Geological control on natural hazards: Earthquake and mass movement hazards in Pakistan

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Pakistan is located at the cross roads of plate boundaries and thus encompasses a region that has remained highly active in terms of tectonic movements during much of its geological history. It comprises a vast mountainous terrain, including Karakoram, Hindukush, Kohistan and Himalaya in the north and Sulaiman-Kirthar Ranges and Chagai-Makran plateau in the west. The present-day geodynamic framework has resulted from accretion of at least four tectonic plates: India, Kohistan, Karakoram-Hindukush and Afghan (Helmund). All of them (except for Kohistan) rifted from Gondwana, an ancient megacontinent, between Permian and Cretaceous and preserved passive continental margin underlain by normal faults and associated rift-basins, until they were reunited through compressional tectonics at the southern margin of Eurasia. More than two major oceanic basins, the Shyok ocean between Kohistan and Karakoram and the Neotethys that separated India from Kohistan in the north and Afghan block in the west, closed during these continent-continent collision events, remnants of which are still preserved as suture zones and sizable ophiolite belts. Most of these ancient oceans closed at the sites of subduction zones, which generated vast terranes of magmatic rocks before their obliteration (e.g., Kohistan, Chagai and Ras Koh). Makran subduction zone is a remnant of the Cretaceous subduction system, which is still active and is responsible for vast Cretaceous-Quaternary Chagai magmatic belt. Chaman fault separating Chagai-Makran plateau from the Kirthar-Suliman Ranges is an active transform fault linking Makran subduction zone with Indus Suture Zone. The Chaman fault, however, does not terminate at the Indus Suture zone, rather extends NE into the Hindukush Seismic Zone, which is the most active intra-continental subduction system in the present-day world.

This volume is an outcome of a four-day workshop, held at the University of Peshawar, Baragali Summer Campus, August 19-22, 2002, organized jointly by the Department and National Centre of Excellence in Geology, University of Peshawar and Pakistan Atomic Energy Commission. The workshop comprised several sessions on techniques and methodologies involved in the study of natural hazards of earthquakes and landslides including geodesy, remote sensing and Geographic Information System (GIS). This volume, however, only includes selected research papers presented at the workshop. The workshop additionally included an open discussion session, which resulted in a unanimous declaration, recommending a line of action in effectively coping with the natural hazards facing Pakistan.

This volume includes altogether 14 papers, of which 11 deal with earthquakes in terms of focal

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mechanism solutions, seismic hazards evaluations and secondary hazards such as liquefaction and lateral spreading. Additionally there is one papers on landslide case study, one is related with use of GIS on flood hazard and one related with active faults.

SEISMOTECTONIC ZONATION

The mountainous region of Pakistan, which makes about 60% of the total area in Pakistan, not only is susceptible to mass movements of landslides, mud/debris flow and avalanches but also includes active faults, which are source of earthquakes. Several distinct seismotectonic zones can be recognized in Pakistan each with a rich past seismicity history and potential for future earthquakes.

Kuchchh Seismotectonic Zone

Starting from the very south, the Kuchchh seismic zone occupying the Rann of Kuchchh at the India-Pakistan border and Kuchchh mailand in the Gujarat province of India is a unique intra-continental seismic zone (Benndick et al., 2001). Rich past seismic history, including the 1819 Allah Band event (Bilham, 1998) and a more recent event of January 26, 2001, indicate active nature of this zone. The first paper in this volume by ***Asif Khan, Abbasi, Hadi and Laghari*** deals with liquefaction hazards in SE Sindh province of Pakistan as an outcome of the Mw 7.8 Bhuj earthquake, January 26, 2001. Since the epicentre of this earthquake was only 150 km from SE border of Pakistan, widespread liquefaction phenomenon was experienced by the southern parts of Thar desert. The paper highlights the response of the stable sand dunes failing by lateral spreading versus the interdunal depressions, which responded by series of fountains at the time of earthquake but now preserved as sand blows. An isoseismal intensity map of SE Sindh has been prepared based on the extent of liquefaction and damage to buildings as a result of ground shaking. The paper highlights earthquake hazard faced by Karachi and lower Indus basin, with a population of over 30 million people, in the wake of high seismicity in SE Sindh Province related with the Kuchchh intra-continental seismic zone. It is notable that normal faults and related structures underlying the lower Indus basin are prone to inversion tectonics and may give rise to future earthquakes in the region. Thick water-saturated quaternary sediments in the lower Indus basin are highly susceptible to liquefaction hazards if an earthquake of magnitude 6 or higher strikes the region, which may lead to extensive damage to buildings in this highly populated region. The paper by ***Pervaiz, Butt, Hussain and Mahmood*** is focussed at a preliminary assessment of peak-ground acceleration at an imaginary site near Karachi, which is determined to be at the maximum 0.2g. The study has potential for further improvement if more real-world data is incorporated. This study has highlighted quantitative seismic hazard analysis for critical structures such as Karachi nuclear power plant. The study is in accordance with IAEA safety guide 50 SG S1-Rev 1. Similar kind of study is recommended to be carried out close to each sensitive installation in the country.

