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SEISMIC HAZARD ASSESSMENT OF *JAM* IN AFGHANISTAN

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SUMMARY

The world's second tallest minaret, the Minaret of *Jam* in Afghanistan built in the XII Century A.D. is on UNESCO's List of World's Endangered Monuments. The 60m tall structure sits precariously at the junction of two rivers and is in danger of collapse due to a 3.4° inclination inducing high stresses in its deteriorated brick masonry. These conditions of the monument render it more susceptible to natural geohazards like earthquakes. Consequently, prior to intervention, it is of foremost importance to assess the seismic hazard at the site. *Jam* lies in close proximity of the *Herat* fault, a prominent strike-slip lineament in northern Afghanistan. For most of its length the fault has not been associated in recent history with the occurrence of large earthquakes. Although no earthquake epicenters have been reported in catalogues close to *Jam*, seismically active zones of *Kabul*, *Mazar-i-Sahrif*, *Bamiyan* and the *Hindukush* subduction zone lie few hundred kilometers away from *Jam*. This article illustrates the results of a Probabilistic Seismic Hazard Assessment (PSHA) performed using the Cornell-McGuire method with a systematic treatment of uncertainties in a logic-tree framework. Uniform hazard spectra have been determined for return periods of 72, 224, 475 and 975 years. The study also includes some results derived from a Deterministic Seismic Hazard Analysis (DSHA) at the site.

INTRODUCTION

A refined estimation of the seismic hazard in a region characterized by qualitative and quantitative deficiency of seismic data is certainly an engineering challenge. Indeed, the study presented in this article is an attempt to develop a rationale for assessing the seismic hazard in a region of the world where the seismic information is incomplete and of poor quality.

The problem is characterized by a scenario where the seismic hazard has to be assessed in a barren, mountainous zone (the *Hindukush* in the Alpine belt) in a country recognized as being seismically very active (Afghanistan). The region has a poorly documented local history of earthquakes rendering it, in essence a "*grey area*". The problem is further convoluted by the need for a refined estimation of the seismic hazard in the domain of minor earthquakes.

The Minaret of *Jam* is located in an isolated region, very far from populated areas where a record of historical earthquakes may be available. Even minor earthquakes may be dangerous for the survival of such an exceptionally slender, tall structure (about 60 m high), which is 800 years old, with badly damaged brickwork at its base and is 3.35 m out-of-plumb.

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The Minaret of *Jam* is, in the opinion of the authors close to structural collapse under the sole effect of gravity aggravated by its inclination. In fact, the edge of its base facing away from the direction of lean is very close to being in a state of tensile stress. Therefore the effect of even a moderate earthquake could be devastating, unlike in an ordinary structure. The concern of the international community that this archaeological masterpiece may be lost to an earthquake is dramatically based on the fact that four, XIV Century minarets collapsed in the city of *Herat* in northwestern Afghanistan since 1915 A.D.

THE MINARET OF *JAM*

The Minaret of *Jam*, which rises 60.4 m above the ground, was built in the XII Century A.D. on the southern bank of the *Hari-rud* River, approximately 1900 m above sea level in *Ghor* Province of northern Afghanistan. Set in a deep river valley at the junction of the *Hari-rud* and its tributary *Jam-rud*, in the midst the western extension of the *Hindukush* Range (see Figure 1), the world's second tallest minaret is of critical significance in comprehending the history of the *Ghurid* Dynasty.

Figure 1: Views of the Minaret of *Jam* in the *Hari-rud* Valley (photo courtesy: A. Bruno, A. Borgia)

The geographical coordinates of the site of the minaret are 34°23' N, 64°31' E. *Jam* is located approximately 260 km east of the historical city of *Herat*. The minaret was in all probability erected between 1163 and 1203 A.D. during the reign of the *Ghurid* Dynasty under Sultan Ghiyath-al-Din at the summit of his rule (Bruno [9]). It is widely believed that the Minaret of *Jam* inspired the construction of the *Qutub Minar* in New Delhi at the end of the XII Century, which is currently the world's tallest minaret. The precise location of the Minaret of *Jam* in the valley was unknown for many years. The Minaret of *Jam* was rediscovered by Ahmed Ali Koazad of the Afghan History Society in 1944 and subsequently by the French archaeologist André Maricq in 1957 (Bruno [9]).

The façade of the minaret is characterized by intricate geometrical and floral motifs and inscriptions from the *Koran*. The cylindrical structure rises on an octagonal base and in this aspect departs from most contemporaneous minarets that characteristically have circular bases. The original entrance of the tower is currently inaccessible and lies below 4-6 m of alluvial deposits from the adjoining river. The tower suffers an inclination of 3.4° north-north-eastwards, for a reason which is yet to be ascertained, but perhaps attributable to scouring due to its precarious location at the junction of the two rivers. Since June 2002, the Minaret of *Jam* is on UNESCO's list of World's Endangered Monuments. Preliminary assessment has revealed that one edge of the base section of the tower is very close to being in a state of tensile stress.

There is no direct evidence of large earthquakes that have occurred at the site in the literature and the nearest epicenter lies about 170 km from *Jam*. Historical and instrumental catalogues of earthquakes (Quittmeyer [17]; Ambraseys [4]) from 25 A.D. to the present day, validate the above statement. However, according to Ambraseys [4], the historical record of Afghanistan's earthquakes is far from being complete in certain remote areas of the country. Fairly recent works have classified this region as a weak seismicity zone (Abdullah [1], [2]). *Jam* lies in close proximity of the *Herat* fault, a prominent right lateral strike-slip lineament running along north Afghanistan for about 1,100 km. For most of its length the fault has not been associated in recent history with occurrence of earthquakes.

Preliminary geological investigations at *Jam* by Borgia [8] for the UNESCO have revealed recent tectonic uplift in the region. Therefore earthquakes of moderate intensity cannot be totally ruled out. Residents of the neighboring village have experienced earthquakes, but the data is far too inadequate to determine the intensity of ground motion or the recurrence interval (Borgia [8]).

SEISMOTECTONIC SETTING

Tectonics at a Global Scale

Afghanistan is positioned on the southern periphery of the Eurasian plate and is subjected to collision with the Arabian plate on the south and transpression with the Indian plate to the southeast at about 30 and 40 mm/year, respectively (Ambraseys [4]). A generalized tectonic structure of the region and directions of plate motion are indicated in Figure 2. A map showing the location of *Jam* relative to other important cities and tectonic features in the region is presented in Figure 3.

