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SEISMIC HAZARD ASSESSMENT OF NW HIMALYAN FOLD AND THRUST BELT, PAKISTAN, USING PROBABILISTIC APPROACH

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Abstract: Seismic Hazard Assessment (SHA) of the entire seismically active NW Himalayan Fold and Thrust Belt Pakistan that incorporates probabilistic approach was carried out. Additional information in the form of earthquake catalogue, delineation of 40 active faults in a structural map, their relationship to the seismicity, establishment of seismotectonic zones was also undertaken and is represented in the form of a map. Distribution of 813 events within study area indicates that seismicity ($\geq 4.0\ M_w$) appears to be associated with both the surface and blind faults. At the same time, clustering of events in specific parts along the surface faults shows that some fault segments, especially in the hinterland zone are more active. In parts of the active deformational front like Salt Range, southern Potwar and Bannu, lesser seismic activity ($\geq 4.0\ M_w$) could be due to the damping effect of the thick Precambrian salt. Considering a number of geological and seismological factors, four seismotectonic zones were established. The b value for the Peshawar-Hazara Seismic Zone (PHSZ) is 1.16 followed by 1.12 for the Surghar-Kurram Seismic Zone (SKSZ). The other two, Swat-Astor Seismic Zone (SASZ) and Kohat-Potwar-Salt Range (KPSZ) have identical values of 0.95, thereby indicating occurrence of more events of relatively higher magnitude as compared to the other two seismic zones. Mean activity rate of earthquakes (λ) ranges from 4.26 to 1.73. In decreasing order, the values are 4.26, 2.62, 2.07 and 1.73 for PHSZ, SASZ, KPSZ and SKSZ, respectively. Using 4 regression relationships, the maximum potential magnitude (m_1) has been determined for the 40 Quaternary faults. In each seismic zone, the highest value within the seismic zone represents its m_1. The results show that m_1 is 7.8 in the hinterland (SASZ and PHSZ) and 7.4 in the foreland part (KPSZ and SKSZ). SHA incorporating probabilistic approach was undertaken at 10 sites (Astore, Bannu, Kaghan, Kohat, Mangla, Malakand, Muzaffarabad, Peshawar, Talagang and Islamabad). In the Probabilistic seismic hazard assessment (PSHA), the peak ground acceleration (PGA) values with 10% probability of exceedance in the 50 years i.e. the return period of 475 have been determined using the EZ-FRISK (6.2 beta version) software. Best-estimated seismic hazard parameters (λ, m_1, m_0 and the β value) of the four seismic zones were used as the input parameters. The results were generated in the form of total hazard curves. Values obtained range from 0.08g (for Bannu) to 0.21g (for Malakand and Kohat). For the other sites these are: Astore (0.082g), Kaghan (0.12g), Muzaffarabad (0.13g), Islamabad and Peshawar (0.15g), Talagang (0.16g) and Mangla (0.18g). High population density and more poorly constructed structures in Rawalpindi (twin city of Islamabad) and Peshawar make them even more hazardous. In addition, disaggregation at the assigned amplitude of 0.2g was also carried out for the ten sites.

Keywords: NW Himalayan Fold and Thrust Belt Pakistan, Seismic Hazard Assessment, probabilistic approach, seismic zones, peak ground acceleration, seismicity pattern

Introduction

The NW Himalayan Fold-and-Thrust, Pakistan, which forms the northwestern portion of the Himalayan frontal arc, is seismically one of the most active intercontinental regions anywhere in the world. The Himalayan mountain ranges have been formed due to the continental collision between the Indo-Pak and Eurasian plates. Between 1897 and 1952 there was a phase of very high seismicity when 14 major earthquakes ($M \geq 7.5$) occurred, including 5 great earthquakes of $M \geq 8$. The study area, which forms the northern and northeastern portions of Pakistan, has recently been activated on 1st and 20th November 2002 (Bunji Earthquakes), and 14th February 2004 (Batgram Earthquake) with two devastating earthquakes of magnitudes ≥5.5 $M_{w.}$ At the same time the most of the country consists of non-engineered structures, which are a constant threat to lives and property. It is not the purpose of present study to device a new building code, but to provide information in the form of seismic zonation and seismic hazard assessment (SHA) of the area that may prove useful in revision of such a code and help to mitigate earthquake disaster in the study area. For this purpose a total of ten sites i.e. Astor, Bannu, Islamabad, Kaghan, Kohat, Mangla, Malakand, Muzaffarabad, Peshawar and Talagang have been selected and Seismic Hazard Assessment (SHA) has been carried out using probabilistic approach.