Makran Seismotectonic Zone

In the west, an active subduction zone along the Makran coast between longitudes 60°E and 66°E is source of mostly deep-seated subduction-zone earthquakes, some of them with hypocentres as north as beneath the Chagai region. The seismic risks along the subduction related region of Makran coast are discussed by ***Hussain, Butt*** and ***Pervaiz***. This area has been seismically active since long and an 8.1 magnitude earthquake devastated the region in 1945. Faults capable of generating major earthquakes have been outlined in this study, suggesting accumulation of stresses in Gwadar area with a potential for future seismic hazard. The paper emphasises the use antiseismic design parameters for major engineering structure such as those currently being constructed in the region.

The Chaman Fault System and the Kirthar-Sulaiman Thrust-Fold Belt

The plate boundary between the Afghan microcontinent (including Makran-Chagi region of Pakistan) and the western margin of the Indian plate is marked by the Chaman Fault System that in addition to the Chaman fault includes Ornach Nala and Ghazadand faults. A belt of over ~ 200 km width including the Chaman Fault System and the Sulaiman and Kirthar fold-trust belt defines a seismic zone marking continued convergence between the Indian Plate and the Afghan microcontinent. The pattern of seismicity in the past century shows activity over a 700-km-long segment of this plate boundary with predominantly strike-slip faulting to the west and thrust faulting to the east (Ambraseys and Bilham, 2003). The M 7.3 1931 Mach earthquake (slip 1.1 m on a 40° east-southeast–dipping reverse fault) released fault-normal stresses that may have triggered the subsequent M 7.7 left-lateral Quetta earthquake in 1935. According to a recent and comprehensive compilation by Ambraseys and Bilham (2003), the segment of the Chaman fault system north of Pakistan border has been largely inactive in the past century, suggesting that up to 4 m of potential slip is stored in this segment to trigger one or more future M > 7 earthquakes in Afghanistan near Kabul.

Two papers in this volume are related with the recent earthquake activity in the Sulaiman Range of this seismotectonic zone. ***Mahmood*** and ***Qaisar*** in their paper highlight strike-slip active faulting in the Sulaiman Range, which is otherwise better known for compressional deformation in a typical foreland thrust-fold belt (e.g., M 7.3 Mach earthquake 1931). These authors determine the source mechanism of the July 13, 2002 earthquake on the Kingri fault, Balochistan by using teleseismic body waves recorded at 12 digital seismic stations. The left-lateral strike slip motion is a characteristic of the western parts of this seismic belt associated with the Chaman Fault System (e.g., M 7.7 Quetta earthquake 1935). This paper is therefore significant in portraying the transpressional style of deformation of entire width of this seismic belt. The paper by ***Baig, Mazhar, Rahman*** and ***Mehmood*** provides a comprehensive review of tectonic activity in the Suliman Range with emphasis on neotectonics as observed in talus creep and conglomerate, and recent to sub-recent alluvial fans. Based on limited seismic data and rupture length of the principal faults in the eastern Sulaiman Range, these authors have calculated maximum potential capability of the known faults (M 6-7.6) and have calculated potential peak ground acceleration (PAG) for the city of Dera Ghazi Khan (0.15g), which occurs in the foothills of the Suliman Range (at a distance of > 45 km from nearest faults at Kingri and Barkhan).