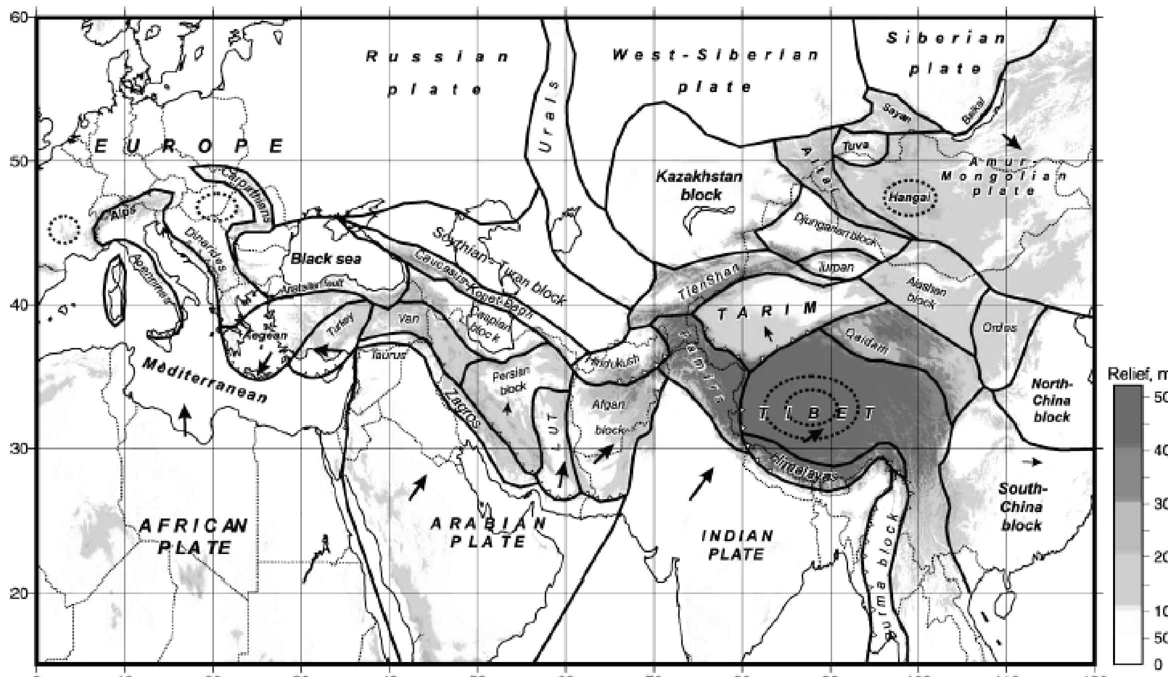

Figure 2: Surface topography and generalized structure of the Alpine-Himalayan belt. Direction of plate motion is schematically shown by arrows (after Koulakov [13])

The collision rate of the Arabian plate is currently close to 22 mm/year with a fraction of this convergence rate being accounted for on Afghanistan's western border with Iran where dextral shear is noticed. The left-lateral slip along the border of the Indian plate through *Baluchistan* and Afghanistan is 29.5 mm per year (Ambraseys [4]). The collision rate of the Arabian plate is currently close to 22 mm/year with a fraction of this convergence rate being accounted for on Afghanistan's western border with Iran where dextral shear is noticed. The left-lateral slip along the border of the Indian plate through *Baluchistan* and Afghanistan is 29.5 mm per year (Ambraseys [4]).

The segment of the Alpine-Himalayan belt extending from Iran in the west, to Burma in the east is one of the most seismically active intercontinental regions in the world and a zone of intricate plate interactions (Gupta [12], Koulakov [13]). This region of strong seismicity is characterized by the occurrence of shallow crustal earthquakes. However deep focus earthquakes also occur in regions like the *Pamir-Hindukush* zone dominated by a subduction-type mechanism.

Wellman [22] mapped the active wrench fault pattern of Iran, Afghanistan and Pakistan from air-photo-mosaics and classified them as active or inactive. Abdullah [1] published a report on the geological and geophysical investigations carried out from 1972 to 1979, with a tectonic map of Afghanistan outlining major faults and a preliminary hazard zoning. In 1984, the Commission for the Geological Map of the World of the UNESCO [18] produced a seismotectonic map of Iran, Afghanistan and Pakistan. Abdullah [2] published a revised preliminary hazard zoning of the country.

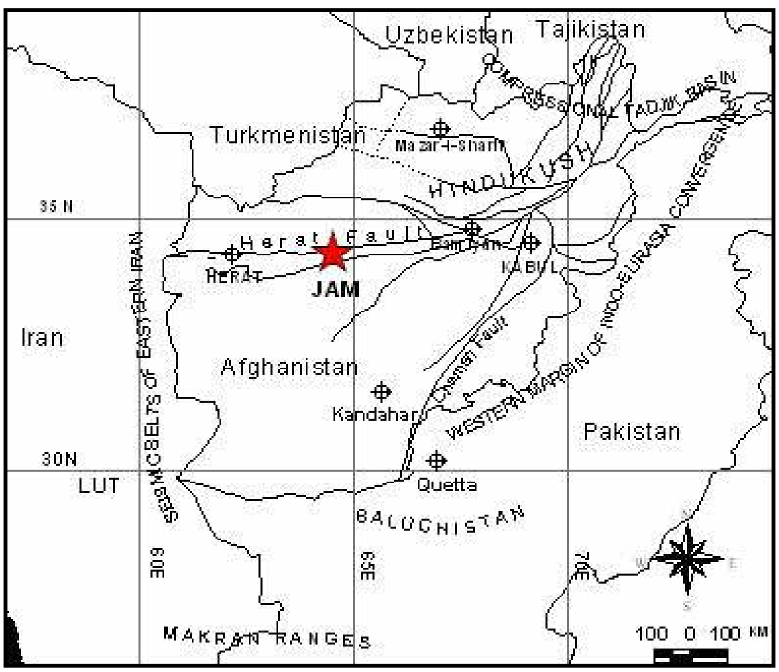

Figure 3: Map showing the location of *Jam,* some important cities and tectonic features

Mainland Afghanistan

A large part of northern Afghanistan is occupied by a plateau separated from central Afghanistan by the *Herat* (a.k.a. *Hari-rud*) fault and in the east and southeast by the *Khokhan* fault from structures of the western *Hindukush* and north-western *Badakhshan* (Abdullah [1]). This plateau is further divided into blocks by a number of faults. Most parts of central and western Afghanistan lie in the interior of the wide deformation belt at the margins of the country and behave kinematically as 'rigid blocks'. Such areas are characterized by a relatively low seismic activity. Epicenters have been recorded throughout the country but their energy, frequency and density vary noticeably. The depth of earthquake foci and magnitude increases from west to east and from southwest to northeast (Gupta [12]). Ambraseys [4] opine that since historic earthquakes have been recorded along the north-facing frontal ranges in western Afghanistan but no recent events, infrequent damaging earthquakes could occur here.

