at a rate of about 3 to 5 cm/year (Johnson et al., 1976). From 80 M.a, it moved at an average rate of 15-25 cm/year relative to Australia and Antarctica (Powell, 1979; Patriat and Achache, 1984). During this period the movement was assisted by extensive sea-floor spreading along the Mid Indian Oceanic Ridge and transform faulting in the Proto-Owen Fracture Zone (Kazmi and Jan, 1997). To the south of the Eurasian Plate, the subsequent drift and northward subduction of the Indian Plate resulted in complete consumption of the leading oceanic edges of the Indian Plate and its ultimate collision with the Kohistan-Ladakh Arc. After crossing the equator, the initial contact between northwestern India and Asia was established around 65 M.a ago (Klootwijk et al., 1992). The abrupt slowing down of India's northward

drift between 55 and 50 M.a ago is attributed to the collision of India with Eurasia; and the closure of the Neo-Tethys in Tibet and Karakoram (Patriat and Achache, 1984; Powell and Conaghan, 1975). Paleomagnetic data also shows a rapid slow down at 55 M.a (Klootwijk et al., 1992). India has progressively rotated anticlockwise during its passage after separation from the Gondwanaland until the collision with the Eurasian Plate. This rotation resulted in closure of the Katawaz and Seistan Basin; collision of various crustal blocks in Iran-Afghanistan region, convergence in Balochistan and formation of the Balochistan fold-and-thrust belt (Powell, 1979). Consequently, the deformation started near the suture zone in form of Main Karakoram Thrust (MKT), which progressively migrated southward away from the early Eocene collision zone at the Main Mantle Thrust (MMT) and reached the Main Boundary Thrust (MBT) by the Miocene time (Figure 2.1). It finally migrated to the Salt Range area as Salt Range Thrust (SRT) and Trans-Indus Ranges Thrust (TIRT) approximately by 2 M.a ago. Seismic and gravimetric studies reveals that the continental crust has an average thickness of 30–40 km in the Indian Plate, thickens beneath the Himalayas upto of 80 km, and a mean value of 60 km under the Tibetan Plateau (Le Fort, 1975; Horton et al., 2004; Unsworth et al., 2005; Hetényi et al., 2006).

The structural and tectonic complexities lead to the formation of an important structural and tectonic feature known as Hazara-Kashmir Syntaxis (HKS) (Tahirkheli, 2010)(Figure 2.1). This mega-geotectonic feature of NW Himalayas deforms the Murree Thrust (MBT) and Panjal Thrust (PT). The PT and MBT are partially merged with each other while looping around the HKS. The study area is a part of the HKS, which is discussed in detail in next section.

2.2 Local Geotectonic Setup

The HKS region of NW Himalaya is tectonically complex, with active convergence and transpressional tectonic setup (MonaLisa et al., 2008) and is not only traversed by the main boundary faults, but also by a number of subsurface faults (Sana and Nath, 2016). Figure 2.2 illustrates the geotectonic setup in the HKS and the surroundings.

The Hazara Kashmir Syntaxis (HKS) is marked by the parallel trend of the MBT and the PT. The HKS can be divided structurally into three parts: the western limb, the syntaxial apex and the eastern limb (Sana and Nath, 2016). Western limb originates from Muzaffarabad and extends northwest till Balakot, where it loops to the east forming syntaxial apex and then turns southeast towards the Pir Panjal Range in Kashmir, making the eastern limb (Calkins et al., 1975). The HKS is predominantly comprised of rocks from the Murree formation, indicating develop-

Figure 2.1 Regional tectonic setup of the area. HKS=Hazara-Kashmir Syntaxis, PT= Panjal Thrust, MF, Muzaffarabad Fault, IKSZ = Indus Kohistan Seismic Zone, I=Islamabad, JK = Jacobabad-Khairpur high, K=Karachi, KB=Kalabagh, KK=Khuzdar Knot, KP=Kalat Plateau, MBH=Mari-Bugti Hills, NH= Nanga Parbat-Haramosh Massif, P=Peshawar, TS= Trans-Indus Salt Range, Q=Quetta, Z=Ziarat. BF=Bannu Fault, GF=Ghazaband Fault, JF=Jhelum Fault, KF=Kalabagh Fault, KRF=Kirthar Fault, PF=Pab Fault, MBT=Main Boundary Thrust, MKT= Main Karakoram Thrust, MMT=Main Mantle Thrust, ST=Salt Range Thrust, A=Karakoram Block, B=Kohistan Island Arc, C=North Western Deformed Fold And Thrust Belt, D=Southern Deformed Fold And Thrust Belt, E=Indo-Gangatic Foredeep, Beachball= Epicenter of the 2005 Kashmir earthquake. Modified from Sarwar and Dejong (1979).

2. Study Area and Kashmir Earthquake

Figure 2.2 Geotectonic setup of the Hazara Kashmir Syntaxis (HKS). the beach-ball indicating epicenter of the 2005 Kashmir earthquake. Modified from Kaneda et al. (2008).

ment of the HKS till post-Miocene (Bossart et al., 1988). The Murree formation is overlain by the Miocene Kamlial formation in the south of Muzaffarabad, and more younger formations of the Siwalik group of Miocene-Pleistocene origin. From Muzaffarabad till Balakot in the north and Kotli in the south, the Murree formation is underlain by Marine Paleocene strata and the Muzaffarabad formation of Precambrian age (Calkins et al., 1975).

On the western limb of the syntaxis, the MBT separates the older rock strata from the main younger formations of the HKS in the east at the axial zone of syntaxis (Calkins et al., 1975; Seeber et al., 1981). The roots of the MBT are tangled at detachment in subsurface, making it a major recipient of the south migrating stress (Sana and Nath, 2016). At the apex of the HKS, the rock stratum in the proximity of Balakot is deformed to tight isoclinal folds with steeply or vertically dipping limbs to the west (Sana and Nath, 2016). The eastern limb of HKS is marked by the PT involving Precambrian formations, and a younger Main Boundary Thrust (MBT), also known as the Murree Thrust (Tahirkheli, 2010). Here, the PT and MBT separates the Carboniferous to Eocene rock formations from the older Salkhala rocks on the east and Murree rocks on the west. The PT is an important tectonic boundary, which played an active role in the tectonic evolution of the Hazara Kashmir Terrain (Tahirkheli, 2010). This thrust is located on the receiving end of the NW directed stress induced by the Himalayan boundary faults. The resulting stress is being transported towards the west, which is accumulating along the western limb of the HKS (Tahirkheli, 2010).

In this study, major faults in the HKS are used for deriving seismic hazard map considering them as potential source for future earthquakes (Chapter 6).

2.3 Muzaffarabad Fault (MF)

The Muzaffarabad Fault (MF) traverses obliquely through the core of the HKS, before merging with the MBT at the western margin of the HKS (Avouac et al., 2006) (Figure 2.2). The MF dips NE, and separates Precambrian limestone and shale on the NE from Miocene Murree Formation on the SW. The presence of MF was first documented by Armbruster et al. (1978) from a local seismic network centered on Tarbela Dam based on an alignment of earthquake epicenters that occurred in the time range 1973–1974. It extended from the Jhelum River, within the HKS NW, to the Indus River, where the Pattan earthquake struck in 1974 (Pennington, 1979). It does not show any surface expression in the north of the HKS but does towards the Indus Kohistan Seismic Zone (IKSZ) in the south

(Seeber and Gornitz, 1983). Kondo et al. (2008) estimated the slip rate of 3 mm/yr.

The MF is the source of the 2005 Kashmir Earthquake of magnitude (Mw) 7.6 (Hussain et al., 2009; MonaLisa et al., 2009). A 75 km segment (Avouac et al., 2006) of this fault from Balakot in the NW, through Muzaffarabad to Bagh in the SE, was ruptured in the Kashmir earthquake (Shafique et al., 2016).

2.4 Seismotectonic Setup

2.4.1 Seimogenic Sources

The Himalayan region has been experiencing major earthquakes with Mw around 8.0 (e.g. the 1905 Kangra earthquake, 1934 Bihar-Nepal, and 1950 Assam earthquake). Some relatively recent damaging earthquakes in Pakistan are the (mb 6.0) 1974 Pattan earthquake, (mb 5.2) 1977 Rawalpindi earthquake, (mb 5.3 and 6.0) 2002 Bunji earthquakes, (mb 5.3 and 5.5) 2004 Batgram earthquakes, and the (Mw 7.6) 2005 Muzaffarabad earthquake. None was as destructive as the 2005 Kashmir earthquake (Avouac et al., 2006). Theoretical studies indicate that the energy stored in the Himalayas suggests a high probability of earthquake of Mw > 8.0 in future (Durrani et al., 2005; Stevens and Avouac, 2016).

The northern part of Pakistan is a seismically active region because of its tectonic location. The subduction of Indian plate under the Eurasian plate at a rate of 40 mm/year (MonaLisa et al., 2009) is the major reason behind earthquakes in the region. The formation of major thrusts such as MKT, MMT and MBT as a result of N and NE directed movement of Indian Plate has already been discussed in the previous Section 2.1. The MMT is not only a source of continuous low to moderate earthquakes, but has also triggered a few major earthquakes with epicenters located in Malakand (2004 Batgram earthquakes, mb 5.3 and 5.5), Astore (2002 Bunji earthquakes, mb 5.3 and 6.0) and Kohistan (1974 Pattan earthquake, mb 6.0) (Sana and Nath, 2016). The Pattan earthquake of 1974 (mb 6.0) is the largest event recorded in the MMT zone adjacent to the Hazara-Kashmir Terrain (Chandra, 1975; Ambraseys et al., 1981). Almost every fault in and around the HKS has triggered disastrous earthquakes (Sana and Nath, 2016). The seismic activity in the HKS has reduced from the time of granitization and metamorphism in this region (Armbruster et al., 1978). However, the 2005 Kashmir earthquake has shown that the HKS is still tectonically active (MonaLisa et al., 2008). The MBT is capable of generating large earthquakes throughout the Himalayas (Tahirkheli, 2010; MonaLisa et al., 2009). The Panjal Thrust has shown numerous earthquakes of Mw between 4 to 5 (Sana and Nath, 2016).

Several earthquakes of Mw greater than 5 and two aftershocks of the 2005 Kashmir earthquake of Mw 6 and 6.4 have also been recorded (Tahirkheli, 2010). Apart from these faults numerous active faults of variable length are present in the region (Nakata et al., 1991; MonaLisa et al., 2009). Apart from these superficial scars of deformation, which are geologically mapped, deep crustal deformations are also responsible for seismicity in the area. The locations and configurations of these deformational zones in Hazara-Kashmir terrain were deduced from the seismic data collected from the Tarbela Dam Seismological Observatory (Tahirkheli, 2010). One of the important zone in context of our study area is Indus Kohistan Seismic Zone (IKSZ), discussed in next section (Section 2.4.2).

2.4.2 Indus Kohistan Seismic Zone (IKSZ)

On the basis of a micro-earthquake survey done in this region during 1973-1974, a wedge-shaped NW trending structure was recognized by Armbruster et al. (1978) who named it the IKSZ (Figure 2.1). Later research (e.g., Seeber and Armbruster (1979); Ni et al. (1991) confirmed the presence of this 100 km long feature between the HKS and the MMT (Figure 2.1). The IKSZ is one of the deep seated, seismically active crustal structures in this part of the Himalaya (Sana and Nath, 2016). This structure located between the MMT and the apex of the HKS is not geologically mapped and is believed to be covered by a 12 km thick sediment cover (Gornitz and Seeber, 1981). On the basis of focal mechanism solutions, the IKSZ is defined as a thrust dipping to the NW and covering an area of about 120 km in length and 25 km in width (Seeber et al., 1981). Its strike is aligned parallel to the Main Boundary Thrust. However, the MBT is defined as the northern boundary of the clastic deposits in the frontal trough, which is not the case for IKSZ. Based on the Coulomb Stress change due to the 2005 Kashmir earthquake, Gahalaut (2006) suggests intense tectonic activity in the future along IKSZ as compared to the MBT and the Hazara Thrust System (HTS) in the east of HKS.

The local network analysis was extended to 1977 by Seeber and Armbruster (1979), who identified a second seismic zone beside IKSZ, the Hazara Lower Seismic Zone (HLSZ), parallel to the first zone and extending through Tarbela Dam. This zone is also seismically active (MonaLisa et al., 2009). Seeber and Gornitz (1983) connected the IKSZ with the band of moderate seismicity extending through the Himalaya farther east and observed a relation between the band of seismicity and relatively high gradients of longitudinal profiles of rivers crossing it. The HLSZ is also marked by a strong topographic gradient at the northeastern edge of the Peshawar Basin.

Despite the not well defined tectonic relationship between the IKSZ and the MMT, it is believed that the increased seismicity close to IKSZ northern end may be attributed to its interaction with the active part of the MMT (Tahirkheli, 2010). The strike of the surface structures in the Hazara arc region contrasts sharply with the IKSZ and HLSZ (Armbruster et al., 1978). A synoptic observation of the NW Himalayan syntaxes reveals that the axis of the Nanga Parbat-Haramosh Massif (NH) and HKS are aligned almost perpendicular to each other (Figure 2.1), with a prominent dent on the western limb of the HKS. As the active front shifted from the MMT to MBT, the northward advance of the Indian plate had a dominant translational factor. However, when the MBT acted as the main facilitator of the tectonic interactions between the Indian plate and the Tibetan plateau, the northward translational movement had a pronounced rotational effect as well; which probably resulted in the northwest tilt in the apex of HKS with reference to the NH (Sana and Nath, 2016).

2.5 2005 Kashmir Earthquake

The Mw 7.6 2005 Kashmir earthquake struck northern Pakistan and adjacent India. According to the UGGS the epicenter was approximately 19 km NE of Muzaffarabad and 95 km NNE of Islamabad, Pakistan (Figure 2.2). Heavy damage was sustained in Pakistani-administered Jammu & Kashmir and the Khyber Pakhtunkhwa Province, and in adjacent parts of Indian-administered Jammu & Kashmir.

It is considered to be the first Himalayan earthquake that was accompanied by surface rupture, reactivating the Muzaffarabad Fault (MF) (Figure 2.1) and, locally, offsetting the MBT (Hussain et al., 2009). Field investigations (Yeats et al., 2005; Kumahara and Nakata, 2006; Dellow et al., 2007; Kaneda et al., 2008) revealed a surface rupture 60–70 km long, with up to 7 m vertical separation, mostly along the pre-existing MF.