The present work is based on the available historic and instrumental data along with geological and tectonic information. The results that are in the form of peak ground acceleration (PGA) curves are based on the statistical behaviour. Therefore, representing the first ever comprehensive study of the area, the results ought to be used with some caution. Notwithstanding, this work serves as a good starting point for further study.

Tectonic Setting of the Area

The active fold and thrust belt along the northwestern margin of the Indo-Pakistan plate is divisible into two parts—the Sulaiman belt and the NW Himalayan fold and thrust belt. The former is believed to be along a zone of transpression, whereas the latter is associated with the main zone of Himalayan convergence [1]. Transpression is considered to be the result of the 80 to 900 km long Chaman and Ornach-Nal Fault Zones [2] and forms the western plate boundary. In the Himalayan zone of convergence (Fig.1), the Main Karakoram Thrust (MKT, also known as the Shyok Suture Zone), Main Mantle Thrust (MMT, also known as the Indus Suture Zone), Main Boundary Thrust (MBT) and the Salt Range Thrust (SRT) delineate the major subdivisions of the collision zone [3,4].

From the above-mentioned major tectonic subdivisions of the Himalayan zone of convergence, the area between the MMT and SRT with its westward extensions (Surghar, Marwat, Bhittani and Manzai ranges) is referred to as the NW Himalayan Fold and Thrust Belt [5]. According to Gee [6] and later workers, the southern sides of these ranges are also marked by thrusts. The tectonic domains of Hazara-Kashmir Syntaxis and the Nanga Parbat Haramosh Massif comprise its eastern boundary. The western limit is not clearly defined. Besides the Kurram Fault in the southwestern portion, a series of thrusts beyond the borders of Pakistan (e.g. the Sarobi Fault in Afghanistan) are considered to delineate this boundary.

In this nearly 250 km wide and 560 km long fold and thrust belt, the Panjal-Khairabad fault (Fig.1) divides it into a northern hinterland zone and the southern foreland zone. The hinterland zone is also referred to as the Hazara Crystalline Zone [7] and Himalayan Crystalline Zone [8]. In the hinterland zone, which lies between the Main Mantle Thrust (MMT) and Panjal Khairabad Fault, mostly crystalline rocks occur, represented by Proterozoic to Mesozoic metamorphic and igneous rocks. Shearing and imbrication has resulted in a complex deformation pattern. The basement is also involved in thrusting. Treloar *et al*. [9] identified six nappe zones (Mohmand-Swat nappe, Besham nappe, Hazara nappe, Banna nappe, Kaghan nappe and Nanga Parbat-Haramosh massif) separated from each other by prominent shears and thrust faults. Besides the nappe zones, in the lower part of the hinterland zone, south of the Mansehra Thrust (and its probable extension, the Balakot shear zone) and Mohmand-Swat nappe zone the area mostly contains metasediments of Precambrian age. Kazmi and Jan [5] refer to this portion of the hinterland zone as the Khyber-Lower Hazara Meta-sedimentary Fold and Thrust Belt. A subdivision of this Metasedimentary belt is called the Peshawar

Basin (Fig. 1). This intermontane basin is believed to have formed during the Middle Tertiary due to south-verging imbricate thrusting on the MBT [10]. According to Hussain and Yeats [10], steep dips in unlithified Quaternary sediments, suggests that deformation involves both folding and faulting, and that the basement is affected by the high angle faults.

In the foreland zone, between the Panjal-Khairabad Fault and the Salt Range Thrust along with its westward extension, a thick sequence (upto about 8 km thick) of sedimentary rocks ranging in age from Upper Proterozoic to Cenozoic overlie the older crystalline basement rocks [11]. This foreland zone comprises many thrust sheets (decollement zones) with a southward translation of up to 100 Km.

Many workers [5,7,11] have classified this part of the study area into different units based on various geological factors. Following the classification of Kazmi and Jan [5], the foreland zone on the basis of deformation style is divisible in to the Salt Range and Kohat-Potwar fold belt, Kurram-Cherat-Margalla fold and thrust belt and the Hazara-Kashmir Syntaxis.