Earthquake Belts of Eastern Iran

The Iran-Afghanistan border, coincidentally, is the eastern extremity of the Arabia-Eurasia collision zone. Walker [21] state that at this longitude nearly all the Arabia-Eurasia convergence (~ 40 mm/year at 60° E) is accommodated in the seismic belts of the *Alborz* and *Kopeh Dagh* in northern Iran, requiring the comparatively aseismic central Iran to move N-NNE relative to Afghanistan. The N-S right-lateral shear component between central Iran and Afghanistan is taken up by a series of N-S trending right-lateral strike-slip faults bordering the relatively aseismic *Dasht-e-Lut* block. On their northern end, these faults terminate in a series of E-W trending right-lateral strike-slip faults and the *Tabas* thrust system while on the southern end, they terminate in the E-W coastal ranges of the *Makran* where the Arabian Sea is subducted northwards (Walker [21]). The *Kopeh Dagh* belt (NW to SE range of mountains separating the *Turan* shield from Central Iran) has right-lateral strike-slip or reverse faulting.

Western Margin of the Indo-Eurasia Collision

The Afghanistan-Pakistan political border is coincident with the western edge of the India-Eurasia plate collision, a widespread fold and thrust belt extending from NW India to S Pakistan, comprising of the *Himalayas*, the *Hazara-Salt* Ranges, and the *Sulaiman-Kirthar* Ranges. A very intense seismic zone, the *Sulaiman* wrench zone exists between the *Sulaiman-Kirthar* ranges around 30° N Latitude. Verma [20] have identified two distinct, intense seismic trends in the *Hindukush*. Thrust and left-lateral slip with shallow to intermediate depth earthquakes prevail. Focal mechanism studies reveal that the *Baluchistan* arc is a major left-lateral shear zone between the *Lut* block in Iran and the Indian shield (Verma [20]).

Subduction Zones

An active zone of subduction is produced in the *Makran* region of south Pakistan and southeast Iran where the Arabian Sea floor is subducting at a shallow angle to the north (Quittmeyer [17]). The compressional *Tadjik* basin, bordered by the *Hindukush* to the south and the *Pamir* to the north touches the western edge of the *Hindukush* seismic zone. Intense earthquake activity is reported here at depths of 70-300 km. According to Ambraseys [4] and Quittmeyer [17], the region is apparently a site of final stage of subduction of oceanic lithosphere along the India-Eurasia collision boundary.

***Herat* Fault**

The Eurasian plate, at its boundaries and within has a number of predominant strike-slip features. The *Herat* fault is a distinct morphological feature that traverses almost the entire length of northern Afghanistan for 1,100 km (Wellman [22]). According to Quittmeyer [17], this is a right-lateral strike-slip feature with a probable history of movement throughout the Cenozoic.

Quittmeyer [17] believe the fault to be 'inactive' with no evidence of fault-related seismicity. Ambraseys [4] state that slip on this fault would be insignificant in accommodating the north-south convergence thus explaining absence of seismic activity during the historic and instrumental period. Verma [20] have concluded that the *Herat* fault is seismically inactive barring its portion that trends northeast towards the *Hindukush*. An event in the IX Century (intensity VII-IX MM) near *Herat* and another in 1874 (VIII-IX MM), north of Kabul seem to be the only events with 'possible connection' to the lineament.

Quite conversely, Wellman [22] classified the fault as being 'active' citing significant evidence of dextral topographical displacement (60-100m) of streams that seemed to have originated more than 10,000 years ago, at two locations along the fault about 200 km east and 500 km west of Kabul.

Geologically, the fault is much less active than the faults of east Iran and recent GPS measurements confirm that even if active, the estimated rate of motion is low (Jackson J: 2004, written communication).

***Chaman* Fault**

The *Chaman* fault is an 800 km long left-lateral strike-slip feature that appears south of the *Herat* fault and then trends south-southwest along the Afghanistan-Pakistan border (Wellman [22]). Verma [20] report appreciable seismic activity over its entire length from 1890 to 1970. This fault apparently accommodates close to 19-24 mm of strike-slip motion per year according to Ambraseys [4].

HISTORICAL AND INSTRUMENTAL SEISMICITY RECORDS OF AFGHANISTAN

Background Information

Retrieval of data on the historical seismicity of this country is certainly not a simple task. The main sources of data for ancient seismicity are Persian documents (Ambraseys [5]), and dependable British and French consular reports (Ambraseys [4]) in the pre-instrumental era. Nevertheless, the existence of vast, uninhabited areas in this part of the world and the changes that have occurred in the past, render the number of events in historical memory quite incomplete.

Quittmeyer [17] compiled and evaluated historical and instrumental catalogues of Pakistan, Afghanistan, NW India and SE Iran from 25 A.D. to 1975. A study of earthquake activity in Persia by Ambraseys [5] is a good source of information. Though the study centers on modern day Iran, regions on the east and west have been considered and the genuine lack of earthquake data to the east is demonstrated in this study. Gupta [12] identified the existing earthquake catalogues for the region from Iran to Burma in the Alpine belt. Ambraseys [4] summarized the written history of earthquakes in Afghanistan from 734 to 2002 in the form of a revaluated catalogue of events.

An apparently vital source of data for many previous studies (Quittmeyer [17], Abdullah [1, 2], Gupta [12], Ambraseys [4]), "Earthquake history, seismicity and tectonics of the regions of Afghanistan" by Heuckroth and Karim published by the Seismological Centre, Kabul University in 1970, was unavailable for the current investigation.

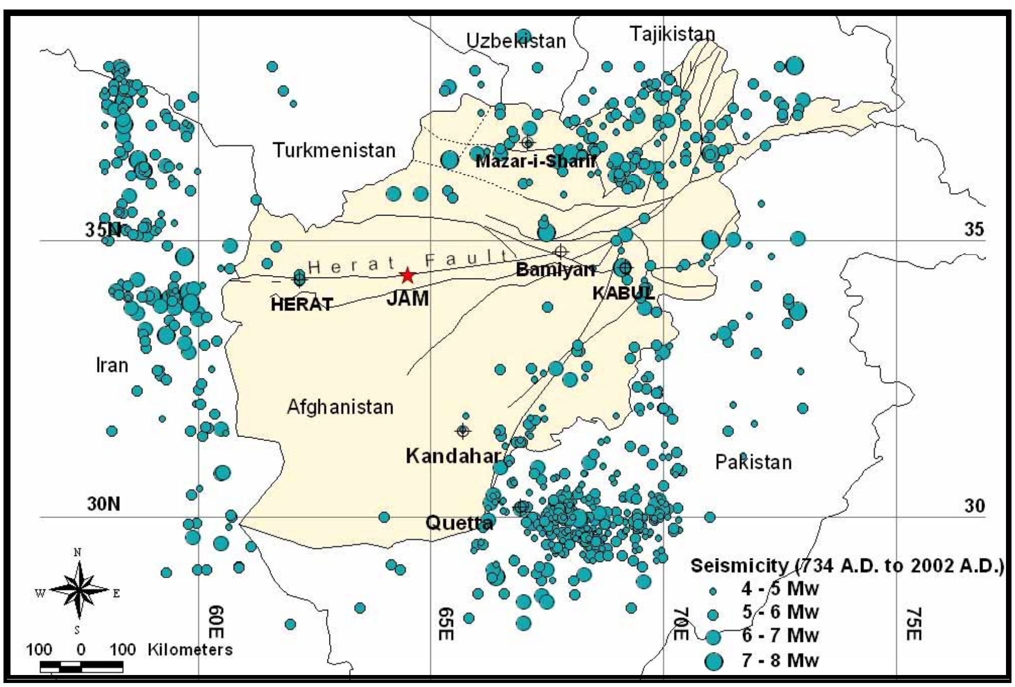

Figure 4: Historical and instrumental seismicity of Afghanistan (734-2002 AD) after Menon [14]