2.5.1 Damage

The International Charter "Space and Major Disasters" was activated following the 2005 Kashmir earthquake and high resolution satellite imagery was made available for the Muzaffarabad region. In a reconnaissance study after the 2005 Kashmir earthquake, Dellow et al. (2007) found that the epicentral area was the most severely damaged region during the earthquake. Shafique et al. (2011b) conducted a detailed field survey following visual interpretation of damage from satellite imagery. They reported the data (Figure 2.3) three classified zone following Hough

Figure 2.3 2005 Kashmir earthquake induced damage data after Shafique et al. (2012).

et al. (2010) of being High (>40 % damaged buildings), moderate (10–40 % damaged buildings) and low (<10 % damaged buildings) (Shafique et al., 2012). This data has been used in Chapter 5 of this study for analyzing correlation between seismic amplification damage during the 2005 earthquake.

2.5.2 Landslides

A large number of landslides and structural damage were concentrated close to the fault on the hanging-wall side (Hussain et al., 2009). Owen et al. (2008) used ASTER and QuickBird satellite images to develop a co-seismic landslide inventory in a study area of >750 km² that was

subsequently validated in the field. They have mapped 1293 co-seismic landslides and characterized their distribution, type and nature. Kamp et al. (2008) mapped 2252 landslides using digital classification of ASTER imagery and field observations in a study area of 2250 km². They have however used only post-earthquake ASTER imagery and therefore also included pre-earthquake landslides. Sato et al. (2007) mapped landslides as points by acquiring a stereoscopic view of the area using post-earthquake SPOT-5 images and field observations to map 2424 co-seismic landslides in a study area of 2805 km². They have observed 79% small (<0.5 ha) and 9% large (>1 ha in area) co-seismic landslides. This map also includes pre-earthquake landslides. Basharat et al. (2014) mapped 1460 co-seismic landslides as points in a study area of 1299 km² using visual classification of post-earthquake SPOT-5 imagery and field investigation. Their map also includes pre-earthquake landslides. Lodhi (2011) mapped seismic induced landslides by applying the IHS, NDVI and PCA image classification techniques on a post-earthquake ASTER image. The mapped landslides were then verified using an IKONOS image, for a subset of the study area, and field observations.

A 2005 Kashmir earthquake induced landslide inventory was developed by the Humanitarian Information Center (HIC), a subsidiary organization of the United Nations Office for Coordination of Humanitarian Affairs (OCHA), which was reported by Shafique et al. (2008). They used the data for investigating impact of direction of incident seismic wave on seismic induced landslides and topographic amplification. Ray et al. (2009) used pre and post-earthquake Cartosat-1, Resourcesat-1, Landsat-TM and ASTER images and mapped 776 co-seismic landslides with the help of field observations encompassing an area of 54.5 km². However, they did not map small landslides with an area ≤ 45 m². Chini et al. (2011) applied digital classification techniques on fine resolution images (Quick-Bird) of pre- and post-earthquake and mapped seismic induced landslides in Muzaffarabad and Balakot. Saba et al. (2010) used pre and post-earthquake high resolution satellite images (IKONOS, Quick-Bird, SPOT and WorldView1) for a study area of 36 km² and mapped 158 co-seismic landslides supported with field observation. Like Saba et al. (2010), Fujiwara et al. (2006) mapped 100 co-seismic landslides only for the northern parts of Muzaffarabad. Kamp et al. (2010) used pre and post-earthquake ASTER images, to map seismic induced landslides. They have observed a sixfold increase in landsliding, and an almost eightfold increase in landslide area during 2001–2005. Reviewing the landslides of 2005 Kashmir earthquake, Shafique et al. (2016) feel that there is a need to develop a complete and comprehensive inventory of the Kashmir earthquake-induced landslides using remote sensing data following the criteria suggested by Harp et al. (2011).

In this study, we try to investigate the impact of direction of incidents

Figure 2.4 Co-seismic landslides inventory was developed by the Humanitarian Information Center (HIC), a subsidiary organization of the United Nations Office for Coordination of Humanitarian Affairs (OCHA), which was reported by Shafique et al. (2008).

wave on seismic induced landslides and topographic amplification. For this purpose, the landslide data of HIC Shafique et al. (2008), covering the study area, is correlated with topographic induced seismic amplification results obtained from simulation of the 2005 Kashmir earthquake in Chapter 5.

Numerical Simulations for Ground Shaking Estimation

3.1 Introduction

Estimation of earthquake induced ground shaking at a site can be done using empirical methods if sufficient earthquake records for the site are available. This, however, is not usually the case. In such conditions, numerical simulations have to be applied for estimating the earthquake induced ground shaking. The development of the simulation codes and computational facilities make it possible to use numerical simulation methods for seismic ground shaking estimation. A brief account to some widely used numerical techniques, each with its advantages and disadvantages (Chaljub et al., 2007) is given in the following paragraphs.

One of the most widely used approach for full waveform simulation in 3D local and regional models is the finite difference method (FDM). It was initially used by Boore (1972) to study the effect of simple topography on seismic response. FDM is capable of addressing simplified geometric (e.g. wedge or U-shaped) problems (Igel and Weber, 1995, 1996; Chaljub and Tarantola, 1997; Chaljub et al., 2007). However, it suffers from limitation when it comes to addressing complex 3D models, such as the presence of realistic topography, basin or major discontinuities within the model (Robertsson, 1996; Ohminato and Chouet, 1997).

Limitations of FDM can be overcome with boundary element methods (BEM) which incorporates realistic surface and interface topography by adopting integral representation theorems combined with discrete wavenumber expansions of Green's functions (Bouchon and Sánchez-Sesma, 2007; Chaljub et al., 2007; Chen, 2007). However, this method is restricted to a finite number of homogeneous regions and can also lead to numerical artefacts (Chaljub et al., 2007; Komatitsch, 2015).

A more advanced method that can handle complex geometries and

interface conditions is the finite element methods (FEM), which has been successfully applied to the study of wave propagation in 3D sedimentary basins (Chaljub et al., 2007). This technique however produces large amount of numerical dispersions (Marfurt, 1984), and is difficult to use on parallel computers with distributed memory (Chaljub et al., 2007). Also, due to limited accuracy knowledge in many cases, empirical rules are used to determine simulation parameters (De Basabe Delgado, 2009).

To overcome the limitations of FEM, a higher order finite element method known as the spectral element method (SEM) is used. SEM can accurately deal complex topography (Chaljub et al., 2007; Lee et al., 2009b), geometrical flexibility, local variation of material property (Dhanya et al., 2016), discontinuities in the sub surface and boundary conditions (De Basabe Delgado, 2009). SEM has shown a very high accuracy and low numerical dispersion and that is also efficient on parallel computers and distribute memory (Komatitsch et al., 2004; Chaljub et al., 2007; Komatitsch, 2011). A detailed account on SEM is given in the next section (Section 3.2).

3.2 Spectral Element Method (SEM)

The SEM was developed by Patera (1984) for computational fluid dynamics, and was first adopted for 3D seismic wave propagation by Komatitsch and Vilotte (1998); Komatitsch and Tromp (1999). Because of its accuracy in handling complex models and efficiency with parallel computing, the method is adopted in several 3D problems from local and regional scale (Faccioli et al., 1997; Komatitsch and Vilotte, 1998; Komatitsch and Tromp, 1999; Komatitsch et al., 2004) to a global scale (Chaljub, 2000; Komatitsch and Tromp, 2002a,b; Komatitsch et al., 2002; Chaljub et al., 2003; Komatitsch et al., 2003; Chaljub and Valette, 2004; Lee et al., 2009b; Chaljub et al., 2015; Komatitsch, 2015) seismic wave propagation.

The following section describes the basic theory behind SEM for simulation of seismic wave propagation.

3.2.1 Equation of Motion

Considering an earth model with volume Ω and outer free surface $\partial\Omega$ (Section 3.2.2, Figure 3.1). The displacement wavefield $\mathbf{s}(\mathbf{x}, t)$, where $\mathbf{x}$ denotes material points in the Earth model and t time, is determined by the seismic wave equation (Equation 3.1) (Tromp et al., 2008).

$$\rho \partial_t^2 \mathbf{s} = \nabla \cdot \mathbf{T} + \mathbf{F} \quad (3.1)$$

Figure 3.1 Finite Earth model with volume Ω and free surface $\partial\Omega$. The model is subdivided into curved spectral elements using quadrangles in 2D (a) and hexahedra in 3-D. Γ is the artificial absorbing boundary, and $\hat{n}$ the unit outward normal on the surface. X_s indicates the location of the source (b). The shape of the elements is adapted to all the major discontinuities in the geological model (e.g. topography, geological layers and faults). Inside each element, the model can be heterogeneous. (modified after Komatitsch et al. (2005))

Where $\mathbf{s}$ denotes the displacement at position $\mathbf{x}$ and time t , $\rho(\mathbf{x})$ is the 3D distribution of mass density, and $\mathbf{F}(\mathbf{x}, t)$ the external body force represents the earthquake. The stress tensor $\mathbf{T}$ is linearly related to the strain tensor by Hooke's law (Equation 3.2)

$$\mathbf{T} = \mathbf{c} : \nabla \mathbf{s} \quad (3.2)$$

Where, $\mathbf{c}$ denotes a fourth-order tensor that describes the properties of the medium.

3.2.2 Earth Model

The modelling domain of SEM can be defined as an earth model with volume Ω , sub-divided into a number of non-overlapping elements Ω_e , $e=1, 2, \dots, n_e$ (Equation 3.3), outer free surface $\partial\Omega$, vertical boundary Γ and the unit outward on the normal surface $\hat{n}$ and the location of earthquake source X_s as shown in Figure 3.1.

$$\Omega = \cup_{e=1}^{n_e} \Omega_e \quad (\text{Komatitsch et al., 2005}) \quad (3.3)$$

For local or regional simulations the vertical boundary Γ acts as a fictitious boundary to absorb the seismic energy. For global simulations no absorbing boundary condition is needed (Komatitsch et al., 2005). However, irrespective of the simulation's spatial extent, the free surface Ω interacts with the seismic energy and the traction must disappear on the free surface (Tromp et al., 2008) as (Equation 3.4):

$$\hat{n} \cdot \mathbf{T} = 0 \quad \text{on} \quad \partial\Omega \quad (3.4)$$

Moreover, at time $t=0$ (i.e. initial condition), the displacement wave field $s(x,t)$ is zero, which is defined as (Equation 3.5)

$$S(x, 0) = 0, \quad \partial_t s(x, 0) = 0 \quad (3.5)$$

3.2.3 Earthquake Characteristics

The earthquake characteristics are defined by location (X_s) and external force (F) (Figure 3.1). These characteristics of the earthquake are represented by a point source, the centroid moment tensor (CMT) (Dziewonski et al., 1981; Ekström et al., 2012). The CMT defines the seismic moment distribution in time and space (providing the centroid's latitude, longitude, depth and time). CMT solutions for most major earthquakes can be obtained from the Global Centroid-Moment-Tensor Project (www.globalcmt.org).

3.2.4 Spectral Elements (Mesh)

The location of each spectral element Ω_e (Figure 3.1) can be defined by cartesian points $X = (x, y, z)$. Each element is mapped in reference to a cube (Figure 3.2, within which the points can be denoted by local coordinates $\xi = (\xi, \eta, \zeta)$ where $-1 \leq \xi, \eta, \zeta \leq 1$. The transformation function is defined by (Equation 3.6):

$$X^e(\xi, \eta, \zeta) = \sum_{a=1}^M X_a^e N_a(\xi, \eta, \zeta) \quad (3.6)$$

Where, X^e are the M anchor points of the e -th element i.e. $X_a^e = X^e(\xi_a, \eta_a, \zeta_a)$, and shape function $N_a(\xi, \eta, \zeta)$ defining the geometry of an element. At least 8 anchors are required to describe the geometry of an element.

The shape function $N_a(\xi, \eta, \zeta)$ are triple products of 1 or 2 degree Lagrange polynomials and their derivatives in the three orthogonal directions of space in the reference cube. SEM normally uses higher degree Lagrange interpolant (degree 4 to 10) to represent the function of an element (Komatitsch and Tromp, 1999; Komatitsch et al., 2005; Tromp et al., 2008). The $N+1$ Lagrange polynomials of degree N are defined as $N+1$ control points $-1 \leq \xi_\alpha \leq 1, \alpha = 0, \dots, n$ as

$$\ell_\alpha^N = \frac{(\xi - \xi_0) \cdots (\xi - \xi_{\alpha-1})(\xi - \xi_{\alpha+1}) \cdots (\xi - \xi_N)}{(\xi_\alpha - \xi_0) \cdots (\xi_\alpha - \xi_{\alpha-1})(\xi_\alpha - \xi_{\alpha+1}) \cdots (\xi_\alpha - \xi_N)} \quad (\text{Tromp et al., 2008}) \quad (3.7)$$

Figure 3.2 The geometry of each of the curved volume hexahedra can be defined by either eight control nodes (a) or 27 control nodes (b). In the case of the 27-node brick, the empty squares indicate the six nodes that lie in the middle of the sides of the element, and the triangle indicates the node that lies at the centre of the element. By ignoring these nodes, one obtains the classical 20-node element that can also be used to define the geometry (Komatitsch and Tromp, 1999).

When the degree of Lagrange polynomials is $N=1$, then number of control points are $(\xi=-1, \xi=1)$ and the polynomials become (Equation 3.8):

$$\ell_{\alpha}^N(\xi) = \frac{\xi - (+1)}{(-1 - (+1))} = \frac{1 - \xi}{2}, \ell_1^1(\xi) = \frac{(\xi - (-1))}{(-1 - (-1))} = \frac{1 + \xi}{2} \quad (3.8)$$

Similarly, if $N=2$, the control points are $\xi=-1, \xi=0, \xi=1$ and the Lagrange polynomials are (Equations 3.9, 3.10 & 3.11):

$$\ell_0^2(\xi) = \frac{(\xi - (+1))(\xi - 0)}{(-1 - (+1))(-1 - 0)} = \frac{\xi^2 - \xi}{2} \quad \ell_0^{2'} = \xi - \frac{1}{2} \quad (3.9)$$

$$\ell_1^2(\xi) = \frac{(\xi - (-1))(\xi - (+1))}{(0 - (-1))(0 - (+1))} = 1 - \xi^2 \quad \ell_1^{2'} = -2\xi \quad (3.10)$$

$$\ell_2^2(\xi) = \frac{(\xi - (-1))(\xi - 0)}{(1 - (-1))(-1 - 0)} = \frac{\xi^2 + \xi}{2} \quad \ell_2^{2'} = \xi + \frac{1}{2} \quad (3.11)$$

Thus the control points ξ_{α} are chosen to be $N+1$ Gauss-Lobatto-Legendre (GLL) points. If Lagrange polynomials and GLL quadrature are used together, the mass matrix is exactly diagonal, which is necessary

Figure 3.3 (a) Lagrange interpolants of degree $N = 4$ on the reference segment $[-1, 1]$. The $N+1=5$ Gauss-Lobatto-Legendre (GLL) points can be distinguished along the horizontal axis. All Lagrange polynomials are, by definition, equal to 1 or 0 at each of these points (Komatitsch et al., 2005). (b) Each 3D spectral element contain a grid of unevenly spaced grid of $(n + 1)^3$ GLL points, and each 2D face of an element contains a grid of $(n + 1)^2$ GLL points, as illustrated here in the case of $n = 4$ (Komatitsch et al., 2005). (c) Illustration of evenly spaced GLL points for simplicity. Each element contains $(N + 1)^3 = 125$ GLL points that constitute the local mesh for each element. GLL point lying on the faces, edges and corners are shared between adjoining elements (Carrington et al., 2008).

for numerical accuracy. The Lagrange points of degree 4 and the distribution of associated GLL points to discretize the wave field are shown in Figure 3.3.