Main Boundary Thrust and associated Foreland Thrust-Fold Belt

The Main Boundary Thrust (MBT) together with the Potwar-Kohat Plateau and Salt-TransIndus Ranges defines the principal mountain front of the Himalayas in Pakistan. The Himalayan mountain front is considered to be accumulating strains at rates > 20 mm/yr (Bilham et al., 1998). Although several segments of the MBT, including the one in Pakistan, have not ruptured, at least 4 major earthquakes (M >8) have occurred along the MBT in the India and Nepal. Kangra earthquake 1905 (Ms 7.8) was one nearest to Pakistan that caused damage to buildings in Lahore and surrounding districts of Punjab (Ambraseys and Bilham, 2000). In Pakistan, MBT has mostly remained inactive with rare seismic activity (e.g., 1992 Kohat earthquake M = 6). Despite this relatively inactive nature of the MBT, the magnetostratigraphic dating of rocks in the Potwar plateau suggest convergence rates of 10 mm/yr since 2 Ma (Baker et al., 1988). Lack of any evidence for macroseismicity in the region coupled with intact nature of the several 200 BC to 700 AD old historical buildings including temples indicate that the Salt Ranges are growing slowly and steadily through creep along the salt surface underlain by the Potwar Plateau and thus pose no risk of seismic hazard. At the other extreme, slip might occur only during the great earthquakes with recurrence time measured in thousands of years rather than 100s, an issue which needs to be resolved through GPS measurement and further archaeological research.

Five papers in this volume relate to earthquakes, landslides and floods in this zone. First of these papers by ***MonaLisa, Khwaja and Qaiser*** addresses focal mechanism solutions of nine earthquakes with Mw > 4 having occurred in the Kohat and northern parts of the Potwar-Kohat plateau, a region defining the footwall of the MBT. The solutions show a complex pattern of deformation including thrust but predominantly strike slip current kinematics in the region. The second of this set of papers by ***Khan, Khan and Qaiser*** presents focal mechanism study of July 16, 2001 Chakwal earthquake, that occurred in the southern parts of the Potwar plateau in the vicinity of Kalarkhar. The data presented indicate presence of a subsurface fault with a right-lateral cum reverse sense of displacement, parallel to and little north of the better-known Kalarkhar fault. The third paper from this zone by ***Khawaja and MonaLisa*** addresses seismic hazard assessments in the Peshawar Plain in the hanging wall of the MBT using probabilistic approach. The paper is a useful illustration of methodology for assessment of seismic hazards based on ~ 100 years of instrumental seismicity data, indicating maximum values of 0.11g (for 50 years return period) and 0.15g (for 100 years of return period) in the Peshawar plain. These low values however may drastically change if one additionally takes into account the historical data on earthquakes (e.g., Ambraseys and Bilham, 2003) as well as the active faults in the region, as outlined in the paper by ***Hussain and Yeats.*** This later paper is a highly useful account of active faults from the Peshawar Plain. Considering that instrumental data is prone to discrepancy particularly in most northern Pakistan where local seismic network is functioning for only past few tens of years, geological data on active faults makes a better database for hazard assessments.

Two papers from the MBT zone are not related with earthquakes but address landslide and flood hazards. ***Abbasi, Khan, Ishfaq*** and ***Mool*** describe mass movement and slope failure processes around the summer resort of Murree that straddles the MBT zone. Slope failure, creep and land sliding are common features and major threat to the roads and other infrastructures in the area due to weak component lithologies and intense deformation associated with major faults such as MBT. They mapped a number of major landslides in detail and carried out geotechnical studies in order to workout their failure mechanism. ***Falak Nawaz*** records human perception and their responses to major flooding around Jhelum city, a worst effected area during 1992, 1995 and 1997 floods. He is of the view that Government machinery is usually concerned with post disaster activities instead of implementing long-term mitigation strategies.

Nanga Parabat Seismotectonic Zone

North Pakistan comprising Himalaya, Karakoram and Hindukush mountains is an active orogen that involves several seismotectonic zones including 1) Hazara Thrust Zone (Ni et al., 1991), 2) Indus Kohistan Seismic Zone (Quittmeyer and Jackob, 1979), 3) Nanga Parbat Seismic Zone (Meltzer et al., 2001), Karakoram Seismic Zone (Larson et al., 1999) and 4) Hindukush Seismic zone (Butman and Molnar, 1993; Pegler and Das, 1998). Of these, active faults are particularly well observed in the Karakoram Seismic Zone, which includes active Karakoram strike slip fault that passes through extreme NE of Pakistan from Kunjrab Pass in the NW through the Siachin glacier in the SE. Peltzer and Tapponnier (1988) proposed an offset of ~1000 km associated with the dextral Karakoram strike slip fault. Searle (1996) however demonstrated that offset was at the maximum 120 km based upon the displacement of c.18-20 Ma Baltoro-type granites.