Catalogues Utilized in the Current Investigation

Historical and instrumental seismicity data for the current study have been retrieved from published catalogues compiled by Quittmeyer [17] and Ambraseys [4], but principally from the latter. Figure 4 illustrates the historical and instrumental seismicity along with the major tectonic features of the region.

The catalogue of Quittmeyer [17] covers an area delineated by 20°-38°N Latitude and 60°-80°E Longitude. Historical events are presented in terms of the MM scale and instrumental data are presented in terms of body-wave (m_b) or surface-wave magnitudes (M_s). Only six events have been reported after the first one in 25 A.D., until the XVI Century.
The catalogue compiled by Ambraseys [4] consists of 1312 events and narrative accounts of 47 significant earthquakes. The study area is delineated by the coordinates 29°N-38°N Latitude and 58°E-73°E Longitude. For pre-XX Century events, M_s values have been estimated based on macroseismic observations. A bilinear relationship between M_s and seismic moment derived from recent earthquakes in the catalogue has been used to estimate the moment magnitudes (M_w) of all events in the catalogue.
Of the 1312 events of the catalogue, about 16% lack any sort of magnitude data; 72 of these are reported with the same spatial and temporal occurrence in the catalogue by Quittmeyer [17]. The assembled catalogue used in the seismic hazard assessment includes events from both these catalogues. Intensity to magnitude conversions have been effected using a region-specific empirical formula from Ambraseys [5]. All events with magnitude less than 4.0 were ignored. The largest event (M_w 7.7) corresponds to the *Quetta* earthquake of 1935.

PROBABILISTIC SEISMIC HAZARD ASSESSMENT (PSHA) OF *JAM*

Delineation of Seismic Source Zones

Irrespective of whether a probabilistic or a deterministic method of analysis is implemented, a preliminary step in seismic hazard assessment is the definition of potential seismic sources that affect the location at which the hazard is being estimated. This procedure, known as *seismogenic zoning*, is perhaps the most crucial part of a seismic hazard analysis, for there are no general rules for its execution. Seismogenic zoning is usually carried out on the basis of a reasonable combination of both geological and seismological information. The likely predominance of one constituent with respect to the other is strongly dependent upon the nature, quantity and quality of data available (Faccioli [10]).

Considering the uncertainties that characterize the information obtainable for this study, seismogenic zoning has been carried out following two alternative scenarios:

Scenario-A based on seismotectonic criteria:
The seismogenic zoning in Scenario-A (see Figure 5) has been based, in principle on the preliminary hazard zoning by Abdullah [1]. In the classification of Abdullah [1], the country was divided into provinces of intense, high, medium and weak seismicity based on seismicity and tectonics data.

Scenario-B based purely on the observed seismicity:
On overlapping epicenters on the zoning adopted in Scenario-A, it emerges that seismicity is being uniformly spread even though epicenters are actually located only in certain portions of the source zones. The central-west Afghanistan zone (SZA3) with very low observed seismicity demonstrates this case (see Figure 5). *Scenario-A* is representative of a 'highly conservative model'. Therefore, as a more realistic case, source zones delineation in the second scenario is based purely on observed seismicity (Figure 6).

Scenario-C: based on the assembled earthquake catalogue (zone-free model):
In an effort to circumvent some of the uncertainty involved in the definition of seismogenic zones, PSHA has been carried out by considering the epicenters of the entire catalogue as the only (point) sources. Peak ground acceleration (median+1σ) at *Jam* due to each event is calculated by using an attenuation relationship. The b-value is determined from the regional seismicity (i.e. entire catalogue) and assigned to every source. On the other hand, the mean annual frequency of occurrence is estimated separately, using an A-value normalized by the cumulative rate of occurrence of the lowest magnitude interval in the catalogue. This has been performed because the A-value pertaining to the regional seismicity cannot be

assigned to every point source. Each point source is assumed to have a maximum magnitude (M_{max}) 0.3 units higher than the magnitude of the earthquake that occurred at that location, thus postulating that every point has the potential of producing an earthquake equal to the maximum historical earthquake (MHE) + 0.3 or lower only.

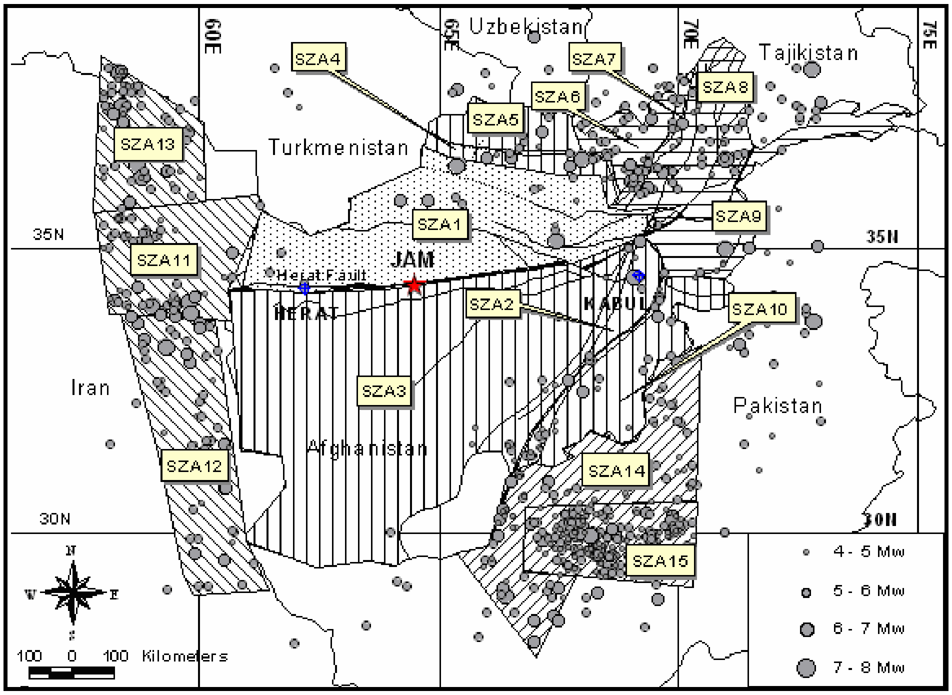

Figure 5: Seismogenic zoning scenario A (after Menon [14])