Numerical simulations suggests that if the degree of Lagrange interpolants is less than 4, the performance of SEM is similar to FEM, resulting in numerical dispersion (Marfurt, 1984; Chaljub et al., 2007). If chosen greater than 10, the accuracy increases but at a cost of computational resources (Chaljub et al., 2007). Due to uneven spacing between GLL points, the GLL points gets clustered at the edge of the element by high degrees. As a result, the distance between the GLL points becomes very short and hence a very small time step is required to run; consequently simulation becomes computationally expensive (Canuto et al., 1988).

In order to ensure the numerical accuracy and stability of SEM simulation, the following conditions must be fulfilled during designing of all-hexahedral conforming mesh:

1. SEM typically uses Lagrange Polynomials of degree (N) 4 to 10, the selection of N for a model depends on the grid spacing of the elements d . The element size should be at least five GLL nodes per minimum wavelength to ensure sampling of the seismic wave field (Komatitsch and Vilotte, 1998). This can be summarized as (Cupillard et al., 2012):
2. To ensure stable time scheme for SEM, the maximum time step being imposed by the Courant-Friedrichs-Lewy (CFL) criterion (Courant et al., 1928) that states that the traveling speed of information

cannot be more than one grid cell per time step (Chaljub et al., 2007). This means that time-step Δt has restriction from Equation 3.12:

$$\Delta t \leq C \min_{\Omega} \left(\frac{\Delta x}{\vartheta} \right) \quad (3.12)$$

Where, C is the Courant stability number usually between 0.3 to 0.4, Ω is the model volume, Δx is the distance between two GLL nodes and ϑ is the P -wave speed.

3. The quality of mesh must be ensured. The quality is ensured by keeping the the level of distortion as minimum as possible in each mesh element. Ideally, the six faces of a hexahedral element are fully in contact with the sides of neighboring elements and the angles are perfectly at 90 degree. The distortion is defined by the deviation from the perfect 90 degree angle, and is given by skewness. When there is no deviation from 90 degree, the skewness value is '0' (perfectly shaped hexahedra), while at maximum deviation, the value is '1' (completely distorted hexadedra). Highly distorted elements can still perform if higher degree of polynomials $N \hat{=} 6$ are used (Oliveira and Seriani, 2011). For $N=4$, the skewness should be limited to <0.8 (Casarotti et al., 2008).

3.3 SPECFEM3D

For an efficient use of SEM, a computational code in the form of SPECFEM is now available. SPECFEM is developed by Computational Infrastructure of Geodynamics (CIG) and can be downloaded from (<https://geodynamics.org/cig/software/specfem3d/>). SPECFEM comes in several models depending on the applications. These are SPECFEM1D, for regional wave simulation in 1D surface, SPEFEM2D, for regional wave simulations in 2D, SPECFEM3D Cartesian, for simulation in 3D basinal/regional studies and SPECFEM3D Globe for global seismic wave simulation. Since our study is focused on a 3D regional scale, we used SPECFEM3D Cartesian.

The main steps involved in process of simulation with SPECFEM3D Cartesian includes, mesh generation, source parameterization, simulation and output visualization. These steps are explained in sequence as under.

3.3.1 Mesh Generation: CUBIT

The first most important task for successful implementation of SEM is designing high quality 3D mesh model for the area of interest (Komatitsch et al., 2005; Casarotti et al., 2008). Mesh designing is time consuming and requires extensive experience and expertise. Several important and tough constraints must be taken in to consideration; the number of grids per shortest desired wavelength, numerical stability condition, acceptable distortion of mesh elements (Komatitsch et al., 2005), and balancing of numerical cost and available computational resources (Casarotti et al., 2008). Unlike FEM, where elements in form of tetrahedral, hexahedra, pyramids and prism can be used, SEM can only use hexahedra elements. This restriction makes the meshing process complicated. A poor mesh design can lead to high computational cost and produce artefact in results. A mesh represent a virtual model of and area and there is usually created once; other parameter (such as source location and characteristics) can be varied according to the requirements (Section 3.2.4 for theory).

The software required for creation of good quality must be able to accommodate general geological models, have minimal user intervention, high resolution, capable for creation of conforming, unstructured hexahedral mesh elements, and a parallel, load-balanced implementation (Casarotti et al., 2008). CUBIT has been found to fulfil these requirement. In SPECSEM3D it is used in conjunction with GeoCubit, which is a python based script designed at the Istituto Nazionale di Geofisica e Vulcanologia (INGV) to automate the mesh generation process.

Topographic mesh models for this study are made using CUBIT 13.0. The first step in this process is the incorporation of topographic surface to CUBIT. The topography is imported from and XYZ Cartesian file format, which is extracted from Digital Elevation Model (DEM). Each XYZ combination creates a vector points (Figure 3.4a), which are joined by a smoothed vector lines (Figure 3.4b), and eventually a topographic surface is created by combining the lines (Figure 3.4c). When the topographic surface is ready, a 3D geometric models is created. In second step, the 3D geometrical model is mesh with hexahedral elements (Figure 3.4d & e). The resolution of mesh depends on resolving desired seismic wave frequencies, computational resources and the complexity of model. A fine resolution mesh is capable of resolving high frequencies and leads to realistic result but comes with extensive computational power requirement. After the mesh is created it is defined with boundary conditions and material properties and eventually exported to a format suitable for simulation in SPECSEM3D.

In order to simulate on multiple processors, SPECSEM3D is capable of partitioning mesh. In this way the spectral element mesh created

Figure 3.4 Illustration of mesh designing procedure. (a) conversion of Digital Elevation Model (DEM) to points, (b) conversion of points to lines by joining with smooth lines, (c) combining lines with to create smooth surface, (d) 3D meshed model with topography and (e) 3D meshed model without topography.

with CUBIT is distributed on the multiple processors. The makes the large scale simulation possible to run efficiently.

3.3.2 Source Parametrization

The source of an earthquake can be of either of two types depending on the size of area and earthquake magnitude; point source and finite fault model. A point source in form of CMT solution (Dziewonski et al., 1981; Ekström et al., 2012) provide fairly accurate representation of small earthquakes of magnitude less than 6.0 (Lee et al., 2014). The CMT solution summarize magnitude, depth and focal mechanism for any seismic event. However, for earthquake with magnitudes greater than 6.0, a finite fault model is recommended (Lee et al., 2014). Also in some cases multiple point source have been used to mimic propagation of fault slip (Tsai et al., 2005; Duputel et al., 2012).

In this study we used point source for the 2005 Kashmir earthquake. It is because the study area (approx. 40 x 40 km) is much smaller compare to the fault plane (approx. 130 x 45 km). In such case a point source in form of CMT solution simple and provides a standard against which the ground motion at near-fault during large earthquake can be compared to differentiate other complex source effects like hanging wall and footwall effects (Yenier and Atkinson, 2014). Since a point source is

often used in seismic hazard analysis for future earthquake (Bommer and Akkar, 2012; Baker, 2013), therefore is considered useful for this work.

3.3.3 Simulation

After the mesh is created and the source is defined, next step involves simulation. The simulator in SPEC3D is called as 'solver'. Before a mesh goes to the solver, certain parameters are set. Some of the important parameters are briefly described below:

1. Simulation type: Here one has an option to select whether to perform forward simulation, adjoint simulation or kernel simulation.
2. UTM Projection Zone: This parameter describe the zone in which the study area/ or meshed model lies. There is also an option to supress projection for performing simulation in synthetic or hypothetical mesh instead of realistic.
3. Number of processors: This involves defining the number of processor on which the mesh would be simulated.
4. Number of time steps: The number of time step controls the length of simulation. The length of simulation increases if the number of time steps are increased; and consequently requires more processing time.
5. Length of time steps: The length of each time step is given in seconds.
6. Shakemap: SPEC3D provide option to create Shakemaps in form of peak ground velocity, displacement and acceleration.
7. Movie: Movie can be obtained for only top surface or whole volume of mesh.

Another main feature that SPEC3D provide is the creation of synthetic seismograms. The location information for seismogram are provided to the SPEC3D in a specified format, which are used by the solver to generate seismograms at the given site. These can be real locations of real seismograms or hypothetical.

3.3.4 Output Visualization

There are several software packages that can be used for visualizing output created during the whole process, right from mesh generation to the outputs in the form of shakemaps, movies and synthetic seismograms. The mesh and shakemaps can be visualized in ParaView or OpenDx. The shakemaps can be obtained in the form XYZ file format which can be visualized and processed with GMT or other GIS/RS software.

Impact of Mesh and DEM Resolutions on Seismic Response

4.1 Introduction

The earth's topography acts as a reflecting surface for seismic energy. Its variation in elevation leads to scattering and focusing of propagating waves (Lee et al., 2008, 2009a). Previous studies (such as, Hartzell et al., 1994; Spudich et al., 1996; Bouchon et al., 1996; Assimaki et al., 2005a; Lee et al., 2009a,b; Hough et al., 2010; Kumagai et al., 2011; Takemura et al., 2015) show that topography amplifies ground shaking at mountain ridges, whereas de-amplification of ground motion has been observed in valleys. Recently, numerical simulations have been used in studying this complicated phenomena of scattering and its effects on ground motion (e.g. Bouckovalas and Papadimitriou, 2005; Lee et al., 2008, 2009a; Takemura et al., 2015; Maufroy et al., 2015).

There is a wide range of digital topography representation, commonly referred to as Digital Elevation Model (DEM). The (spatial) resolution is a property of the DEM (Smith et al., 2006; Sørensen and Seibert, 2007; Wu et al., 2008). DEMs come in various resolutions, ranging from fine (e.g. LIDAR at ~ 12 cm) to coarse (e.g. GTOPO30 at ~ 1 km) (see Section 4.5). The DEM resolution sets a limitation to the realism of the topographic data. For example, coarse resolution data smoothens topography and results in a loss of topographic features (Shafique et al., 2008, 2011a; Vaze et al., 2010). Shafique et al. (2008) evaluated the impact of DEM resolution and its derived attributes on topographic representation and derived seismic response. Their study shows that DEM source and

¹This chapter is based on the following paper

Khan, S., van der Meijde, M., van der Werff, H., Shafique, M., 2017. Impact of Mesh and DEM Resolutions in SEM Simulation of 3D Seismic Response, *Bull. Seismol. Soc. Am.* 107, no. 5, doi: 10.1785/0120160213

spatial resolution has an effect on the computed output. However, the study was based on topography-derived proxies and lacked simulation.

A DEM resolution, and the representation of that DEM on various mesh resolutions when used for 3D numerical modeling approaches, becomes more important when it comes to regional studies (e.g. 100s of km²). Existing models such as USGS-ShakeMap and PAGER are at a coarse resolution of 1 km (Jaiswal et al., 2011), thus giving generalization (Vaze et al., 2010). On the other hand, geotechnical studies evaluating the impact of topography with higher resolution are limited to a small spatial scale. A coarse resolution may save time but comes at a cost of accuracy while a fine resolution may save accuracy but comes at a cost of applicability (i.e. cannot be applied to a regional scale investigation).

For performing 3D numerical simulations such as the Spectral Element Method (SEM), a 3D geometrical model is prepared from a DEM that represents the topographic surface. The 3D model is then meshed with a hexagonal mesh (which consist of hexahedra elements). The mesh is defined with material and structural properties that defines how will it react to applied conditions (e.g. an earthquake). The meshed model is then taken to a simulator (such as SPECFEM3D in this study), which produces simulated output. The hexagonal mesh is required to have a suitable resolution that could correctly resolve the surface obtained from a DEM in a 3D geometric model. For example, a model created with a 30 m DEM, when meshed with a coarser resolution would not be able to correctly resolve the surface, and hence many small scale topographic features would be left out. It is thus necessary to take into account both DEM and mesh resolution while performing such studies.

Theoretically, a model with the finest mesh and DEM resolution should provide the best possible result. At the same time, fine resolution models would require a large amount of computational power and hence may not be possible. High resolution DEM availability and related costs may also be an issue. Thus it is important to have knowledge about how coarse a mesh and/or DEM resolution can be while still providing realistic results compared to as if calculated with highest possible resolutions. Efficient use of time and computation must be considered, and therefore the generated result should still be applicable regionally. Therefore, the aim of this study is to find the coarsest mesh and/or DEM resolution that can be used in a 3D numerical simulation involving regional scale topography, without compromising on accuracy.

Figure 4.1 Digital elevation model (DEM) of the study area, including the simulated earthquake epicenter, shifted to fit in the model.

4.2 Area, Data and Method

4.2.1 Area

We selected a study area around the city of Muzaffarabad in northern Pakistan (Figure 4.1). The area consists of rugged terrain with high relief and has showed manifestations of topographic amplification during the 2005 Kashmir earthquake (Shafique et al., 2008). We focused on a single ridge trending NW-SE. Its ridge crest is perpendicular to the direction of wave propagation. The setting allows us to study the effects of valleys and ridges in an isolated and controlled environment.

4.2.2 Data

We acquired an ASTER GDEM of 30 m spatial resolution (see Section 4.5). The original 30 m resolution was resampled with a pixel aggregate technique to 90 m, 270 m, 540 m and 1080 m. In this technique, the individual values within a group of pixels were aggregated by calculating the mean to produce a single coarser resolution pixel of the mean value. Each of these DEM resolutions were then resolved with mesh resolutions

4. Impact of Mesh and DEM Resolutions on Seismic Response

Figure 4.2 Study area in bird's-eye view (looking northwest) showing a graphical representation of different combinations of DEM and mesh resolutions on which spectral element method (SEM) test was performed. Top surface is the DEM-derived topographic surface, whereas the same surface after meshing is shown below it. The DEM-derived surface gets smoothed by losing fine features when the DEM gets coarsened (left to right). The DEM-derived topographic surface at 30 m resolution contains fine topographic features which disappear when the surface is smoothed as a result of DEM coarsening. The DEM-derived topographic surface gets accurately resolved with the fine meshes.

of 90 m, 270 m 540 m and 1080 m, constituting a total of 20 models (Figure 4.2). Models meshed with 90m can resolve maximum frequencies up to ~ 16.6 Hz, 270 m up to ~ 5.5 Hz, 540 m up to ~ 2.7 Hz and 1080 m up to ~ 1.4 Hz. The number of Gauss-Lobatto-Legendre (GLL) points per grid spacing was kept at 5.