In this part of Pakistan (NW Himalayan fold and thrust belt), recent work of some workers [12, 13,14] as well as the present study suggests that transpression (strike slip faulting) is also operative in

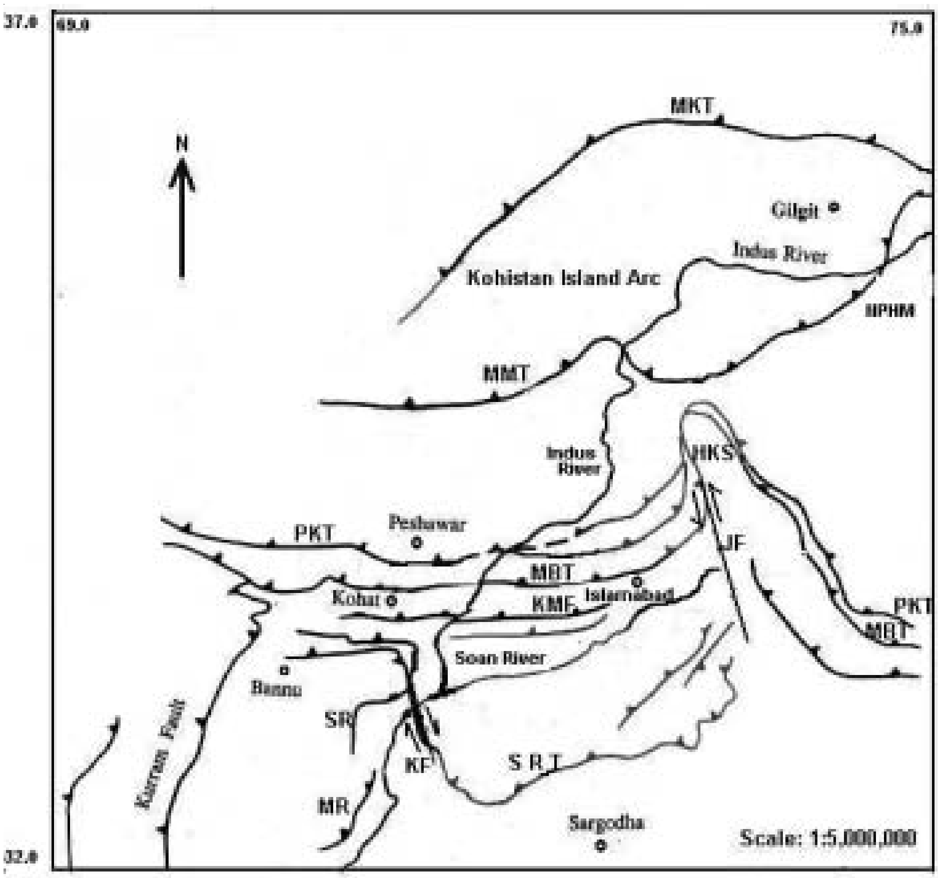

Figure 1. Structural and tectonic map of the study area and adjoining regions. Here MBT=Main Boundary Thrust. MKT=Main Karakoram Thrust. MMT= Main Mantle Thrust. PKT= Panjal Khairabad Thrust. KMF= Khair-I-Murat Fault. SR= Surghar Range. SRT= Salt Range Thrust. JF= Jhelum Fault. HKS= Hazara Kashmir Syntaxis. NPHM=Nanga Parbat Haramosh massif.

this compressional regime.

Quaternary Faults

It is commonly accepted that the recurrence interval of many earthquakes associated with faults is so large that considering only the instrumental (and/or historical) seismicity for evaluating seismic potential of a fault may not be a reliable indicator. At the same time, workers dealing with neotectonics consider all faults that may have been active during the last 10,000 to 12,000 years (i.e. during the Holocene) to be active faults. Thus, the prevailing practice in seismic hazard evaluation is to consider all Holocene faulting to be a part of the active fault system of the area i.e. having the potential of generating earthquakes in the future also.

The structural map (Fig. 2) prepared in the present work shows the 40 major active faults identified by different workers from within the study area. All these forty faults are considered to be seismically active with capability of causing significant damage.