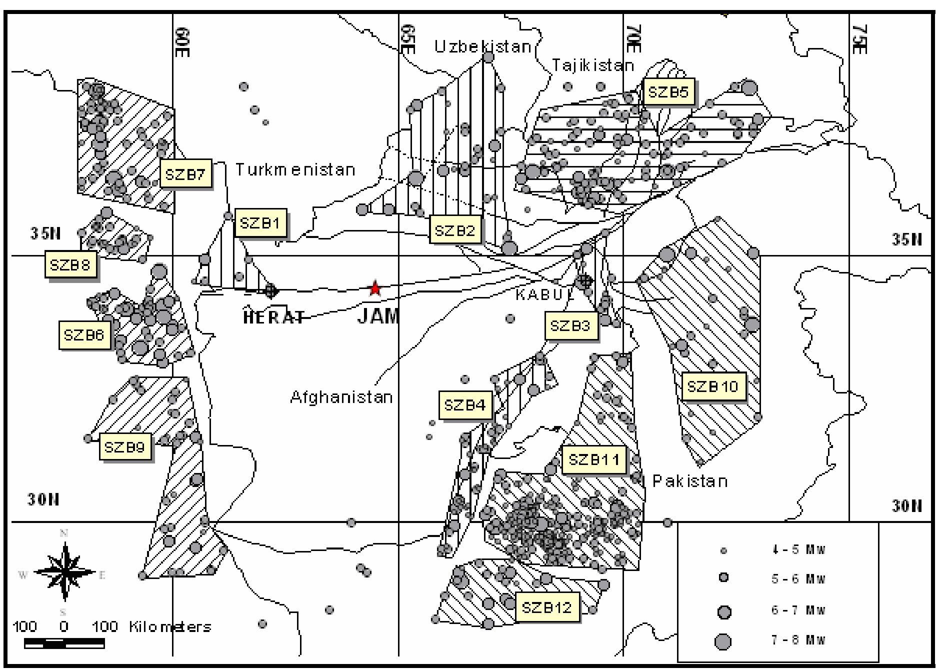

Figure 6: Seismogenic zoning scenario B (after Menon [14])

Processing the Assembled Earthquake Catalogue

Elimination of aftershocks and foreshocks

The assumption that occurrence of earthquakes follows a *Poissonian* stochastic process where the sequences of seismic events are considered temporally independent, entails identification and removal of foreshocks and aftershocks from the earthquake catalogue because the sequence of foreshocks and aftershocks follows a probability distribution different from the sequence of main events.

This operation has been accomplished by using the algorithm developed by Gardner [11] for southern Californian earthquakes. The duration (D_r) of the cluster of foreshocks and aftershocks and their spatial extension (L_r) have been computed using the coefficients of regression: $a_1 = 0.564$, $b_1 = 0.637$, $a_2 = 0.126$ and $b_2 = 0.98$. 17% of the events with reported magnitude in the catalogue were identified as foreshocks or aftershocks and subsequently removed by applying this algorithm. The final catalogue used in the hazard analysis consists of 824 events. 62.6% of this final list consists of events greater than M_w 5, 12.7% greater than M_w 6 and 2.7% greater than M_w 7.

Completeness analysis of the catalogue

For historical earthquakes, recorded seismicity is far lesser than the 'true' seismicity and in early instrumental catalogues too, *incompleteness* is seen across different ranges of magnitude. Therefore, time windows within which the catalogue is complete have to be defined. *Completeness analysis* has been performed using the 'Visual Cumulative Method' by Mulargia [15], a simple graphical procedure based on the observation that if earthquakes of a given magnitude are assumed to follow a stationary occurrence process, in a complete earthquake catalogue the average rate of occurrence of seismic events must be a constant.

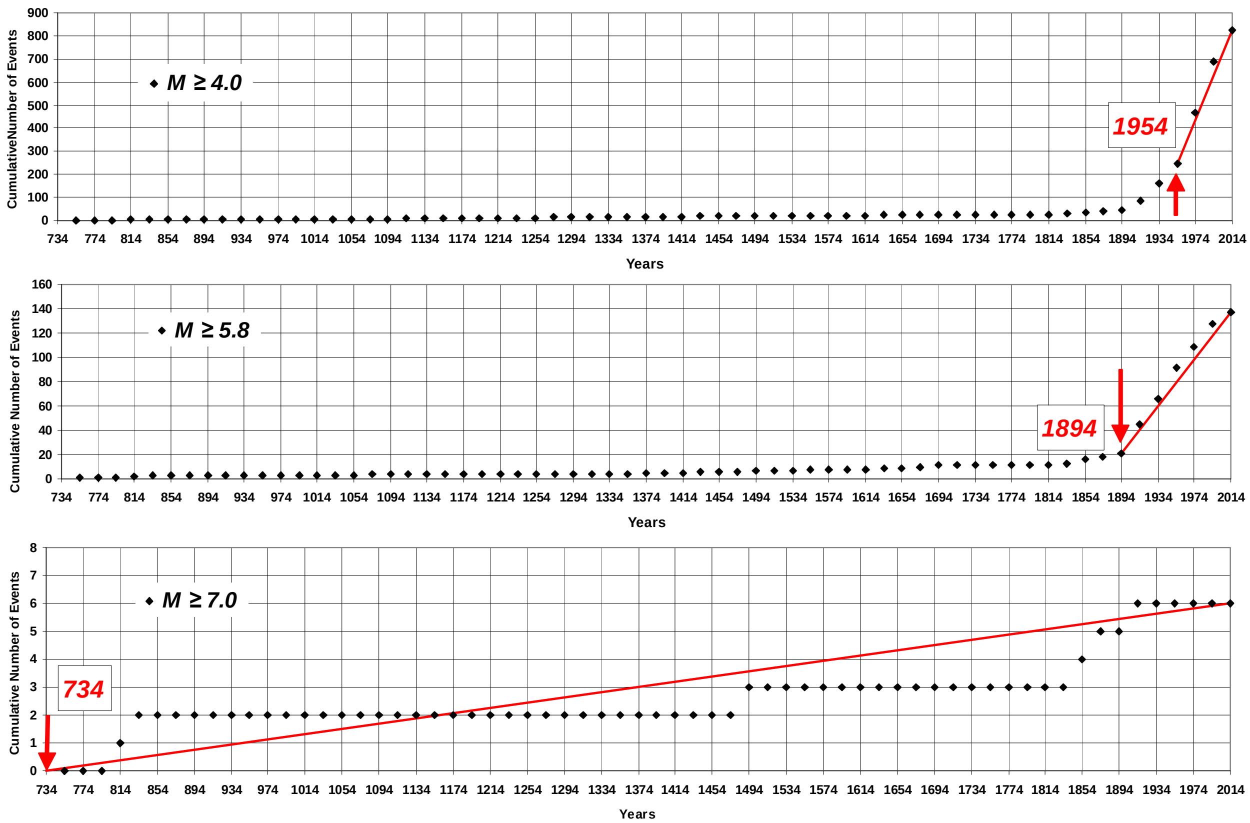

Figure 7: Visual Cumulative Method (CUVI) to determine catalogue completeness for the entire catalogue