To create a 3D geometrical model for each of the tests, we used software package Cubit v.13.0 (see Section 4.5). Cubit is a software toolkit for the generation of 2D and 3D finite-element meshes.

In this study, we incorporated a DEM to the mesh and extended the mesh to a depth of 7 km. The topographic surface was set as a free surface; the rest of five plane surfaces were set as absorbing surfaces. The models were meshed with a hex meshing techniques with refining (when required) near the topographic surface to make sure there are no deformed elements.

4.2.3 Method

For mesh generation, Cubit is used in conjunction with GeoCubit. GeoCubit is python based software developed at Istituto Nazionale di Geofisica e Vulcanologia (INGV), which automates the mesh generation process. The automated process involves three major steps. The first step is the construction of a 3D geometry. GeoCubit creates points from a DEM, combines these points to make lines, and eventually create a surface by combining the lines. After creating the topographic surface, a 3D geometrical model is created. The second step is meshing the geometry. After creation of the 3D geometrical model, the model is meshed with hexahedral elements. The last step involves defining boundary conditions and mesh export for simulation.

Mesh elements were exported to a format readable for the simulator. All tests were simulated with SPECFEM3D Cartesian, which is capable of simulating acoustic, elastic, coupled acoustic/elastic, poro-elastic or seismic wave propagation in any type of conforming mesh of hexahedra (see Section 4.5). We considered a point source data represented by the Centroid Moment Tensor (CMT) solution of the 2005 Kashmir earthquake acquired from the Global CMT Catalogue (see Section 4.5). Since we perform an analysis to evaluate the impact of the resolution of models rather than simulating the actual effect of the earthquake, we have moved the source to a position where it was optimally located to study the effect of DEM and model resolution on topographic amplification. The original location was changed to bring the source inside the model and in a direction perpendicular to the targeted ridge's crest (Figure 4.1). A delta source time function was used by keeping the half duration at '0'. The changing mesh resolution changes source frequencies from 5.5 Hz for the 90 m and 270 m mesh, to 2.7 Hz for the 540 m mesh, and finally 1.4 Hz for the 1080m mesh. The moment tensor parameters were kept constant in each simulation. Due to unavailability of a realistic wave speed model for the area, we assigned constant wave speeds ($V_p=2800$ m/s, $V_s=1500$ m/s) and density ($\rho=2300$ kg/m³), representative of upper crustal conditions, throughout the model and across all tests. Hence for all tests, all parameters were kept constant except the mesh and topography resolution (in order to isolate resolution effects on topographic amplification).

We analyzed Peak Ground Displacement (PGD) in order to evaluate the effect of changing mesh and DEM resolution. PGD mostly relates to the relatively lower frequency component of earthquakes (Kramer, 1996) and at the same time, the SEM technique efficiently simulates low-frequency earthquake ground motion (Dhanya et al., 2016). It is assumed that a fine DEM represents topography with higher accuracy and when resolved with a fine mesh would give our reference 'realistic' output.

4.3 Results and Discussion

The DEM data is incorporated to Cubit as point data. These points are then joined with a smooth line and eventually a surface is created based on these lines. In this process the DEM derived surface gets smoothened by losing fine features when the DEM gets coarsened as shown in Figure 4.2. The combination of the highest resolution DEM and mesh contains small-scale topographic features and the model is a close representation of the ‘true’ topography at 30 m resolution. These fine features disappear and the surface is smoothened when the DEM resolution coarsens (going from left to right in Figure 4.2). When keeping the DEM resolution equal but now varying the mesh resolution, we observe that the model is not capable of representing the model properly anymore; the similarity is lost (going from top to bottom in Figure 4.2). Features smaller than the mesh resolution are lost and consequently produce stair-step wise features. These features influence the simulation and produce artifacts. An example of such artifacts can be observed in Figure 4.3 at 540 m mesh resolution where the output does not match the topography. Chances of stair-step features are increased when a fine resolution DEM derived surface is resolved with a coarser mesh. Vice versa, when a coarser DEM derived topographic surface is resolved with a finer mesh, the surface is accurately resolved and the simulation produces output without any artifacts.

For analyzing the impact of mesh and DEM resolution we show PGD (Figure 4.3) obtained from 15 (out of 20) combinations of mesh and DEM resolutions shown in Figure 4.2. Results from the 30 m mesh are unavailable due to computational limitations. We refer to each model output with a code. A resulting model based on a mesh of 90 m and a DEM of 30 m would be mentioned as m90d30. Since this model is the result of the finest mesh and DEM resolution, it has therefore been taken as reference for other models for comparison and analysis.

Upon visual analysis of the PGD images (Figure 4.3), we can see that the effect of ridges and valleys get smoother when the DEM gets coarsened (left to right). High amplitudes of PGD can be seen in the south-east of the images which corresponds with the topography of the area (Figure 4.1). This amplitude’s pattern is consistent with previous studies on topographic amplification showing high amplitudes at ridges and lower amplitudes in valleys (e.g. Hartzell et al., 1994; Spudich et al., 1996; Bouchon et al., 1996; Assimaki et al., 2005a; Lee et al., 2009a; Hough et al., 2010; Kumagai et al., 2011; Takemura et al., 2015). This effect is more pronounced in images obtained from models meshed with 90 m and 270 m (row1 and row2, respectively). With the increase of mesh resolution to 540 m, and further, the correlation between amplitudes

Figure 4.3 Peak ground displacement (PGD) of 15 tests out of a total 20 carried out in this study. Images in rows 1, 2, and 3 belong to models meshed with 90, 270, and 540 m, respectively. Images in columns 1, 2, 3, 4, and 5 belong to models using DEM of 30, 90, 270, 540, and 1080 m, respectively.

and topography becomes less pronounced.

We observe a general trend of increasing amplitudes with coarsening DEM resolution. This trend is because of the scattering effect of detailed irregularities at the topographic surface. At finer resolutions, there is an abundance of irregularities in the surface. These small irregularities on slopes interfere with incoming seismic wave in a destructive manner, lead to additional scattering of the upward moving seismic waves, and prevent it from focusing; thus resulting in lower amplitudes. When the DEM/mesh resolution is relatively coarse, any irregularities smaller than its resolution are smoothened (Shafique et al., 2011a) and destructive interferences are reduced, resulting in higher amplitudes. Coarsening of the mesh resolution, to 540 m and beyond, results in an inaccurate representation of topography and in turn gives inaccurate information about ground response.

Results show more difference in terms of feature response if there is a change in DEM resolution compared with a change in mesh resolution at the same resolution ratio. It is because the hexahedral meshes have the ability to adjust their geometry to the input topographic data, even when meshed at coarser resolution. Therefore, even if the mesh resolution is coarser than the resolution of the DEM, it is still possible to maintain a realistic representation of the actual topography.

We compare the output of each of the 14 models (referrals) with the output of model m90d30 (the reference) (Figure 4.4). The scatter

plots show PGD amplitudes between the reference and referral image. The PGD of the reference (m90d30) is on the x-axes while the referral images are on the y-axes. Slope, intercept, R^2 , ordinary least square (OLS) and best-fit lines for each referral are given with the respective plots. Increased scattering, with respect to best-fit line, has been observed when the DEM resolution is changed, compared to change in mesh resolution at the same ratio. Based on the spatial images and statistical data, we set criteria for an acceptable range of DEM and mesh resolutions. A first criterion for acceptance is that the output must follow the topographic features in the response (i.e. high amplitudes on ridge crest and low amplitudes in valleys). Using this criterion it was found that any model meshed with a resolution of 540 m or coarser is unacceptable (Figure 4.3). The second and third criteria of acceptability are based on statistics. The perfect fit 1-to-1 line is an indicator of the perfect match between the reference and referral image (i.e. both have same data). Slope, intercept and R^2 of the best-fit line indicate how the referral image is different from the reference image. They show that with coarsening of mesh or DEM resolution, the accuracy decreases. This decrease can be interpreted from the decrease in R^2 , change in slope from 1, and shift of best-fit line from the perfect fit line. OLS also indicates that, while coarsening the DEM and/or mesh resolution, the error in amplitude increases. The last criterion is that the best-fit line must touch the perfect fit line. Overall, we have set that the slope must be 1.0 ± 0.15 , R^2 must be greater than 0.90, and OLS cannot be greater than 20. Models not fulfilling these criteria are considered as inaccurate/unrealistic and therefore unacceptable. Based upon these criteria of acceptability, any model based on a 540 m or coarser mesh and/or DEM generate unacceptable/unrealistic results. The criteria of acceptance can also be expressed in terms of the ratio of each combination of mesh and DEM resolution with respect to the finest resolution (Figure 4.5). We do our selection based on the criteria that the majority of an area must have a ratio of less than 0.2 (20%), with respect to 1.0. It can be noted that models with DEM resolutions of 30, 90, and 270 m at mesh resolution of 90 and 270 m have the majority of their area at ratio values of less than 0.2. A further increasing of the DEM resolution results in an increase in spatial extent of higher ratios. At the same time, a further increase in mesh resolution results in extreme (>0.2) ratio values. The following discussion focuses on changes that occurred due to mesh and DEM changes within the acceptable resolution range, but as coarse as possible. We selected four model outputs, each combination of 90 m and 270 m DEM and mesh resolutions (marked in Figure 4.3), to understand how changes occur between models with varying mesh and DEM resolution (Figures 4.6 and 4.7).

In the scatter plots in Figure 4.6 we observe that m90d90 and

Figure 4.4 Scatter plots of PGD of reference model (x axis) against PGD of 14 tests (y axis). (top left) m90d30 is the reference model. Statistical data for each model are also given in the bottom right corner of each image.

Figure 4.5 Ratios of each model with reference model (m90d30) of the finest mesh and DEM combination.

4. Impact of Mesh and DEM Resolutions on Seismic Response

Figure 4.6 Scatter plots between models of 90 and 270 m mesh and DEM resolutions. (g) Scatter plot is product of (a) m90d90 and (d) m270d90, (h) plot of (b) m90d270 and (e) m270d270, (i) plot of (a) m90d90 and (e) m270d270, (f) plot of (d) m270d90 and (e) m270d270, (c) plot of (a) m90d90 and (b) m90d270.

m270d90 give the most similar results of all comparisons. The statistics based on the scatter plot give a best fit and R-square of almost 1.0, and the intercept is very close to 0. An almost comparable good correlation is found between m90d270 and m270d270. This clearly indicates that changing the mesh from 90 m to 270 m has very little impact on the modeled results. For the other two comparisons we see that R^2 is also close to 1.0 but for the slope and the intercept we observe larger variations. The slope decreases to around 0.75 and intercepts are in the range of 70–75 range. We observe there an overestimation of the lower PGD values, compared to m90d90. So, changing mesh resolution has less impact than changing the DEM resolution, for this range of resolutions.

In the ratio images (Figure 4.7) we show ratios for the same images

Figure 4.7 Ratios between models of 90 and 270 m mesh and DEM resolutions. (g) is product of (a) m90d90 and (d) m270d90, (h) plot of (b) m90d270 and (e) m270d270, (i) plot of (a) m90d90 and (e) m270d270, (f) plot of (d) m270d90 and (e) m270d270, and (c) plot of (a) m90d90 and (b) m90d270.

as of Figure 4.6 and find similar results. Changing the mesh resolution while keeping the DEM resolution equal (Figure 4.7g,h) results in a ratio image that is everywhere very close to 1.0. Changing the DEM resolution (Figure 4.7c,f,i) leads to large positive ratio values of up to 1.4, particularly for the flatter regions in the northern part of the study area.

A last thing to consider is that the mesh resolution defines the frequency resolving capability of a SEM model. The maximum and mean resolved frequencies for each DEM derived topographic surface model varies across different mesh resolution (Figure 4.8). The mean of the resolved surface frequencies are also indicated with dashed line in the same color. It can be seen that fine meshes are able to resolve higher frequencies compared to coarse meshes. It is important to realize that despite the fact that models with a 90 m and 270 m mesh seem to give

4. Impact of Mesh and DEM Resolutions on Seismic Response

Figure 4.8 Maximum and mean frequencies resolved at topographic surface of the model for 90, 270, 540, and 1080 m resolution meshes.

very similar results, the frequency content is quite different. In summary one can state that models with a mesh and DEM resolutions of 540 m and greater lead to unrealistic results when compared to the highest possible resolution models. Models with a resolution of 270 m and finer give comparable results, whereas changes in DEM resolution have more impact on the output models than changes in mesh resolution. It should be noted that these results might be dependent on the spatial scale of the topography and the ruggedness of the terrain. Results on mesh and DEM resolution are therefore valid for comparable terrains, but might not be directly applicable in regions with distinctly different geomorphological characteristics.

4.4 Conclusion

Studies for simulation of topography related seismic amplification rely strongly on the resolution of the topographic model as well as the modeling mesh. In this study we analyzed how coarse a mesh and/or DEM resolution can be but still maintain accuracy compared to the most well resolved case. We tested models of different mesh and DEM resolutions and compared it with the highest resolution possible (in our case a model with a mesh of 90 m and a DEM of 30 m). Our results and analysis show that models with a resolution of 270 m and finer give comparable results, whereas changes in DEM resolution have more

impact on the output models than changes in mesh resolution. Any model with a mesh and/or DEM resolution of 540 m or coarser produce inaccurate results compared to the highest resolution model with a 90 m mesh and a 30 m DEM.

It was found that in finer resolutions, abundance of topographic irregularities resulted for some locations in a destructive interference and hence result in lower amplitudes compare to those coming from coarse resolution. When the DEM/mesh resolution is relatively more coarse, irregularities are smoothened and destructive interferences reduced, resulting in higher amplitudes. Results on mesh and DEM resolution are valid for comparable terrains, but might not be directly applicable in regions with distinctly different geomorphological characteristics.

4.5 Data and Resources

More information about the light detection and ranging (lidar) can be obtained from https://lta.cr.usgs.gov/lidar_digialelevation (last accessed June 2016). More information about the Global 30 Arc-Second Elevation (GTOPO30) model can be obtained from <https://lta.cr.usgs.gov/GTOPO30> (last accessed January 2016). ASTER GDEM data were downloaded from LP DAAC Global Data Explorer <http://gdex.cr.usgs.gov/gdex/> (last accessed June 2016). More information about Cubit can be found at Sandia National Laboratories website <https://cubit.sandia.gov/> (last accessed August 2015). More information about SPECFEM3D Cartesian (devel version) was downloaded from the Computational Infrastructure for Geodynamics (CIG) website <https://geodynamics.org/cig/software/specfem3d/> (last accessed August 2015). The centroid moment tensor (CMT) of the 2005 Kashmir earthquake was acquired from the Global CMT website <http://www.globalcmt.org/> (last accessed October 2016). Generic Mapping Tools (GMT) was used for visualization of the results <http://gmt.soest.hawaii.edu/> (last accessed May 2017).