Seismicity of the Area

Pakistan and adjoining countries experience high frequency of earthquakes, which in some cases have resulted in great loss of life and destruction. In Pakistan, besides the two active fold and thrust belts (Sulaiman and NW Himalayan Fold and Thrust Belt), high zones of seismicity exist in other parts of the country also. Available information [5] indicates that the Makran coastal earthquake of 1945 having a magnitude of m_b 8.3 was the severest earthquake to affect Pakistan. This event created a number of offshore islands along the Makran coastline. In the vicinity of the study area, the 1905 Kangra earthquake (in India) of m_b 8.4 activated the MBT, a major fault that extends into the study area also. More recently, Pattan (1974), Rawalpindi (1977), Bunji (2002) and Batgram (2004) earthquakes badly affected the study area.

In the present work, preparation of a composite earthquake catalogue has been undertaken by including all available earthquake data. This catalogue lists a total of 813 earthquakes in chronological order for the period of 1904-2002. The events in this composite catalogue occurred between latitude 32^0-$35^0 30'$N and longitudes 70^0-$75^0 15'$E and have moment magnitude (M_w) ≥ 4.0. Some further information about the catalogue preparation is provided below.

A report was made available by Pakistan Meteorological Department of the Mangla Joint Venture that was submitted to Pakistan Water and Power Development Authority in 2002 and revised in 2003. It includes a composite catalogue containing 631 earthquakes of ≥ 4.0 M_w between latitude 31^0-$35^0 30'$N and longitudes 70^0-76^0E for the period of 1904-2002. This catalogue has been prepared by Prof. N.N. Ambraseys of Imperial College, London. In our view this composite catalogue is the most reliable as it was prepared by incorporating data from the previous catalogues [15,16] and many other local as well international sources. The epicentral locations given in the catalogue for events prior to 1964 are the same as those determined by [16]. For later events, locations and depths recomputed by [17] were adopted. In the case of magnitude, a single scale i.e. moment magnitude (M_w) was adopted by using the relationships of Ambraseys and Bommer [18].

This catalogue contains 182 additional events to those 631 events catalogued by Prof. Ambraseys. The Tarbela, Mangla and microseismic network of Pakistan Atomic Energy Commission (PAEC) provided data for these events. Hypo71 and Hypo inverse softwares were used to compute epicentral locations and depths. For earthquake events from 2000 onwards, PAEC used the SEISAN software [19]. The local observatory data of Tarbela and Mangla has an error of less than 2.5km for location and depths; whereas the data of PAEC has an error of 2 to 5km. This data, for moment magnitude, was converted by using the relationships of Ambraseys and Bommer [18] given above. This has helped to create uniformity in the catalogue.

In the seismicity map (attached map and prepared using the above mentioned data), there are areas such as the Salt Range, Southern Potwar near Talagang and the Bannu Basin with little or no epicentral distribution. One reason is that in spite of general agreement of Salt Range and southern Potwar being a part of an active deformational front, only low magnitude levels (≤ 4.0 m_b) have been recorded as previously observed by Seeber and Armbruster [20] and Quittmeyer *et al.* [16]; whereas in the seismicity map only events having magnitude ≥4 have been plotted. Another reason may be the presence of a thick sequence of EoCambrian salt in the Salt Range and Potwar area that may be having a damping effect. Further, the lithologies occurring in the Salt Range/Potwar are believed to be extending into the Bannu Basin also [11] thereby implying the presence of salt in this part also.

Seismotectonic Zonation

For any seismic hazard assessment to be carried out, seismotectonic zonation is considered to be an essential prerequisite. In order to establish the seismotectonic zones a number of factors related to seismological characteristics, geology and geophysics of the region of interest are taken into consideration. According to Udias [21], the characteristics of the occurrence of earthquakes in relation to regional tectonics and general geodynamic conditions form part of seismotectonic studies. This includes geographic distribution of epicentres, magnitude, depth, focal mechanism solutions and their correspondence to various types of faults, stress orientations and kinematic aspects of tectonics. In the present work using all these parameters, a seismotectonic map has been compiled (Fig. 2). Information related to the tectonics, seismological characteristics that aid in establishing the seismic zones have been provided in the previous sections. In this section a brief account of the previous work regarding zonation, their seismological characteristics and statistical analysis dealing with seismic hazard parameters is described.

Workers from the Columbia University [20, 22] based on microseismicity data from the Tarbela Observatory recognized three seismic zones (Indus Kohistan Seismic Zone, Hazara Lower Seismic Zone and Tarbela Seismic Zone) in parts of the study area. Quittmeyer *et al.* [16] divided the whole of Pakistan into 15 seismotectonic provinces out of which 5 covered the study area. Of these 5 zones, excepting one (namely the Hazara region), the others (Sulaiman Range; Gardez, Kunar and Safed Koh Fault Zone; Salt Range and the Himalayas) only partly cover the study area. Their division is based on the interpretation of the regional tectonic evolution and patterns of seismicity (including magnitude).