The catalogue has been considered complete over the entire period (734–2002) for magnitudes exceeding 7, with a certain degree of conservativeness so that, large earthquakes in the early period of the catalogue that may significantly influence the recurrence computation are not neglected. Figure 7 illustrates the completeness intervals for three magnitude classes of the entire catalogue. However, associating the results of the completeness analysis of the entire catalogue to each individual seismogenic zone would be a gross approximation as the former is characterized by a marked spatial heterogeneity. The numbers of events in individual seismogenic zones vary from 7 to 279. Therefore completeness analyses have been performed separately for each seismogenic zone after sorting out events falling within individual zones.

Recurrence relationship

The seismicity of each seismogenic zone has been quantified by the standard Gutenberg-Richter recurrence relationship which postulates the existence of an exponential correlation between the mean annual rate of exceedance of an earthquake of specified magnitude and the magnitude itself. As an example of the application, Figure 8 shows the results obtained for seismogenic zones SZB2, SZB7. The values of A and b are affected by some uncertainty owing to the scatter in the results.

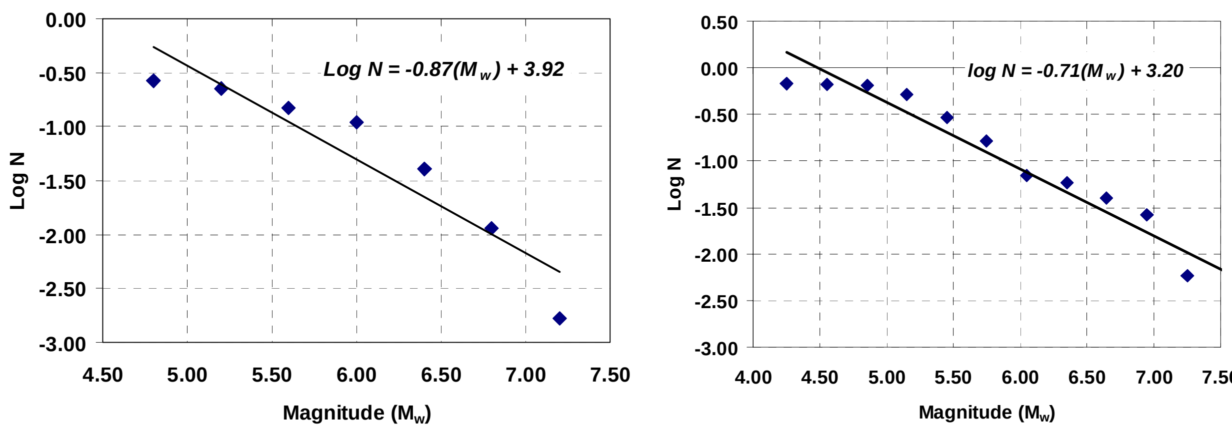

Figure 8: Frequency-magnitude recurrence relationship for SZB2 (31 events) and SZB7 (71 events)

Selection of Strong Motion Attenuation Relationships for the Hazard Assessment

Many parts of the world are devoid of strong motion records and consequently no attenuation relationships can be developed for such areas. In these cases attenuation relationships derived for zones with similar features in terms of both seismicity and structural geology, would have to be adopted. As to Afghanistan, no strong-motion records are presently available for any region of that country [Ambraseys, N.N., 2003, *written communication*]. Two recording stations that were operational in the past in *Kabul* were seismographic and not accelerographic stations [Douglas, J., 2003, *written communication*] and hence do not have any strong-motion record. This posed a severe problem as the attenuation relationships initially selected for the study could not be verified against the peak ground accelerations from real records. Therefore presence of epicenters from regions surrounding the area under study in the data set used for the derivation of an attenuation relationship formed an important criterion for the selection of a specific attenuation law. Availability of coefficients of regression for spectral ordinates for horizontal and vertical ground motion to enable definition of the uniform hazard response spectra was another vital criterion. The attenuation relations that have been used in the seismogenic zones characterized by shallow crustal events are:

- Ambraseys [6] and Ambraseys [7] developed for Europe with as many as 20 records from Iranian earthquakes for vertical and horizontal ground motion, respectively
- Abrahamson [3] developed for shallow crustal earthquakes that contains one major earthquake from Iran in the data set
- Zarè [24] developed based on the Iranian stong-motion database

Youngs [23] attenuation relationship was used for the *Hindukush* subduction source zone (for interface events). The preliminary inference of Borgia [8] that the bedrock below the alluvial deposits of the river terrace in the *Hari-rud* valley is formed by relatively unfractured, massive metamorphic rocks that crop out on the side of the valley, motivated the estimation of ground motion on rock.

Computer Code used for PSHA

CRISIS99 Version 1.017 by Ordaz [16] was the computer code used here to perform the PSHA. In accordance with the Cornell-McGuire approach to PSHA, probability of earthquake occurrence has been modeled as a Poissonian process. CRISIS99 also allows performing PSHA using the '*characteristic*' earthquake model or a hybrid '*Poissonian-characteristic*' approach. The program permits the 3D modeling of up to 200 seismic sources and 15 attenuation models simultaneously, and is supplemented with a reasonably advanced GUI.

The *Logic-Tree* Approach as Rational Means for Treating Uncertainties

Besides the scatter in attenuation relationships and recurrence relationships, hazard assessment is affected by uncertainties from other sources such as, the delineation of seismogenic sources and scenarios, their geometry, definition of M_{max} for each source zone, incompleteness of earthquake catalogues and the subjective nature of completeness analysis, errors in earthquake catalogue (location and magnitude of historical events) and the type of recurrence law used to describe the activity rate.