Role of Topography During 2005 Kashmir Earthquake

5.1 Introduction

The earth's topography acts as a reflecting surface for upcoming seismic energy and produces surface waves (Lee et al., 2009a,b). The undulating nature of surface topography leads to scattering or focusing of propagating waves (Lee et al., 2009a,b). Previous studies found that topography amplifies the ground shaking at mountain tops and ridges, while it de-amplifies in valleys; for example Hartzell et al. (1994) and Spudich et al. (1996) in California; Lee et al. (2009a,b) in Taiwan; Hough et al. (2010) in Haiti, Kumagai et al. (2011) in Ecuador, and Restrepo et al. (2016) in Colombia. Most seismic active areas are rugged in nature, which makes these regions prone to topographic (de-)amplification (Lee et al., 2009a; Hough et al., 2010; Shafique and van der Meijde, 2015). Incorporating the topographic impact on seismic response is thus important for seismic hazard assessment, mitigation and seismic shaking prediction (Wu et al., 2008; Bauer et al., 2001; Shafique et al., 2011a).

During the 2005 Kashmir earthquake in northern Pakistan, the city of Muzaffarabad and its surroundings were severely damaged. The earthquake has been studied on various aspects. Ali et al. (2009) studied the impact of surface faults on infrastructure and environment; primarily based on field surveys done immediately after the earthquake. Several satellite based studies primarily focused on field displacement and slip distribution, such as Parsons et al. (2006); Avouac et al. (2006); Pathier et al. (2006); Wang et al. (2007). Others addressed relationships between co-seismic displacement and landslides (e.g. Kamp et al., 2010;

¹This chapter is based on the following paper

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Dunning et al., 2007; Saba et al., 2010). Topographic aggravation of seismic responses in Kashmir was first evaluated by Shafique et al. (2008) using the topographic aggravation factor (TAF) after Bouckovalas and Papadimitriou (2005). Their method involved the use of topography derived parameters such as terrain slope and relative height as a proxy for terrain characteristics in homogeneous halfspace. One of the major simplifications in their work was the use of these pixel-wise proxies instead of a full 3D topographic model. In this paper, we use a 3D spectral element method (SEM) modelling approach that incorporates an elevation model and full elastic waveform simulations, including all possible waves, based on the source characteristics of the earthquake in a homogeneous halfspace.

The SEM was developed by Patera (1984) for computational fluid dynamics, and was introduced for 3D seismic wave propagation by (Komatitsch and Vilotte, 1998; Komatitsch and Tromp, 1999). The method is adopted in several studies afterwards; Komatitsch et al. (2004) simulated ground motion in the Los Angeles Basin for the 2001 Mw 4.2 Hollywood earthquake and the 2002 Mw 4.2 Yorba Linda earthquake. Pilz et al. (2011) modeled basin effects on earthquake ground motion in the Santiago de Chile basin using scenario earthquake of Mw 6.0. Magnoni et al. (2014) simulated the 2009 Mw 6.3 L'Aquila Earthquake, considering topographic and basinal features in central Italy. Lee et al. (2008, 2009b,a, 2013, 2014) developed a real-time online earthquake simulation system based on SEM in Taiwan. Liu et al. (2015) simulated scenario earthquake strong ground motion in the Shidian basin to study basinal influence on seismic amplification and distribution of strong ground motion. Evangelista et al. (2016) studied site response at the Aterno basin (Italy). Paolucci et al. (2016) estimated ground motion for the historical 1915 Marsica earthquake in the Facino basin incorporating topography and bedrock morphology. Restrepo et al. (2016) simulated 4 scenario earthquakes of Mw 5 along the Romeral fault for the metropolitan area of Medellín (Colombia) demonstrating how topography affects ground response. Smerzini et al. (2017) studied site effects by taking the historical Mw 6.5 1978 Volvi earthquake in the Thessaloniki urban area (Greece). In this study we exclusively study the role of topography in on ground motion for the area of Muzaffarabad and surrounding areas during the 2005 Kashmir earthquake.

5.2 Study Area

Within the area affected by the 2005 Kashmir earthquake, we selected an area of approximately 40 x 40 km around the city of Muzaffarabad (Figure 5.1). Being part of the western Himalayas, its position on a conver-

ging plate boundary makes this region particularly prone to earthquakes. Its rugged terrain is sensitive to topographic (de-)amplification (Lee et al., 2009a; Hough et al., 2010; Shafique and van der Meijde, 2015). The earthquake was caused by reactivation of the Muzaffarabad fault (also known as the Balakot-Bagh fault) (Hussain et al., 2009) shown in (Figure 5.1). The Centroid Moment Tensor (CMT) of the (Mw 7.6) 8 October 2005 Kashmir earthquake (Dziewonski et al., 1981; Ekström et al., 2012), retrieved from (<http://www.globalcmt.org/>) was used for the simulation and lies in the centre of the study area (Figure 5.1). The depth of CMT lies at 12 km. The USGS (<https://earthquake.usgs.gov/earthquakes/>) reported, after comparing waveform fits based on the two planes of the input moment tensor (Figure 5.1), that the nodal plane (strike= 320.0 deg., dip= 29.0 deg.) fits the data better. The seismic moment release based upon this plane is 3.0×10^{27} dyne.cm and was calculated using a 1D crustal model interpolated from CRUST2.0 (Bassin et al., 2000). Several studies (e.g. Avouac et al., 2006; Pathier et al., 2006; Wang et al., 2007) provide detailed information about the fault dynamics, including moment tensor solutions and finite fault models.

Figure 5.1 Digital Elevation Model (DEM) of the study area of Muzaffarabad (Pakistan). Major faults in the study area (after Hussain et al. (2009)) are shown along with Centroid Moment Tensor (CMT) solution.

5.3 Methodology

We based our analysis on modelling with the spectral element method (SEM) for simulating 3D seismic wave propagation. The software package SPECFEM3D (Computational Infrastructure for Geodynamics, 2016), is used for SEM simulations. SPECFEM3D can simulate global, regional and local seismic wave propagation. It uses the continuous Galerkin spectral-element method to simulate elastic wave propagation caused by earthquakes (Komatitsch and Tromp, 1999).

SEM based modelling relies on meshed objects or volumes. A high-quality 3D mesh is a key factor for a successful application of SEM (Casarotti et al., 2008). A mesh is composed of hexahedra elements that are isomorphous to a cube (Komatitsch et al., 2002). It is defined with material and structural properties that defines how it will react to applied conditions (e.g. an earthquake). We used the Cubit v.13.0 software (Sandia National Laboratories, 2011) for generation of the meshes. Surface topography is based on the ASTER Global DEM, a product of National Aeronautics and Space Administration (NASA) and Japan Ministry of Economy, Trade and Industry (METI). It was retrieved from the Global Data Explorer, courtesy of the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, <http://gdex.cr.usgs.gov/gdex/>.

Previous study has explored at which resolution you can best model the topography in relation to mesh resolution (Khan et al., 2017a). They analysed the impact of data resolution (mesh and DEM) on seismic response using SPECFEM3D. Different combinations of mesh and DEM resolutions were modelled to find the optimal mesh and DEM resolution for getting accurate results while keeping computational resources to the minimum. Their conclusion was that a mesh and topography of 270 m resolution was optimal for the topography around Muzaffarabad. Our model adopts this resolution and thereby allows for seismic wave simulations with frequencies up to ~ 5.5 Hz. We use a polynomial degree $N = 4$ to sample the wave field; therefore each spectral element contains $(N + 1)^3 = 125$ Gauss-Lobatto-Legendre (GLL) points, which is 5 GLL points per wavelength. In order to correctly sample the wave field, one needs to use roughly five GLL points per wave length (Komatitsch et al., 2004). The mesh extends to a depth of 40 km, and contains two tripling layers. Tripling is a refinement technique in meshing for subdividing hexahedral elements in a conforming fashion. Tripling layers increase the spatial resolution of the mesh from 270 m at the surface to 2430 m at the bottom of the model (at a depth of 40 km). This is done in order to reduce the computational time and cost by reducing the total number

of mesh elements following the approach as proposed in several other studies (e.g. Lee et al., 2008). Due to the unavailability of a wave speed model for the area, we assigned constant wave speeds ($V_p=2800$ m/s, $V_s=1500$ m/s) and density ($\rho=2300$ kg/m³) in the modelling, representative for upper crustal conditions (Taborda and Roten, 2015; Wang et al., 2016; Makra and Raptakis, 2016).

To investigate the effect of regional topography on seismic amplification, we ran the 3D model once with a topographic surface and once without topography (having a plain surface instead). As source for the simulation we used the 3D wave field as described in the CMT solution of 2005 Kashmir earthquake. Since SEM is efficient in simulating low frequency ground displacement and has limited capability in simulation of high frequency accelerations (Dhanya et al., 2016) we present our results in peak ground displacement maps (PGD) and PGD ratio maps based on models with and without topography. Based on these PGD maps we created an amplification map. In order to evaluate the impact of topography the pattern of amplification was compared with the topography of the area. The impact of topography on seismic response was also evaluated by correlating the amplification pattern with damage and landslide data. The damage data (Figure 5.2) is taken from Shafique et al. (2012), who categorized damage to infrastructure as high, moderate and less. The landslide data (Figure 5.3) is taken from Humanitarian Information Center Pakistan (HIC-Pakistan), first published by Shafique et al. (2008). Based on the orientation of slopes relative to the CMT location, the aspects of slopes were categorized into away (facing away from the CMT), towards (facing towards the CMT), and other (facing in directions other than towards and away). The categorization is based on 60° offset of aspect with respect to its angle towards the CMT location.

5.4 Results

The modelling results show that seismic response is sensitive to slope angle, aspect, geometry, and height of the terrain features. The modelled PGD amplitudes differ for a homogeneous halfspace without topography (Figure 5.4a) and with topography (Figure 5.4b). The higher amplitudes coincide with mountain ridges, as shown in the DEM (Figure 5.4c). Without topography, the PGD falls within the range of 0.23–5.8 m (Figure 5.4a), but increases to a range of 0.36–7.85 m (Figure 5.4b) when topography is taken into account. The difference between the PGDs of the two models (Δ PGD) is shown in Figure 5.4(d). The difference in PGD between a model with topography versus the same model without topography is represented in terms of amplification. For positive values we use term amplification, meaning the seismic signal has become

5. Role of Topography During 2005 Kashmir Earthquake

Figure 5.2 2005 Kashmir earthquake induced damage data after Shafique et al. (2012).

stronger due to topography compared to simulation without topography. Whereas, for negative values we use de-amplification, meaning the seismic signal has become weaker due to topography compared to the simulation without topography. The topographic (de-)amplification causes local changes of approximately -2.50 to $+3.00$ m (Figure 5.4d).

For a detailed analysis of the effect of topography we compare topography, PGD (with and without topography) and Δ PGD along profile lines. A comparison (Figure 5.5, 5.6 & 5.7) is made along the white profile lines shown in Figure 5.4 (AA', BB' and CC', respectively). The profile line AA' is approximately 47.5 km long, and passes over the CMT location in the centre of the profile (marked with a dotted arrow). We observe, in general, amplification at ridges and de-amplification in valleys. For ex-

Figure 5.3 Co-seismic landslides inventory was developed by the Humanitarian Information Center (HIC), a subsidiary organization of the United Nations Office for Coordination of Humanitarian Affairs (OCHA), which was reported by Shafique et al. (2008).

ample, at the CMT location where de-amplification is occurring because its location in a valley. The amplification and de-amplification related to ridges and valleys, respectively, has a shift toward the ridge slope facing away from the CMT location (Figure 5.5). We find that slopes facing away from the epicenter have an amplified seismic response. Similarly, slopes facing towards the CMT have a de-amplified seismic response. The most clear and prominent example of this amplification is at location (a) (Figure 5.5). The slope facing away from the CMT location is experiencing amplified PGD amplitudes. The maximum amplitudes occur at the top and near the top on the slope facing away from the CMT location. On

the slope side facing towards the CMT location, we see a rapid decrease in amplification, turning into de-amplification for the lower part of the slope. This pattern of decay with elevation we also see for the amplified side but the decay there is much slower and the model shows amplified signals till much further down the slope. Similar patterns can be observed for the ridges at locations (b) and (c) we find that the slope facing towards the source has experienced de-amplification, while the slope facing away is showing amplification. The same phenomena of amplification and de-amplification can also be observed on slope along profiles BB' and CC' (at locations a, b & c) in Figure 5.6 and 5.7 for profile lines BB' and CC', respectively. The trapping of energy due to the shape of the mountain is observed and reflection of energy towards the top of the mountain leads to increased amplification effects with increase in elevation from the base of the mountain, particularly on the side of the mountain that is directly exposed to the incoming seismic waves. A clear shadow effects due to terrain features can be seen at some locations. At locations (d) and (e) (Figure 5.5) we observe that a deep valley blocks the continuation of seismic wave energy into the next topographic high, thereby leading to de-amplification. Similarly, at location (d) in Figure 5.6 and Fig 5.7 we observe a similar shadow effect, and resulting de-amplification, due to blocking of seismic waves by deep valleys between the ridge and the CMT.

The Δ PGD shown in Figure 5.4(d) is compared with damage data (Figure 5.2) of the 2005 Kashmir earthquake in Figure 5.8. Shafique et al. (2012) reported damage into three categories; high (red), moderate (yellow) and low (green). The high damage zone constitutes 11% of the damaged part of the Muzaffarabad area, while moderate and low damage respectively cover 51% and 38% of the damaged area. There is clear correlation between (de-)amplification and damage level. For the highest class of damage, 98% of the damaged buildings are found in the amplified zone (positive Δ PGD, Figure 5.4(d)). On the other hand, 80% of the least damaged buildings lies within the de-amplified zone. Overall the distribution of damage is equally distributed over amplified and de-amplified zones, but amplification does have an impact on the level of damage.

Following the hypothesis that the direction of slopes has an impact on the amplification we would expect that the away facing slopes show a relatively higher Δ PGD than slopes facing toward or any other direction. Analysis of the terrain shows that 30% of the slopes face away from the CMT location, 35% face towards the CMT location, and 35% face another direction (Figure 5.9). On average we observe that around 2/3 of the area (63%) experiences a de-amplification, and around 1/3 (37%) shows amplification. When comparing these statistics with the statistics for the different aspect classes a relative increase is observed for slopes

that face away from the CMT location to 47%. Contrary, a decrease is observed, to 25%, for slopes facing towards the CMT location. So, the effect of slope direction on the amplification is significant.