From amongst the unpublished reports, the report of the Mangla Joint Venture (2001) and subsequent reports of the Mangla Observatory contain 6 seismotectonic zones (MBT, Riasi, Hazara, Potwar, Salt Range and Punjab Seismic Zones) for this part of Pakistan. From these 6 zones, Riasi only partly covers the study area whereas the Punjab Seismic Zone lies beyond the southern boundary. Also, parts of the study area such as the Kohat and adjacent regions in the west and those located in the northern portion are not covered. These zones (area sources) were considered to be homogenous in their tectonic and seismic characteristics.

Presently Formulated Seismotectonic Zonation

Initially in the present study, the tectonic subdivisions of Kazmi and Jan [5] were taken to be representing the seismotectonic zonation of the study area also. The problem in adopting such an approach has been lack of sufficient earthquake events in most of these subdivisions for undertaking statistical analysis leading to high statistical uncertainty.

Considering the geological and seismological information provided in the previous sections, the following four seismotectonic zones have been established (Fig. 2): Swat-Astor Seismic Zone (SASZ), Peshawar-Hazara Seismic Zone (PHSZ), the Kohat-Potwar-Salt Range Seismic Zone (KPSZ) and the Surghar-Kurram Seismic Zone (SKSZ). These zones contain several tectonic features (faults) within them.

Overall, they are a combination of the tectonic subdivisions of Kazmi and Jan [5] in which nearly similar subdivisions like their different crystalline nappe zones and HKS have been grouped into the Swat-Astore Seismic Zone. However, each seismic zone if compared with each other differs in their lithological/stratigraphic/structural/tectonic characteristics. At the same time, there are differences in their seismicity behaviour and in other statistically dependent seismic parameters. Further, as performance of statistical analysis is a prerequisite in any seismic hazard assessment, the seismic zones should contain sufficient number of events for carrying out such an analysis. In the present case, the best estimated seismic hazard parameters i.e.λ, m_1 and the β parameter for every seismic zone were determined for use in seismic hazard assessment. The results are summarized in Tables 2-5 (see Fig.2). The symbol β although not discussed previously is a substitute for the b value, where $\beta = b \ln 10$. The threshold magnitude (m_0) is taken as 4.0 and the focal depth given for each zone is the average for all instrumentally recorded earthquakes of that particular zone.

Evaluation of Peak Ground Accelerations (PGA) Using the Probabilistic Approach

Commonly there are two approaches are used for the determination of seismic hazard assessment (SHA) i.e. Deterministic Seismic Hazard Assessment (DSHA) and Probabilistic Seismic Hazard Assessment (PSHA). The DSHA is comparatively simple and does not account for the uncertainties and probability of occurrence of an earthquake. The PSHA is denoted by the probability that ground motion (acceleration) reaches certain amplitudes or seismic intensities exceeding a particular value within a specified time interval. Inverse of the probability of exceedance is known as the return period for that acceleration and is used to define the seismic hazard. In probabilistic hazard evaluation, the seismic activity of seismic sources (line or area) is specified by a recurrence relationship, defining the cumulative number of events per year versus their magnitude. Distribution of earthquakes is assumed to be uniform within the source zone and independent of time [23]. Seismic hazard calculated for different sites can be used to generate maps or curves (hazard curves) with intensities or ground accelerations expected with a given probability for a specified interval of time. In the present work, four seismic zones were established and their PSHA was carried out.

On the basis of the seismic hazard parameters evaluated in the preceding section, PSHA was carried out on ten sites i.e. Astor, Bannu, Islamabad, Kaghan, Kohat, Mangla, Malakand, Muzaffarabad, Peshawar and Talagang selected for this purpose using the EZ-FRISK software. Further information about the specific contributory parameters was obtained by applying disaggregation (deaggregation).

Generally, it is recommended that high quality accelerograms data be used in the relationships. However, this type of data is lacking or limited in quantity for most regions of the world. In such areas where an attenuation relationship is yet to be established, one or more than one relationship derived for other regions, preferably with similar or nearly similar tectonics is used. Criteria for selection of an appropriate attenuation relationship are available [24]. Similar situation of lack of a relationship also exists in Pakistan. According to [25], the first accellerographs were installed in 1990. Insufficient data have been generated so far. This strong motion data has previously been incorporated by Ambraseys and Bommer [26] and Ambraseys [24] in their database for the derivation of attenuation equation in Europe. It formed only a small portion (3%) of their database.