The Nangaparbat Seismotectonic zone is likewise, associated with a demonstrably active fault that is superimposed on the Main Mantle Thrust

(MMT: the suture zone between the collided Indian and Kohistan plates). This active fault coincides with the western margin of the crustal scale Nanga Parbat syntaxis and can be observed at several places, which from north to south include, Sassi, Shahbatot, Liacher, Raikot and Bunar Gah (Lawrence and Ghauri, 1983; Butler and Prior, 1988; Edwards et al., 2000).

There are two papers in this volume that address the recent earthquakes associated with the Raikot active fault in the Nanga Parbat Seismotectonic zone. ***Mahmood, Qaiser and Ali*** determine the source mechanism of the Astor valley earthquake of November 20, 2002. Contrary to the know kinematics of the Raikot fault (i.e., strike slip sense of displacement associated with the Sassi-Shahboat segment and NW verging thrusting along the Liacher-Raikot segment), the focal mechanism solution determined by these authors suggests normal sense of displacement associated with the fault responsible for the two November 2002 earthquakes, which they attribute to gravity sliding following the dramatic uplift of the Nanga Parabat syntaxis during the last 10 millions years. It may be noted that Jackson and Yielding (1983) have cautioned about the use of telesismically-recorded data from N. Pakistan. They state, "Without good station coverage, preferably including local stations, focal depths determined from arrival times alone may be very inaccurate (cf. Jackson, 1980)". The second paper by ***Riaz and Khattak*** deals with the account of damage related with the November 2002 earthquakes in the Nanga Parbat region. These authors caution about the possible seismic hazards affecting the Basha dam, if constructed. An isoseismal intensity distribution map based on damage resulting from the November 2002 earthquakes could have greatly helped in locating the epicentres of the two earthquakes and their tectonic origin, which still needs to be attempted.

Finally, the paper by ***Shah, Qaiser and Mahmood*** highlights the seismic monitoring network of the Pakistan Atomic Energy Commission and its use for monitoring seismic activity across the country. The Commission is now using 24-bit digital seismograph network, which is very helpful to understand the earthquake source process, earth structures and seismotectonics of the region. An extension of this network to the north of Islamabad, preferably as far north as Khunjerab Pass, Skardu and Chitral will be a valuable contribution by the Atomic Energy Commission in developing this crucial database. Likewise, Nagar Pàrker region as well as the lower Indus basin is also highly recommended for extension of this network.

DISCUSSIONS

Pakistan is located in the active orogenic belt of Himalayas, Karakoram and Hindukush. Seismotectonic zones with active faults, rich seismicity record and continued plate-boundary interaction, all indicate high potential for seismic hazards. Likewise, the mountain ranges of Pakistan, especially those in the Himalayas, including the Karakoram and Hindukush are characterized by deeply carved valleys with steep valley slopes always susceptible to landslides, mud flows and avalanches. Bilham et al. (2000), based on a comprehensive analysis of historic earthquakes, suggest that several major earthquakes are overdue in the Himalayas. According to these authors, just one of the possibly overdue Himalayan earthquakes may lead to 200,000 predictable fatalities.

Unfortunately, while the hazard level is that high, the awareness and preparedness in Pakistan to meet the challenge is virtually negligible. After the devastating earthquake of Quetta 1935, when over 60,000 people died, the British Government introduced a building code to make the newly constructed building least vulnerable to future ground shaking associated with earthquakes. Most buildings in Quetta built within ~ 50 years of the Quetta earthquake, partially or completely abided by this building code. However, in last quarter of century, the extensive urbanization coupled with heavy population pressure has led to buildings in all parts of the country, including Quetta, that hardly followed any antiseismic building code. The importance of buildings capable of withstanding earthquakes is amply highlighted by the M 6.6 December 26, 2003 Bam earthquake, Iran. Over 40 thousand people died in the city of Bam and hundreds of thousands dislodged from their houses. In comparison, in three California earthquakes of similar magnitude having occurred between 1989 and 2003, only 125 people died.