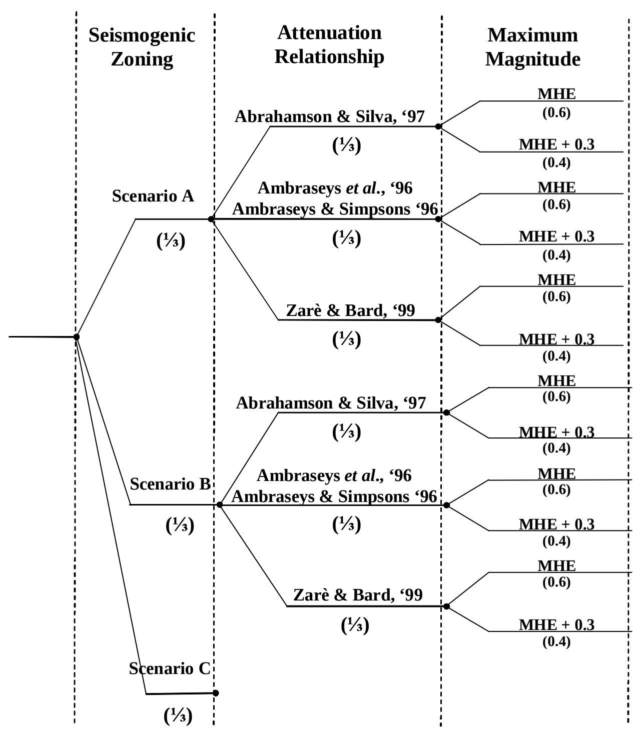

Figure 9: Logic-tree framework used in the current study (after Menon [14])

The use of a *logic-tree* device in PSHA provides an appropriate framework for explicitly handling the epistemic uncertainties that cannot be quantified statistically. It is also a very convenient way of specifying alternatives to some input parameters as well as to stipulate a degree of confidence to them. The three *controlling variables* of the *logic-tree* (see Figure 9) considered in this study are:

- *Seismogenic zoning*
- *Attenuation relationships and*
- *Maximum magnitude*

For the first variable, i.e. delineation of the seismogenic zones, there are neither specific rules nor widely accepted standards. Since the degree of uncertainty associated to models *A*, *B* and *C* is essentially the same, equal weightages have been assigned to the three scenarios (whose definition has been thoroughly discussed in the section entitled *Delineation of seismic source zones*). The three attenuation relationships considered for shallow crustal earthquakes are: Ambraseys [6] and Ambraseys [7], Abrahamson [3] and Zarè [24] (see Figure 9).
With regard to the parameter M_{max}, the main reference for its definition has been the MHE retrieved from the catalogue in each source zone. The first case considered here is with M_{max} equal to the MHE whereas the second is with M_{max} 0.3 units higher than the MHE. The corresponding weighting factors assigned are 0.6 and 0.4 for the case with M_{max} = MHE and M_{max} = MHE + 0.3, respectively. The higher weighing factor for the former is motivated by the fact that the completeness intervals of the strongest earthquakes span almost the entire length of the catalogue implying a lower possibility of MHE being exceeded.

Influence of the Hindukush Subduction Zone

The *Hindukush* deep seismic zone is characterized by an annual average of four earthquakes of magnitude greater than 5, according to USGS [19]. *Jam* is about 400 km away from the region where earthquakes of the subduction mechanism are observed. The contribution from the seismic source zones with subduction-type mechanism resulted to be negligible for every level of PGA and spectral ordinate. This conclusion is valid also for spectral ordinates at intermediate response periods corresponding to the fundamental period of vibration of the minaret (~1 second). Although the rate of attenuation of ground motion from subduction earthquakes is lower than that of shallow crustal earthquakes (Youngs [23]), from the current study it is evident that, the level of perceptibility of the subduction zone earthquakes from an engineering point of view, at *Jam* is negligible. Consequently, these seismic source zones have been excluded in the hazard analysis.

Characteristic Earthquake at *Herat*

A clustering of *eight* earthquake epicenters (M_w 4.7-5.9) close to the city of *Herat* from 849-1964 A.D. may suggest a *characteristic earthquake* scenario. However, the completeness of the catalogue (from 1869 for $M_w \geq 5.5$) and the rate of seismic activity of this area, which is clearly in accordance with that predicted by the Gutenberg-Richter recurrence law for the entire seismogenic zone, substantiate the fact that these *eight* epicenters do not suggest the occurrence of a characteristic earthquake at *Herat*. The lack of geological evidence linking the *eight* epicenters to the *Herat* fault further corroborates this conclusion.

Discussion of Results

The outputs of the PSHA in the form of relationships between the peak ground accelerations (PGA) and the annual frequency of exceedance for the three seismogenic zoning scenarios are illustrated in Figure 10. The final mean hazard curves resulting from the logic-tree algorithm for horizontal and vertical PGA are shown in Figure 11. Figure 12 reports the final PGA values and the uniform hazard spectra for horizontal spectral ordinates for return periods of 72, 224, 475 and 975 years.

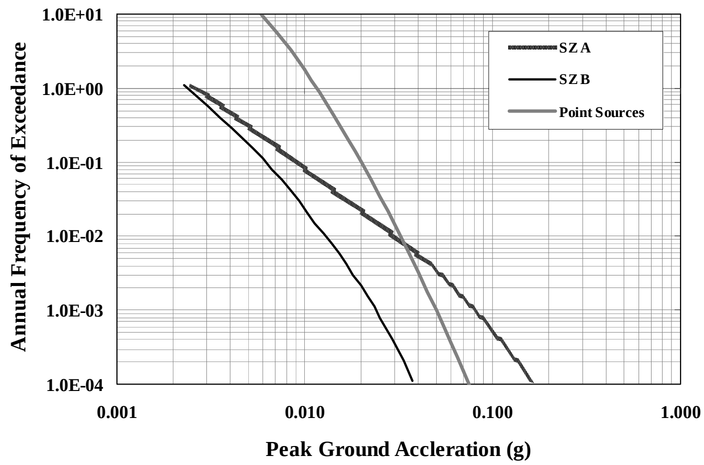

Figure 10: PGA vs. annual frequency of exceedance for the three seismogenic zoning scenarios

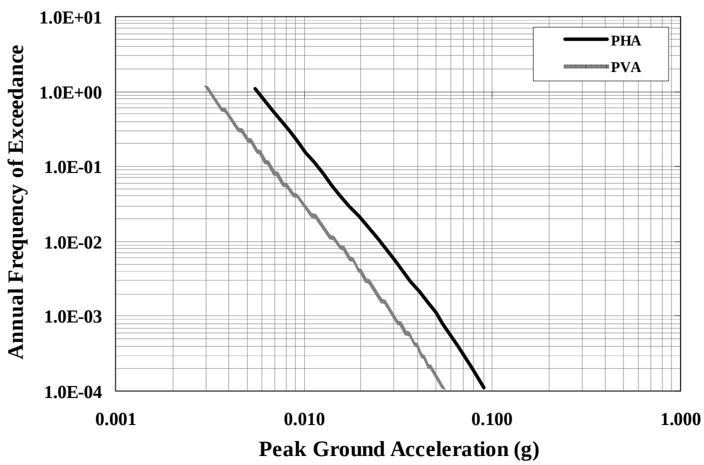

Figure 11: Horizontal and vertical PGA vs. annual frequency of exceedance at *Jam* from PSHA using the logic-tree methodology