In line with these observations, there have been studies (e.g. Ashford and Sitar, 1997; Ashford et al., 1997), that suggested a correlation between landslide occurrence and earthquake location as a possible result of amplification (Shafique et al., 2008; Meunier et al., 2008; Qi et al., 2010; Xu et al., 2013). For the Muzaffarabad area, the Δ PGD was compared with landslide data (Figure 5.3) collected shortly after the earthquake by HIC-Pakistan Shafique et al. (2008)(Figure 5.10). This shows a similar pattern as for the previous analysis. On slopes facing away from the CMT location we observe 53% of the landslides in the amplified zone, whereas on slopes facing towards the CMT this is only 16%.

5.5 Discussion

Our results show that, by incorporating topography in spectral element modelling, the minimum and maximum amplitude of the peak ground displacement changes. The results show manifestations of topographic influence on damage during the 2005 Kashmir earthquake. We find that the majority (98%) of the high damaged area lies in the topographically amplified response region. Conversely, the majority (80%) of the area with less damage lies in the topographically de-amplified response region. The relation between damage and amplification indicates that the topography was a contributing factor to the damage during the 2005 Kashmir earthquake. It is also important to consider other factors that could play role in damage to infrastructure. Shafique et al. (2011b) has shown that regolith thickness had an influence on damages during the 2005 Kashmir earthquake. Actual damage is also dependent on building quality. Although Asian Development Bank and World Bank (2005) reported that building material and poor construction was homogeneous in the area, Shafique et al. (2011b) observed differences between different sectors in the area. Poor construction practices such as connected buildings and poor reinforcements, are also considered as contributing factor for damage in the area in response to the 2005 Kashmir earthquake (Shafique et al., 2011b) and might have influenced, in a positive or negative sense, the comparison between amplification and damage.

Most of the structures in the area are low- to medium-high, which are normally most sensitive to high-frequency amplification effects. However, considering such high PGDs in this area, combined with building style not earthquake proof, the relation between PGD and damage might

not be optimal but is thought to show a strong correlation. Furthermore, during this study, PGD, peak ground velocity (PGV) and peak ground acceleration (PGA) have been found spatially very strongly correlated, with only some minor amplitude deviations at specific topographic features. So the overall pattern in a comparison would still look very similar to the damage vs Δ PGD comparison we show in the paper.

The directions of incident seismic waves have a significant impact on seismic-induced landslides (Ashford and Sitar, 1997; Shafique et al., 2008; Meunier et al., 2008; Qi et al., 2010; Xu et al., 2013). In our results this effect is not directly clear. For example, only 37% of the landslides fall within the amplified zone, the other 63% fall within the de-amplified zone (Figure 5.10). However, when the relative distribution of landslides is compared to slopes facing away (prone to amplification) versus slopes facing towards the CMT location, a correlation is observed. The majority of the landslides on slopes facing away from the CMT location are in the amplified zone (53%) while for slopes facing towards the CMT location this is only 16%. These figures are much lower than what Shafique et al. (2008) found for the same area and the same landslide catalogue. The main difference between their study and ours is the location to which the slope direction is compared. While Shafique et al. (2008) used the onset of the earthquake (the Epicenter location, Figure 5.1), we used in our modelling the CMT location (the location of maximum energy release, Figure 5.1). It was assumed that the maximum seismic amplitudes, and corresponding amplification will lead to the occurrence of landslides but apparently this is not true. Based on the comparison of the two results it is very likely that a much lower displacement value may have already triggered the landslides. The threshold at which the landslides will occur cannot be derived from this study but it is evident that already at much earlier stage in the earthquake propagation enough energy is created to activate landslides. The maximum energy release related to the CMT location occurs only later in the earthquake process and clearly has less control since the critical ground displacement required for activating a landslide might have already been exceeded. This can explain the abundance of landslides in the de-amplified zone based on modelling from the CMT location.

The aforementioned evidence of amplified seismic response on slopes facing away from the source could be a possible reason behind triggering landslides. However, it is important to consider complications associated with landslides. The 2005 Kashmir earthquake induced landslides have been addressed in several studies, from different perspectives. Owen et al. (2008) reported that more than half of the landslides were in some way associated with road construction and other human activity. According to Kamp et al. (2008), bedrock lithology (comprising highly fractured slate, shale, dolomite, limestone

and clastic sediments) was the most important landslide controlling parameter during the 2005 Kashmir earthquake. Dellow et al. (2007) reported a highly asymmetric size and distribution of 2005 Kashmir earthquake induced landslides. According to this last paper, the landslides can be classified into the following three types: (1) landslides formed over/adjacent to the fault rupture, (2) landslides which extend about 10–20 km from the fault trace on the hanging side of the fault and (3) landslides on the footwall side which are generally rare except within 2–3 km of the fault trace. And as mentioned earlier, Shafique et al. (2008) compared the aspect of landslides relative to the initial rupture point and found that about 80% of the landslides had an aspect facing away from the rupture point. In summary, the major controlling factors for 2005 Kashmir earthquake induced landslides were (1) human activity (Owen et al., 2008), (2) bedrock lithology (Kamp et al., 2008), (3) proximity with reference to fault trace (Dellow et al., 2007) and (4) slope direction with respect to source (Shafique et al., 2008). In our study, we analysed landslide aspects with respect to the point of maximum release of energy (CMT solution). The percentage of landslides facing away were found to be 25%, facing towards 33% and facing other directions 42%. Keeping in mind factors such as human activity and bedrock lithology beside the relation of landslides with the fault trace, it is uncertain at which stage of the rupture the landslides have been triggered. It could be because of the initial rupture (used by Shafique et al. (2008)), the fault trace (Dellow et al., 2007), the moment of maximum release of energy (the CMT solution location used in this study), or somewhere in between.

The 2005 Kashmir earthquake was a shallow earthquake. In such case a seismic wave field will reach the surface at an angle, rather than vertical when originating at a larger distance away. This can lead to the creation of a so-called shadow zone effect due to deep valley blocking the propagation of a seismic wave field into a topographic feature. This phenomenon has also been observed in this study. Because of this shadow effect, ridges which are expected to show amplification, show de-amplification (location (d) & (e) in Figure 5.5, location (d) in Figure 5.6 & 5.7). This effect however, may not be visible for deep seated seismic sources or sources at a larger epicentral distance. The deeper or further away the source of the earthquake the more vertical will be the incoming seismic wave field. A similar effect is possible if we have significantly reduced seismic velocities close to the surface, due to e.g. sediments, that will also turn the wavefield towards the vertical.

This study has been carried out in data sparse environment and therefore we opted to use a homogeneous halfspace model. There is not a single tomographic velocity model available in a relevant resolution. All tomographic velocity models are too coarse; the best resolution is

1 degree (Johnson and Vincent, 2002). Seismic lines are not available for the region, and nearby seismic lines (Bhukta and Tewari, 2007) cannot provide sufficient detail on the Muzaffarabad region. However, to overcome this simplification, we have tried to establish the velocities as accurate as possible by comparing our results with observed displacements by Pathier et al. (2006); Avouac et al. (2006); Wang et al. (2007). Our displacement values, based on the homogeneous velocity model, are fairly comparable with their results and our velocities are comparable to upper crustal velocities in coarse tomographic models for the region (Johnson and Vincent, 2002; Bhukta and Tewari, 2007). Furthermore, with changing velocities, the absolute values will change but the amplification pattern will still remain the same; for events at the same location the effect of amplification is largely magnitude and velocity independent.

5.6 Conclusion

Topography affects the diffraction and reflection of incident seismic waves, thereby amplifying or de-amplifying the seismic response. The impact of topography on seismic induced ground shaking was evaluated for the 2005 Kashmir earthquake in Muzaffarabad (Pakistan) using a spectral element method, SPECFEM3D. An ASTER Global DEM, re-sampled to 270 m spatial resolution, was used for representing topography of the study area. A mesh of 270 m spatial resolution was used to model the topography and geometry of the topography and subsurface conditions in the Muzaffarabad region. Overall, topography induced amplification of seismic response is found on ridges and slopes facing away from the CMT location and de-amplification is found in valleys and at the bottom of slopes facing towards the CMT location, which is consistent with previous studies. The study demonstrates that topography changed the PGD values from approximately -2.5 m to +3 m when compared to a plain mesh surface. It is shown that topography played a significant role in earthquake induced damage during the 2005 Kashmir earthquake: 98% of the highly damaged area lies within the topographically amplified seismic response area.

Figure 5.4 (a) Peak Ground Displacement (PGD) for model without topography, (b) PGD for model with topography, (c) topography (ASTER Global DEM at 270 m), (d) difference between (a) and (b) (Δ PGD). The red tones (positive values) indicate amplification, blue tones (negative values) indicate de-amplification, while the green represents zero difference. The CMT location is represent by red beachball.

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Figure 5.5 Profile along line AA' (Figure 5.4) of PGD with topography (dotted green) and without topography (dotted olive), their difference (Δ PGD, solid red) and elevation (solid blue). PGD are scaled on the left y-axis along line, elevation (solid blue) is shown on the right y-axis. The profile line has a length of ~ 47.5 km and passes over the CMT location which is located approximately in the centre of the profile ($\sim 23,000$ m), marked with a dotted arrow.

Figure 5.6 Profile along line BB' (Figure 5.4) of PGD with topography (dotted green) and without topography (dotted olive), their difference (Δ PGD, solid red) and elevation (solid blue). PGD are scaled on the left y-axis along line, elevation (solid blue) is shown on the right y-axis. The profile line has a length of ~ 54.5 km and passes over the CMT location which is located approximately in the centre of the profile ($\sim 25,000$ m), marked with a dotted arrow.

Figure 5.7 Profile along line CC' (Figure 5.4) of PGD with topography (dotted green) and without topography (dotted olive), their difference (Δ PGD, solid red) and elevation (solid blue). PGD are scaled on the left y-axis along line, elevation (solid blue) is shown on the right y-axis. The profile line has a length of ~50 km and passes over the CMT location which is located approximately in the centre of the profile (~23,000 m), marked with a dotted arrow.

Figure 5.8 The difference in peak ground displacement (Δ PGD) between models with and without topography (Figure 5.4d) compared with damage data of Shafique et al. (2012). The top part shows the relation between damaged areas with (de-)amplification in table form. The bottom part shows the distribution of damage with Δ PGD graphically. The high damage zone constitutes 11% of the Muzaffarabad damaged area, while moderate and low damage respectively cover 51% and 38% of the damaged area.

Figure 5.9 The difference in peak ground displacement (Δ PGD) between model with and without topography (Figure 5.4d) is compared with the aspects of the study area. The aspects are categorized into away (facing away from epicenter), towards (facing epicenter), and other (facing a direction other than towards and away). The categorization is based on 60° offset of aspect with respect to its angle towards the CMT.

Figure 5.10 The difference in peak ground displacement (Δ PGD) between the models with and without topography (Figure 5.4d) is compared with the aspects of earthquake induced landslides (Source: Humanitarian Information Center Pakistan (HIC-Pakistan), by courtesy of Shafique et al. (2008)). The aspects are categorized into away (facing away from epicenter), towards (facing epicenter), and other (facing a direction other than towards and away). The categorization is based on 60° offset of aspect with respect to its angle towards the CMT.

Scenario based Seismic Hazard Analysis

6.1 Introduction

Seismic hazard studies on a regional scale are, traditionally, based on statistical analysis of earthquake recurrence in a certain area in a certain period of time. An estimation of ground shaking is carried out by using either a deterministic seismic hazard analysis (DSHA) or a probabilistic seismic hazard analysis (PSHA) approach. DSHA typically considers 'worst-case' earthquake scenarios (Reiter, 1990; Kramer, 1996; Bommer, 2002), while PSHA considers all possible earthquakes and computes the probability of each scenario (Abrahamson, 2000; Bommer, 2002).

Deterministic earthquake ground motion simulation is a common technique for estimating seismic induced ground shaking (Wang, 2015). The technique uses numerical methods and models that incorporate the physics of an earthquake source and the propagation of seismic waves (Taborda and Roten, 2015). Deterministic scenarios are useful for simulating worst-case events that could affect an area (McGuire, 2001). An example is the Great Southern California ShakeOut, in which an M 7.8 scenario earthquake, rupturing the southern segment of the San Andreas Fault, was simulated (Bielak et al., 2010). Other examples are the simulation of scenario earthquakes along the Central Marmara Fault (CMF) and North Boundary Fault (NBF) in Turkey (Pulido et al., 2004), and the simulation of an Mw 6 scenario earthquake in the Grenoble Valley (France) by Stupazzini et al. (2009).

For the region exposed to the 2005 Kashmir earthquake in northern Pakistan, only PSHA approaches have been used till date (e.g. PMD and

¹This chapter is based on the following paper

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NORSAR (2007); MonaLisa et al. (2008)). The Mw 7.6 2005 Kashmir earthquake raised concerns for another major earthquake in this region (Durrani et al., 2005). The earthquake occurred on the Muzaffarabad Fault (MF) (Hussain et al., 2009), but the nearby Murree Fault (MBT) and Punjal Fault (PF) are also potential sources for a major earthquake (MonaLisa et al., 2009). Wyss (2006) and Bilham and Hough (2006) predict large magnitude future earthquakes for the region with a high number of expected casualties. MonaLisa et al. (2008) carried out a PSHA for the seismically active NW Himalayan Fold and Thrust Belt in Pakistan. On a larger scale, PMD and NORSAR (2007), Zaman et al. (2012) and Sultan (2015) conducted a probabilistic seismic hazard assessment covering entire Pakistan, including the Muzaffarabad region.

In PSHA, the near-surface effects of an earthquake, such as topographic amplification, are often not included. However, the topography of the earth surface does reflect seismic energy. Depending on the surface geometry, it could lead to scattering and/or focusing of propagating seismic waves (Lee et al., 2008, 2009a; Khan et al., 2017b). Previous studies show that topography amplifies seismic induced ground shaking at mountain ridges, while it de-amplifies in valleys (Hartzell et al., 1994; Spudich et al., 1996; Bouchon et al., 1996; Assimaki et al., 2005a; Lee et al., 2009a,b; Hough et al., 2010; Kumagai et al., 2011; Takemura et al., 2015; Khan et al., 2017a). The directions of incident seismic waves also have an impact on the amplification of ground shaking (Pedersen et al., 1994; Ashford and Sitar, 1997; Ashford et al., 1997; Shafique et al., 2008; Meunier et al., 2008; Qi et al., 2010; Xu et al., 2013; Khan et al., 2017b). Topography induced scattering of seismic energy and its effect on ground shaking (de-)amplification has been studied with numerical simulations (Lee et al., 2008; Takemura et al., 2015; Khan et al., 2017b). This was however mostly done for single slopes or for study areas with a limited spatial extent.