Bommer [25] in his detailed work on

attenuation equations for Pakistan concluded that there are no equations available even from neighbouring countries that can be adopted for seismic hazard assessment. The attenuation equations of Ambraseys *et al.* [27] and Boore *et al.* [28] have previously been utilized for the computation of peak ground accelerations (PGA) at the Mangla Dam [25]. Also, Jain *et al*. [29] concluded that their regression analysis for Central Himalayas closely fits the equation of Boore *et al.* [28].

PSHA has been carried out using the software called EZ-FRISK (6.2 beta version, 2004 modified form). The program calculates the earthquake hazard at a site under certain assumptions specified by the user. These assumptions involve identifying where earthquakes will occur, what their characteristics will be, and what will be the ground motions generated. These capabilities allow a wide range of seismic hazard problems to be solved, with straightforward specification of input. Its easy use allows in identifying the critical inputs and decisions affecting seismic hazard evaluations. The results of probabilistic calculations are annual frequencies of exceedance of various ground motion levels at the site of interest.

Further, seismic hazard is determined using the standard methodology described in McGuire [30]. The range of values used as input parameters can account for multiple hypotheses and computation of uncertainty in the resultant hazard values. The earlier mentioned seismic hazard parameters i.e.l, m_1, m_0 and the b parameter of each seismic zone i.e. area sources have been taken as input parameters in the present study. Besides representing the total hazard curves this software has aided in determining the most contributory seismic source zone and in carrying out deaggregation also.

Results and Discussion

Probabilistic results (Fig. 2) of seismic hazard assessment, as mentioned previously, have been generated in the form of hazard curves for the 10 selected sites that were distributed within the 4 seismic source zones. An alternate approach could have been the representation of the acceleration values in the form of contours on maps.

The hazard curve is a plot showing the change in ground motion amplitudes relative to return period. Ground motion amplitude always increases with increasing return period in Poisson hazard models. It may be noted that the maximum distance in PSHA is 200km radius. The total hazard curves, in the form of peak horizontal ground acceleration (PGA) at each and individual site versus their annual frequency of exceedance, were obtained. Results based on the attenuation equation of Ambraseys *et al.* [27] are in all cases less and are shown only to help in comparison with the values obtained through use of the equation of Boore *et al.* [28]. The reasons for preferring the latter have already been discussed earlier. At the same time, it is reiterated that instead of using representative equations derived for other places, an attenuation equation of Pakistan is needed. From these curves, acceleration values for different return periods can be determined. Following normal practice, the PGA values with 10% probability of exceedance in the 50 years i.e. the return period of 475 years are generally quoted.

The PGAs determined for the 10 selected sites range from 0.08g to 0.21g as shown in Tables 6 and 7 (see Fig. 2). In the present case, Kohat and Malakand depict the highest values of 0.21g whereas the lowest are obtained for Bannu. Critical tectonic features that may affect these sites have already been identified (Table 7, see Fig. 2). Islamabad and Peshawar although having relatively lower values (0.15g) have a higher population density as compared to the other sites with higher PGAs (Kohat and Malakand). However, Peshawar and Rawalpindi (twin city of Islamabad) are big cities of Pakistan with more poorly constructed structures and can experience appreciable damage as compared to the other less populated sites with higher PGAs. Therefore, an earthquake affecting them would pose a greater hazard as compared to the other sites.

All results obtained from this study have been used in the compilation of a seismotectonic map of the area (Fig. 2), which displays the focal mechanism solutions of 45 earthquakes occurred during the period of 1964-2004, 40 active faults, seismicity from 25 AD-2002, statistical parameters (Tables 2-5, see Fig. 2), most critical tectonic features with maximum potential magnitudes for major ten locations and peak ground accelerations (PGAs) for ten sites using Probabilistic Seismic Hazard Assessment (PSHA). This map, it is hoped would serve as a guide to the different organizations engaged in obtaining a better understanding of the tectonics of the area and in mitigating loss/damage to lives and property. It can certainly be further improved if larger coverage by local networks is undertaken. Strong motion data can also further improve the results. Determination of velocity structure and further subsurface information, based on other geophysical techniques, can also help.

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