Probability of Exceedance	T_r (years)	PGA Horizontal (g)	PGA Vertical (g)
50% probability of exceedance in 50 years	72	0.022	0.013
20% probability of exceedance in 50 years	224	0.032	0.019
10% probability of exceedance in 50 years	475	0.041	0.024
5% probability of exceedance in 50 years	975	0.050	0.030

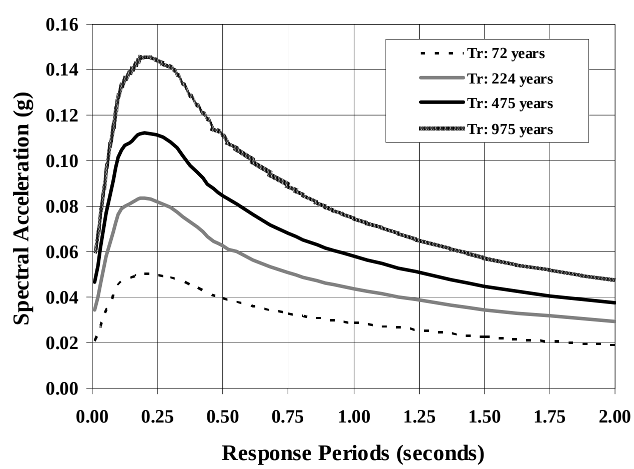

Figure 12: PGA and uniform hazard response spectra for return periods 72, 224, 475 and 975 years.

The following inferences have been drawn after evaluating the results of the PSHA:

- Seismogenic zoning based on seismotectonic data (*Scenario-A*) provides an upper bound of predictions for the hazard estimation whereas zoning based purely on observed seismicity (*Scenario-B*) forms a lower bound. The *Zone-free model* provides an upper bound for small return periods and forms a median for higher return periods. The abundance of point sources and the assumption that each of them are capable of generating a range of earthquakes from magnitude 4.0 to MHE+0.3 is, presumably the reason for this outcome.
- In *Scenario-A*, the prediction by the Ambraseys [7] attenuation relationship is an upper bound and that by the Zarè [24] relationship forms a lower bound. In *Scenario-B*, the prediction by Abrahamson [3] attenuation relationship forms an upper bound and those by Ambraseys [7] and Zarè [24] form lower bounds. In *Scenario-A*, Jam lies within SZA1; therefore potential source-site distances are very small in comparison to *Scenario-B* where the shortest source-site distance is around 200 km. The sensitivity of the attenuation relationship in the small range of source-site distances could be the reason behind the switch in the bounds of the predicted exceedance rates between the Ambraseys [7] and Abrahamson [3] relationships for *Scenarios A* and *B*.
- The effect of the maximum magnitude (M_{max}) is apparently very small for all the analyzed cases.

DETERMINISTIC SEISMIC HAZARD ASSESSMENT (DHSA) OF *JAM*

In the current study, a DSHA also has been attempted with the objective of complementing and verifying the outputs of the PSHA. As reported in Table 1, three controlling events were short-listed by identifying critical ‘magnitude-epicentral distance pairs’ relative to *Jam* (*Maximum Probable Earthquake*-MPE). The closest earthquake in the catalogue (Ambraseys [4]) is at an epicentral distance of 170 km, but no magnitude has been associated to this event rendering it deficient for the study.

An earthquake of M_w 7.4, with epicenter close to *Mazar-i-sharif* that occurred in 819 A.D. ([Ambraseys [4]) and affected a large part of northern Afghanistan could well represent the MPE at *Jam*. The seismic hazard at Jam could be reasonably represented by a horizontal PGA of 0.04g due to an earthquake of M_w 7.4 at an epicentral distance of 238 km. The corresponding vertical PGA would be 0.02g.

Associating a recurrence interval to the level of ground motion generated by the controlling event is a complicated affair, although not completely ruled out. This is practicable if well-qualified data pertaining to the selected controlling event (MPE) is available.

Table 1: Controlling events identified from the earthquake catalogue for the DSHA at *Jam*

N°	Year	Month	Day	Latitude, Longitude (°N, °E)	Magnitude (M_w)	*Epicentral Distance* (km)	Horizontal PGA (g)
1.	819	6	-	36.40, 65.40	7.4	238	**0.04**
2.	1428	-	-	35.80, 64.20	6.5	160	0.03
3.	1956	6	9	35.13, 67.48	7.4	283	0.03

CONCLUSIONS

This article illustrated the procedure and outcome of a study designed to assess the seismic hazard at the archeological site of the Minaret of *Jam* in Afghanistan. The scope of the seismic hazard assessment was the definition of the earthquake input for the structural assessment of the minaret. The seismic hazard of *Jam* has been quantified in terms of both horizontal and vertical uniform hazard response spectra associated to reference return periods: 72, 224, 475 and 975 years. The main conclusions of the seismic hazard study are recapitulated as follows:

1. The seismic hazard at *Jam* resulting from the **PSHA** is ***low*** with an expected horizontal **PGA** of **0.04g with a 10% exceedance in 50 years** (the 475-year return period event).
2. The **DSHA** approach yielded a horizontal PGA of **0.04g** which is comparable to the PGA of the 475-year return period event of the PSHA. A scenario for the ***Maximum Probable Earthquake*** (MPE) could be represented by an event with $\mathbf{M_W}$ **7.4** at an epicentral distance of **238 km** causing a horizontal **PGA of 0.04g** and a vertical PGA of about 0.02g.
3. Earthquakes from the ***Hindukush*** **subduction zone** produce negligible effects at *Jam* in terms of seismic hazard due to the strong attenuation of ground motion owing to the distance from *Jam*. This conclusion is valid for the PGA as well as for the spectral ordinates at the fundamental periods of vibration of the minaret (~ 1 sec).
4. The low seismic hazard at Jam is consistent with both the seismotectonic setting and the historical seismicity of the region. *Jam* lies in north-western Afghanistan in a zone characterized by a relative seismic quiescence. Though *Jam* is located in close proximity to the ***Herat*** **(*Hari-Rud*) fault**, a prominent strike-slip tectonic lineament in north Afghanistan, currently obtainable data appear to suggest that the geological feature is characterized by a *very low level of activity*, if any. This inference is complemented by historical seismicity dating back to 734 A.D.
5. Although, there has been no earlier attempt to evaluate the seismic hazard of *Jam*, the above conclusions are consistent with **recent works of macrozonation of Afghanistan**. The 475-year return period PGA in the region of *Jam* is in the range of 0.04g – 0.08g according to the Global Seismic Hazard Assessment Program (GSHAP) in Continental Asia by Zhang [25].

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