In this study, we use SEM, instead of PSHA, for the first time to estimate ground motion for the larger Muzaffarabad region, the results of which are applicable both on regional and local scale. Moreover, it also allows incorporation of topographic effects, which has not been addressed before. SEM has been widely used in simulating 3D seismic response (e.g. Komatitsch and Vilotte (1998); Lee et al. (2008); Stupazzini et al. (2009); Chaljub et al. (2015)). This approach allows simulating seismic waves by incorporating source, path and site effects (e.g. Atkinson and Macias, 2009; Stupazzini et al., 2009; Bielak et al., 2010).

The centroid moment tensor (CMT) solution of the 2005 Kashmir earthquake (Dziewonski et al., 1981; Ekström et al., 2012), obtained from the Global Centroid-Moment-Tensor Project (<http://www.globalcmt.org/>; Last accessed September 2017), is used as source for a total of 25 scenario earthquakes, which includes the actual 2005 Kashmir earth-

quake. The results from these scenarios are combined in a probabilistic seismic hazard map for the region. The map show probable ground displacement due to topography and its variability.

6.2 Study Area

The city of Muzaffarabad lies in an active tectonic zone and is surrounded by several major active faults (Figure 6.1). This region is prone to large magnitude earthquakes (MonaLisa et al., 2009) as it is situated on the collision zone of the Indian plate subducting underneath the Eurasian plate at a rate of 31 mm/year (Bettinelli et al., 2006). Apart from the 2005 Kashmir earthquake along the Muzaffarabad Fault (MF), several other earthquakes greater than Mw 5 have been recorded, as well as two (Mw 6 and Mw 6.4) aftershocks of the 2005 Kashmir earthquake (Tahirkheli, 2010). Studies indicate that the energy stored in the Himalayas gives a high probability of earthquakes of Mw > 8.0 in the future (Durrani et al., 2005; Stevens and Avouac, 2016). The rugged topography of the study area, with close to 4 km elevation difference, makes it prone to topographic (de-)amplification (Lee et al., 2009b; Hough et al., 2010; Shafique and van der Meijde, 2015).

6.3 Materials and Methods

We use SEM for simulating 3D seismic wave propagation to estimate ground shaking. SEM was originally developed by Patera (1984) for computational fluid dynamics. It was adapted for 3D seismic wave propagation by Komatitsch and Vilotte (1998) and Komatitsch and Tromp (1999). SEM incorporates a 3D physical model, taking into account the velocity, density and free-surface topography for a full elastic waveform simulation including all possible waves, based on source characteristics of an earthquake (Chaljub et al., 2007). We used SPECfem3D Cartesian (<https://geodynamics.org/cig/software/specfem3d/>; last accessed September 2017) software as SEM simulator in this study.

Before a SEM simulation is run, a 3D mesh model is developed to represent the physical characteristics of area under investigation (Casarotti et al., 2008). The mesh is composed of hexahedra elements that are isomorphous to a cube (Komatitsch et al., 2002). The mesh elements have material and structural properties that define how it reacts to applied conditions such as an earthquake. We used Cubit v.13.0 software, developed at Sandia National Laboratories (Sandia National Laboratories, 2011) in conjunction with GeoCubit (Computational Infrastructure for Geodynamics, 2016) for meshing. GeoCubit is developed at the Istituto

6. Scenario based Seismic Hazard Analysis

Figure 6.1 A map of the study area showing major faults in the region surrounding the city of Muzaffarabad, overlaid on an ASTER GDEM elevation model (resampled to 270 m spatial resolution). The centroid moment tensor (CMT) solution of the 2005 Kashmir earthquake is indicated by the red beachball icon. To test the sensitivity of the region to earthquakes along the regional faults, the same CMT is placed at different locations along the regional faults. The locations of these ‘hypothetical sources’ are indicated by red dots and labeled with source number for reference.

Nazionale di Geofisica e Vulcanologia (INGV) in Italy. This software automates mesh generation in three steps. The first step is the construction of a 3D geometry. GeoCubit creates points from a DEM, combines these points to make lines, and eventually creates a surface by combining the lines. After creating the topographic surface, a 3D geometrical model is created. The second step is meshing the geometry with hexahedral elements. The last step involves defining boundary conditions, such as free and absorbing surfaces, and mesh export for simulation with SEM.

The surface topography of the geometric model is based on Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global DEM data. It is retrieved from the Global Data Explorer, courtesy of the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, <http://gdex.cr.usgs.gov/gdex/>. The geometric model extends to a depth of 40 km. Introduction of two tripling layers to the mesh increases the spatial resolution of the mesh from 2430 m at the bottom depth of 40 km to 270 m at the topographic

surface. There are no seismic waves speed models available for this area: Tomographic velocity models are too coarse, the best resolution is 1 degree (Johnson and Vincent, 2002). Seismic lines are not available for the region, and nearby seismic lines (Bhukta and Tewari, 2007) cannot provide sufficient detail on the Muzaffarabad region. We therefore assign constant wave speeds ($V_p=2800$ m/s, $V_s=1500$ m/s) and density ($\rho=2300$ kg/m³) throughout the model, which is representative of upper crustal conditions (Johnson and Vincent, 2002; Bhukta and Tewari, 2007). The mesh can resolve frequencies up to approximately 5.5 Hz (Khan et al., 2017a). The topographic surface was set as free surface; the remaining 5 plane surfaces are set as absorbing surfaces. In order to estimate topography related (de-)amplification, we also construct a mesh model with same properties but without topography (i.e. having a plain top surface). Amplification maps are based on the ratio between maps with and without topography, respectively, of modeled maximum displacement for each model point.

The seismic point source is the centroid moment tensor (CMT) solution of the 2005 Kashmir earthquake. In order to observe the impact of possible future earthquakes, the same CMT is placed at 24 different locations at approximately 6 km intervals along major faults (MF, MBT, PF) in the study area Figure 6.1). All simulations are performed in SPECFEM3D with a delta source time function of half duration '0' at a duration of 35 sec. Since SEM is efficient in simulating low frequency ground displacement and has limited capability in simulation of high frequency accelerations (Dhanya et al., 2016), our analysis utilizes the shakemaps obtained from these simulations in the form of peak ground displacement (PGD) (Figure 6.2). A mean of PGDs (Figure 6.3a) obtained from all 25 simulations is calculated together with the corresponding standard deviations (Figure 6.3b). The mean and standard deviation are subsequently used to create a seismic hazard map (Figure 6.3c).

The seismic hazard map is shown as a Hue, Saturation and Value (HSV) color composite. The mean PGD was put as 'hue' with a color ramp of green to red. The standard deviation (rescaled to a range of 0-1 and inverted) as 'saturation'. The 'value' was uniformly given a value of 1. This results in a map (Figure 6.3c) that has areas with low to high mean PGD in green to red tones, respectively, and with low standard deviation areas in darker tones and high standard deviation areas in lighter (white) tones.

To obtain amplification maps, the PGD shakemaps obtained from plain surface models are subtracted from the shakemaps of models with topography. Amplification maps are presented for each location along the different faults (Figure 6.4). The average of all amplification maps was used with its corresponding standard deviation to show the variability of PGD amplitudes with respect to topography and changing

6. Scenario based Seismic Hazard Analysis

Figure 6.2 The Peak Ground Displacement (PGD) obtained from 25 simulations with changing location of the centroid moment tensor (CMT). Simulation ‘0’ has the original source location of the 2005 Kashmir earthquake. The source is represented by a yellow circle and number corresponding to the source locations shown in Figure 6.1. It can be observed that, in each image the spatial pattern of the PGD amplitudes is influenced by the topography and the changing source location.

source location (Figure 6.5), indicating regions that might experience strong topographic effects.

6.4 Results

25 simulations are carried out (Figure 6.2), in which the CMT solution of the 2005 Kashmir earthquake moves from its actual position to imaginary positions along major faults in the region (Figure 6.1). In general, the PGD amplitude decreases with increasing distance from the CMT solution (Figure 6.2), except for places where topographic (de-)amplification occurs. It can be observed that, by comparing Figure 6.2

Figure 6.3 (a) The Mean Peak Ground Displacement from all 25 simulations, showing high average values on ridges (red tones) and low average values in valleys (blue tones). (b) The Standard Deviation of Peak Ground Displacement, indicating higher variation on ridges compare to valleys. (c) Topography based seismic hazard map for the study area derived from mean PGD (a) and its standard deviation (b). The red area indicates a relatively high hazard, yellow indicates medium and green indicates a relatively low hazard area. The saturation represent the standard deviation and whitish tones therefore represent uncertainty (more white is more uncertainty, and *vice-versa*). (d) Digital Elevation Model of the study area.

6. Scenario based Seismic Hazard Analysis

Figure 6.4 Difference of Peak Ground Displacements (Δ PGDs) obtained from 25 simulations. Simulation '0' is the original 2005 Kashmir earthquake. Each source is represented by a yellow circle and a number corresponding to the source locations shown in Figure 6.1. The pattern of amplification (positives values) and reduction (negative values) follows the topography and is influenced by the changing location of the CMT.

with Figure 6.1, in each model output the spatial pattern of the PGD amplitudes is influenced by the local topography. From Figure 6.2, it can be seen that not only the topography itself, but also the location of the source relative to topographic features, has an influence for the observed variation in amplitude: The direction of incoming waves with respect to the orientation of the slopes has an impact on the occurrence of possible (de)amplification. A ridge with high values of PGDs gets lower, or *vice-versa*, when the location of source is changed. This is consistent with observations in Khan et al. (2017b).

The mean PGD of all 25 simulations (Figure 6.3a) shows a radial pattern with high values (approximately 3.2 m) in the central part of the study area, while reaching lower values (approximately 1 m) at the edges. A relation between the topography (Figure 6.3d) and the mean

Figure 6.5 (a) is the Digital Elevation Model of the area; (b) is the Mean Peak Ground Displacement Difference (Δ PGDs) from all 25 simulations, showing an overall amplification on ridges (red) and de-amplification (blue) in valleys. (c) is the standard deviation of Δ PGDs, indicating a higher variation of (de-)amplification on ridges when compared to valleys).

PGD (Figure 6.3a) can be observed visually. In general, higher mean PGD values can be observed for elevated areas (ridges) compared to low-lying surrounding areas (valleys).

Depending on the direction of wave propagation, the exposure to incoming waves and distance from the CMT locations, the PGD values vary between the 25 simulations. This is visible in the standard deviation of the 25 PGD simulations, which shows a variability between approximately 25 cm and 200 cm.

The central part of the study area has overall higher values. The deepest parts of valleys have relatively low values, but where the topography is higher, also the standard deviations increases. The largest standard deviations are located along the Muzaffarabad fault in the elevated areas to the northeast (Figure 6.3b).

A seismic hazard map based on the mean PGD (Figure 6.3a) and corresponding standard deviation (Figure 6.3b) is derived in Figure 6.3c. This HSV map shows the mean PGD in green to red hues: Areas with a high mean PGD are considered to be high hazardous areas, and *vice-versa*. The standard deviation of the PGD is shown in saturation: Areas with low standard deviation appear as (intense) saturated tones and areas with high standard deviation appear as (whitish) unsaturated tones. This is, for example, clearly visible in the region N of Muzaffarabad which has high average PGD with high standard deviation, compared to an area east of Muzaffarabad that is more prominently visible with a high PGD and low standard deviation.

Although topographic effects are visible in Figures 6.2 & 6.3, it is difficult to quantify the impact of topography on the PGD. To explore

the topographic effect, the topographic amplification effect is obtained from models with and without topography (Figure 6.4) following the procedure as described by Khan et al. (2017b). The resulting pattern of amplification (positive values) and de-amplification (negative values) appears to follow the topography and is also influenced by the changing location of the CMT. We observe the same directional dependence as observed in Figure 6.3, as described by Khan et al. (2017b). Depending on the location of the CMT, the same slope can either be amplified or de-amplified. For example, the eastern region has a de-amplified response for the original CMT location (Figure 6.4-0); but gets an amplified response when the location of CMT is changed (e.g. Figure 6.4-8,13,23). On average, the topography increases the modeled PGD with 125 cm.

When all simulations shown in Figure 6.4 are averaged (Figure 6.5b), a correlation with topography (Figure 6.5a) becomes visible: Ridges are subjected to an overall amplified response while valleys show a de-amplified response. The standard deviation (Figure 6.5c) shows that the difference in amplification depends on topography and ranges from 5 cm in valleys and flat areas to 125 cm on some of the ridges. When slopes surrounding Muzaffarabad are facing away from a simulated source, they show an amplified seismic response. Similarly, when slopes are facing towards a CMT location, they are in the shadow zone of seismic energy and show a de-amplified seismic response. For example, the slopes facing W-SW around $N 34^{\circ}30' - E 73^{\circ}30'$ have an amplified response when the source is located near the faults in NE of the area (Figure 6.4-12,13,14,15,16). The standard deviation (Figure 6.5c) also shows higher values on same slopes, indicating high variability in amplification due to changing location of the earthquake source.

6.5 Discussion

In this study, we estimate ground motion for hypothetical earthquakes in the area of Muzaffarabad, Pakistan with the CMT solution of the 2005 Kashmir earthquake. This source is moved to 24 different locations along major faults in the region, at approximately 6 km intervals.

The rough terrain of the study area has an impact on seismic response in the area, as can be observed in Figure 6.2. During the 2005 Kashmir earthquake (Figure 6.2-0), ridges experienced higher amplitudes of PGD compared to valleys.

We also investigate how much the area is subjected to topographic (de-)amplification, compared to the hypothetical case when there would be no topographic variation (i.e. plain surface). The amount of (de-)amplification, beside the slope, geometry and height of topographic features, also depends on its location with respect to the seismic source.

(CMT). It was found that the PGD of models with topography can have an approximate factor 1.7 increase in magnitude, when compared to plain surface models. The spatial extent of areas with a high PGD may get reduced by topography controlled destructive interference or a seismic shadow zone. Areas near the CMT should have high amplitudes of PGDs, but due to topography these amplitudes can be de-amplified (e.g. the bluish areas in Figure 6.4). The ridges, on the other hand, have an amplified seismic response (e.g. the reddish regions in Figure 6.4). This amplified response can be observed even when a ridge is far from the CMT. In principle, the amplification factor is distance independent and will only vary due to directional variations. The mean amplification in terms of difference (Δ PGD) ranges shows the same phenomena of amplification (reddish) on the ridges and de-amplification (bluish) in the valleys (Figure 6.5b). Like the standard deviation for PGD, standard deviation for Δ PGD also shows high variation on the ridges, with low variation in the valleys, due to changing CMT location (Figure 6.5c). Key to this analysis is that ridges show higher absolute values of PGD and higher amplification values. But there is a strong dependency on the location of the earthquake, and the incoming direction of the seismic energy with respect to the orientation of the topography. This results in increased standard deviations for the average PGD and Δ PGDs for ridges in comparison with values for valleys or flat areas. This makes predicting the effect of earthquakes on slopes much more uncertain but also makes very clear that topography can lead to very strongly enhanced seismic impact.