In Pakistan, building codes for new buildings and concept of retrofitting to old buildings is not the only factor lacking, but the approach to disaster management is also highly flawed. Firstly, there is hardly any systematic study to outline the regions prone to hazards of earthquakes and/or mass movement. Secondly, even in those areas known for their vulnerability, there is hardly any data on basic attributes such as quality of buildings, number of people at risk and existence infrastructure. The concept of disaster management is restricted to rescue and relief operations after the disaster strikes. Even these operations loose their momentum within few days after the disaster and the effected population is left on their own to cope with the consequences. Astor region of N. Pakistan that suffered two earthquakes in November 2002 (each with M > 6) is a suitable example of level of disaster management in Pakistan. Soon after the earthquakes, army as well as the local government launched a major rescue and relief operation that greatly helped to minimize the hardships faced by the poor population of the region. A recent visit to this region showed that a large portion of the population is still living in the tents provided during the relief work. Some of the people did repair or build new houses but failed to follow any antiseismic design both because of poverty but more so because of lack of knowledge and know how.

RECOMMENDATIONS

The Natural Hazard Workshop, Baragali Campus, University of Peshawar August 19-23, 2002 held a special discussion session at the conclusion of the workshop to propose recommendations for the strategy for disaster management resulting from natural hazards. Chaired by Professor Dr. M. Qasim Jan (T.I., S.I.) and Dr. Khurshid Alam Butt (Atomic Energy Mineral Centre, Lahore), the session not only reviewed the results of the workshop but received useful input from the participants. The recommendations of the session are summarized as below.

1. Lack of data on seismicity and recent tectonic movements is a major hindrance in seismotectonic hazard assessment in Pakistan. Whereas, Meteorology Department as well as the Pakistan Atomic Energy Commission have separate networks of seismic stations, a vast part of the country including entire Himalaya-Karakoram-Hindukush mountain belt north of Islamabad, Makran coast and Thar desert do not have any local seismic stations. Geodesy, based especially on Global Positioning System is currently considered a prime technique in measuring recent crustal movements. University of Peshawar has pioneered limited geodetic studies using GPS in parts of N. Pakistan and Nagar Parker. However, there is a dire need for a comprehensive network of Seismic and GPS stations covering most parts of Pakistan, especially those outlined as seismotectonic zones, probably under a joint commission comprising Pakistan Atomic Energy Commission, Meteorology Department, Survey of Pakistan, WAPDA and Geology and Geophysics Departments in the universities.

2. Studies on natural hazards and environment are becoming increasingly relevant due to population pressure and need for utilizing natural resources and large scale civil engineering projects. It is believed that technical know-how and awareness are inadequate. It is proposed that multi-institutional and multidisciplinary approach should be applied to evaluate the risks due to earthquakes, mass movement and floods. From the presentation made during the workshops, it is clear that the geological com-

munity has started taking keen interest in the field of natural hazards and there is a need to pursue it further.

3. Although there are bylaws and building codes in most of the townships relating to safety measures, the regulatory authorities need to implement such laws more strictly than at present. There is also a need to update building codes in metropolitans. It should be mandatory for major construction companies carrying out large-scale construction work to conduct site risk investigations by professional engineers and geoscientists. It is possible that people dealing with small-scale construction activities usually cannot afford such specialized studies. General public will demand safety measures once they are aware of the risks due to natural hazards such as earthquakes. A set of recommendations should be prepared for the construction industry involved in small to medium scale structures for safety measures. Large as well as small-scale sensitive installations should be designed according to risk assessment of the construction site and area around it. It is proposed that a geoscientist should be included in the decision making of such projects. It was suggested that geoscientific input should be made mandatory during work on installations of sensitive nature.

4. There is a need for better communication amongst the geoscientists to avoid duplication of work. A commission may be constituted to plan, implement, supervise and facilitates the ongoing scientific studies on natural hazards, more or less on line with the Flood commission of Pakistan. With combined efforts seismic zonation map of the country should be updated and made available to general public.

5. There is not much of know-how and awareness amongst common people as well as the Government agencies about threats posed by the natural hazards. It is proposed that technical know-how should be provided through dissemination of knowledge amongst various government agencies. Frequent seminars and workshops will help to achieve this goal. Local people should also be involved in decision making while launching projects.

6. In order to achieve awareness about natural hazards amongst common people as well as Government agencies it is proposed to institute a working forum of Geoscientists, (named as Commission on Seismotectonics), which should meet at least once a year. The recommendations of this working forum should be sent to relevant Government agencies in the form of reports. These recommendations should also be publicized to create awareness amongst common people.

7. A data bank on natural hazards should be prepared to make basis for large-scale hazard and risk maps. Hazard prone areas may be targeted for development of comprehensive data banks, preferably using Geographic Information System. Comprehensive disaster management strategies may be prepared in advance for each of the hazard prone region on the bases of these data to effectively meet the challenge of rescue, relief and rehabilitation.

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