Our seismic hazard map (Figure 6.3c) integrates the mean PGD and standard deviation values in a single map. This map summarizes the topographic and potential source location effect on seismic induced ground shaking in the study area. Its scale is relative, meaning that reddish tones indicate more hazardous areas and green tones indicate safer (but not per definition safe) areas. In our analysis, we assume that an area with high PGD and low standard deviation is more hazardous than an area with high PGD but with high standard deviation. Despite the fact that such a location might experience a higher absolute PGD in any of the 25 simulations, the overall effect on the area is lower since it also experiences much lower amplitude events. One could argue that an area with high PGD and high standard deviation be more hazardous compare to high PGD but with low standard deviation, but in our study we opt to adopt this definition. Compared to the average PGD map alone, we also add information on the certainty that an area might be hit by a high impact event.

Our hazard map, showing the hazard level with corresponding uncertainty, can be used for disaster management purposes. Combined with other maps, obtained for individual scenario earthquakes, it can

provide a guide to potential hazard and preparedness. The models do not account for different source mechanisms, magnitudes and can still be improved by incorporating regolith and/or sediments, as well as incorporating an actual 3D velocity model for the study area.

6.6 Conclusion

This study simulated the seismic response of possible future earthquakes in the area surrounding the city of Muzaffarabad (Pakistan). 25 simulations were carried out, in which the CMT solution of the 2005 Kashmir earthquake was moved from its original and actual position to imaginary positions along major faults in the region. Generally, the PGD amplitude decreases with increasing distance from the CMT solution, but is superimposed by a clearly visible topographic amplification effect. Not only the topography itself, but also the relative location of the source with respect to a slope, has an influence on the observed variation in amplitude. The mean PGD of all 25 simulations varies between approximately 1 m at the borders of the study area to approximately 3.2 m for the elevated parts in the center of the study area. Depending on the direction of propagation, the exposure to incoming waves, and the average distance from a CMT location, the PGD values vary between simulations. This becomes visible in the standard deviation of the PGD simulations, which shows a large variability from approximately 25 cm up to almost 200 cm.

We presented a seismic hazard map, based on an integration of the mean PGD and its standard deviation, summarizing the topographic and potential source location effect on seismic induced ground shaking in the study area. It provides a classification from hazardous to safe in relative terms (so not per definition safe in absolute sense). Combining the hazard of multiple future scenarios, this map indicates potential seismic hazard and is a guide in earthquake preparedness.

The earth's topography acts as a reflecting surface for seismic energy and leads to scattering and focusing of seismic waves. It can, thereby, amplify or de-amplify the incoming seismic wave field.

The aim of this research was to evaluate the impact of topography on seismic induced ground shaking, using a 3D modelling approach. Existing techniques for estimation of the impact of geomorphological characteristics of a site on seismic induced ground shaking using 1D or 2D numerical models are usually limited to a synthetic laboratory experiments or an individual ridge. However, because of the regional extent of the seismically active areas, it is of significant importance to evaluate the topographic impact on seismic response at a regional scale. Efforts in this direction, like the near-real time seismic induced ground shaking and potential damage maps from the USGS-ShakeMap and PAGER, respectively, are at a coarse resolution of 1 km, hence giving much generalization in results. The applicability of these maps on a local scale are limited. Furthermore, these and other similar approaches adopt proxies instead of realistic models to estimate the effect of the landscape on seismic motion. This research attempts to cover the gap between these two extremes of scales by applying the spectral element method (SEM) technique. It allows for adaptation of realistic 3D modeling approaches considering full elastic wave propagation and the interaction with full topographic models to evaluate the impact of topography on ground shaking.

7.1 Modeling Size and Resolution Matters

In order to simulate earthquakes using SEM, a 3D geometrical finite element model is essential (Chapter 3). Freely available DEMs, based on spaceborne satellite missions, are considered to be the optimal choice for incorporating topography in such a model while studying topographic impact on seismic response at a regional scale. Beside that it

is free it is also globally available in a resolution that is high enough for modeling on a regional scale. One of the first to use and evaluate this kind of data Shafique et al. (2008) has assessed the impact of DEM resolution and its derived attributes on topographic representation and corresponding derived seismic response. Their study shows that DEM source and spatial resolution have an effect on the computed output. However, their study was based on topography-derived proxies and lacked realistic full waveform simulations. In this study, the impact of DEM resolution by performing full waveform simulations in a realistic meshed model using SEM is investigated. Beside DEM, the mesh resolution also contribute to the realism of topography. A 30 m resolution DEM derived topographic surface cannot be accurately resolved by a mesh of 1000 m spatial resolution; because topographic features smaller than 1000 m would not be realistically and accurately modelled. It was therefore necessary to investigate the impact of mesh resolution on topographic seismic response in conjunction with the DEM resolution. Furthermore, the choice of resolution has also a direct impact on the resolution, and quality, of the output in e.g. the form of shakemap as it has the same spatial resolution as that of the input mesh. We prepared geometric models using different combinations of mesh and DEM resolutions (Chapter 4). After simulation with each model, their output was compared with the finest mesh and DEM combination model. It was found that any mesh or DEM combination with a resolution of 540 m or coarser leads to unrealistic results compared to the finest resolution model. The boundary between realistic and unrealistic output lies somewhere between 270 m and 540 m. This conclusion, however, is based on specific terrain characteristics for Muzaffarabad in northern Pakistan. Its broader applicability might therefore be limited to this region or to regions with similar geomorphological. For other areas with less or more pronounced topography or different steepness of slopes, one may find that other resolutions(either higher or lower) are required to ensure realistic modeling output. Apart from the impact of mesh and DEM resolutions on realistic topographic representation and output accuracy, it also has an impact on computational power and processing time. In order to run the SEM simulation on a regional scale, such as the 40 X 40 km as in Chapters 5 & 6, the requirement of computational resources and processing time increases. In such case, using high resolution mesh and DEM resolution may not be possible without significantly increasing the computation time and corresponding computer resources. In Chapter 4, it was possible to identify the coarsest mesh and DEM resolutions, which could give realistic results even without high computational resources (such as a supercomputer). The findings from this chapter helped in the creation of a model for an extended area of 40 X 40 km to evaluate the impact of topography on

seismic induced ground shaking by efficiently incorporating topography in a realistic 3D modeling approach at a regional scale.

7.2 Ground Shaking Amplification Effects

In order to study topographic impact on seismic induced ground shaking, the 2005 Kashmir earthquake in northern Pakistan was simulated with a finite element model based on a 270 m mesh and DEM resolution in a homogeneous halfspace. In general, topographic induced amplification of seismic response was found on ridges and slopes facing away from the CMT location and de-amplification was found in valleys and at the bottom of slopes facing towards the CMT location, which is consistent with previous studies (e.g. Lee et al. (2009a); Qi et al. (2010); Xu et al. (2013); Shafique and van der Meijde (2015)). This study demonstrates that topography changed the PGD values from approximately -250 cm to +300 cm, when compared to a plain surface. It was also found that topography played a significant role in earthquake-induced damage during the 2005 Kashmir earthquake: 98% of the highly damaged area lies within the topographically amplified seismic response area. The evidence of amplified seismic response on slopes facing away from the earthquake source can have an influence on slope stability towards the head of slopes and a possible reason for triggering landslides. However, as it turned out this relation is not as straightforward as thought and considerable complicating factors might influence the occurrence of landslides. This was already suggested by several studies on the 2005 Kashmir earthquake induced landslides (Owen et al., 2008; Kamp et al., 2008; Dellow et al., 2007). In our study, we analyzed landslide aspects with respect to the point of maximum release of energy (CMT solution). The majority of the landslides on slopes facing away from the CMT location are in the amplified zone (53%) while for slopes facing towards the CMT location this is only 16%. This is not directly supportive of a causal relation between seismic amplification and landslide occurrence. Of course, factors such as human activity and bedrock lithology are of importance and can influence such relationships. But maybe more relevant from a scientific perspective is the actual relation that we might be investigating. We used the CMT location, so the location with maximum energy release. But it might be that the landslides have already been triggered at an earlier stage when the slope was already destabilized due to a much lower ground motion than the maximum that we considered in our study. It is uncertain at which stage of the rupture the landslides have been triggered. It could be because of the initial rupture (epicenter location used by Shafique et al. (2008)), due to motion excited anywhere along the fault trace (Dellow et al., 2007), the

moment of maximum release of energy (the CMT solution location used in this study), or a combination of factors. Since there is no exact timing for the landslides we can only rely on spatial statistics. And these show that the comparison with the epicenter location (so the initiation of the earthquake) showed a much higher relation than the CMT location that we used. This is strongly suggesting that already with lower PGD the slopes lost their stability and landslides were triggered. This might be further influenced by the geometry of the topography since we show, in Chapter 6, that some slopes may get (much stronger) amplified seismic response due to one source location compared to others. Thus, the location of earthquake source can also be a decisive factor triggering a landslide on a particular slope.

7.3 Hazard Assessment

After setting up the methodology for simulating earthquakes in a realistic topographic model using SEM, it was further implemented in the development of a methodology for the production of a seismic hazard map. The extended model of Muzaffarabad and its surrounding areas created for analyzing the topographic impact during the 2005 Kashmir earthquake in earlier chapters was used for this purpose. Seismic hazard analysis (SHA) is typically carried out either with a deterministic seismic hazard analysis (DSHA) or probabilistic seismic hazard analysis (PSHA) approach. DSHA considers a worst-case scenario for a particular seismic source, referred as the Maximum Credible Earthquake (MCE), to estimate the level of ground shaking. On the other hand, PSHA considers the likelihood of various earthquakes from multiple potential seismic sources, each having a range of uncertainty in source characteristics (e.g., rupture length, distance, fault dip, maximum magnitude, slip rate). Uncertainty is treated explicitly, and the annual probability of exceeding a specified ground motion are computed. The approach adopted in this study is a mix of DSHA and PSHA, where it considers the worst-case scenario in the form of the 2005 Kashmir earthquake as source and makes use of multiple potential sources (by changing its location). 25 simulations, including the original 2005 Kashmir earthquake, were simulated by moving the CMT along the probable causative faults in the study area. Each individual earthquake simulation and analysis based on its output can be considered as an individual DSHA. A probabilistic seismic hazard map (Figure 6.3c) was derived from the mean and standard deviation of the 25 resultant shakemaps, thereby showing not only the mean expected PGDs but also the uncertainty associated with it. It was found that, depending on the location of future earthquake of similar magnitude to the 2005 Kashmir earthquake, the PGD can reach

up to 10 m on individual ridge tops. On average, it was observed that the local topography can amplify the seismic response by 1.25 m.

7.4 Hazard Mitigation using SEM

The seismic hazard map can also be used by disaster managers for risk calculation to identify vulnerable areas and level of exposure. The information then can be used in for risk reduction, preparedness and taking mitigation measure to avoid and/or minimize the potential economic, social and environmental consequences of earthquakes that may occur in future. Similarly, it can also be helpful for engineers and town planners in designing and planning infrastructure (such as bridges, buildings, town planning etc.) in the area so that it may be able to sustain in case of any future seismic event. Furthermore, in areas of high topographic relief, there is an increased probability of co-seismic landsliding. The information obtained from scenario earthquakes and the corresponding derived seismic hazard map, jointly with other causative factors like anthropogenic factors and geology, can be used in identifying potential landslides zones and their run-off areas. One example where such information on seismic amplification can be useful is the case of Balakot City which was among the severely damage areas during the 2005 Kashmir earthquake. The Government of Pakistan decided to relocate and make a new city, the New Balakot City. Availability of hazards maps as provided by this study would be helpful in the future to identify a safer location for new cities. Not only based on that specific earthquake but also considering the effects of future earthquakes. Based on the maximum expected ground motions, with corresponding uncertainties in occurrence, will assist in developing highly relevant building codes for reconstruction or even re-location, thereby reducing risk to life and infrastructure.

7.5 Future Recommendations

Following recommendations are suggested, that can lead to future research on this topic.

1. Seismic induced ground shaking at a site is a combined effect of topography, regolith and geology. Incorporation of an actual seismic velocity model of the subsurface along with the regolith data can lead to a better representation of realistic scenarios in a 3D computational model. Simulation of seismic wave fields including all these parameters, provided the computational resources

available, can estimate more realistically ground shaking. Subsequently, the effect of site conditions on ground shaking can be better understood.

2. We have used the CMT location to model the effects of the 2005 Kashmir earthquake. But we have seen that this assumption is not always leading to the most accurate results when compared to damage and landslides. Large earthquakes (such as the 2005 Kashmir earthquake) are always very well studied and finite fault models are derived that represent the propagation of the earthquake over time. In order to study the impact of large earthquake, a finite faults model can be introduced in the SEM for a better representation of source characteristics. In such case, the area under investigation possibly needs to be extended so that it covers the full finite fault plane. Subsequently, this will also lead to increase in computational cost.
3. This research increased our understanding of the past earthquake but it also potentially provides insights on the possible effects of future earthquakes. This research has been limited to presentation of a seismic hazard map without further 'translation' into disaster management relevant products or recommendations. Future research can focus on how to implement the findings of this research in the work done by local disaster management authorities to enhance their capacity in formulation of earthquake management strategies.

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Biography

Saad Khan was born on 09 January 1987 in Swabi - Pakistan. He obtained his Bachelor of Science degree in Geology from University of Peshawar, Peshawar and Master of Science in Remote Sensing and GIS from Institute of Space Technology, Islamabad. He pursued his doctorate studies at the Department of Earth System Analysis (ESA), Faculty ITC, University of Twente, Netherlands. His professional career begins by joining National Center of Excellence in Geology (NCEG), University of Peshawar through a research project of hydrocarbon exploration in FATA. In 2011, he left NCEG for Department of Geology, Palosa Campus of Abdul Wali Khan University Mardan (AWKUM). In 2012, the Palosa campus of AWKUM was converted in to a full fledge university, Bacha Khan University Charsadda (BKUC), where he is still continues his career.

Saad Khan's research approach has always been multidisciplinary Geoscientific. He was involve in oil and gas exploration project, flood modeling and currently working on modeling earthquake induced ground shaking. He is especially interested in using geo-information/remote sensing technology for hazards and disaster management and geological/geophysical exploration activities.

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Khan, S., Rahman, S., Haq, M., & Munir, S., 2016. Hyperspectral Remote Sensing for Detection of Natural Hydrocarbon Seeps. *Asian Journal of Multidisciplinary Studies* 4 (2), 1-10.

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