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Seismic hazard from instrumentally recorded, historical and simulated earthquakes: Application to the Tibet–Himalayan region

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ABSTRACT

We present a new approach to assessment of regional seismic hazard, which accounts for observed (instrumentally recorded and historic) earthquakes, as well as for seismic events simulated for a significantly longer period of time than that of observations. We apply this approach to probabilistic seismic hazard analysis (PSHA) for the Tibet–Himalayan region. The large magnitude synthetic events, which are consistent with the geophysical and geodetic data, together with the observed earthquakes are employed for the Monte-Carlo PSHA. Earthquake scenarios for hazard assessment are generated stochastically to sample the magnitude and spatial distribution of seismicity, as well as the distribution of ground motion for each seismic event. The peak ground acceleration values, which are estimated for the return period of 475 yr, show that the hazard level associated with large events in the Tibet–Himalayan region significantly increases if the long record of simulated seismicity is considered in the PSHA. The magnitude and the source location of the 2008 Wenchuan $M = 7.9$ earthquake are among the range of those described by the seismic source model accepted in our analysis. We analyze the relationship between the ground motion data obtained in the earthquake's epicentral area and the obtained PSHA estimations using a deaggregation technique. The proposed approach provides a better understanding of ground shaking due to possible large-magnitude events and could be useful for risk assessment, earthquake engineering purposes, and emergency planning.

1. Introduction

The 2011 Great East Japan (Tohoku) $M = 9.1$ earthquake as well as other recent earthquakes (e.g., the 2008 Sichuan $M = 7.9$ and the 2010 Haiti $M = 7.0$ earthquakes) have occurred in the areas predicted by the existing seismic hazard maps to be 'relatively safe' (Stein et al., 2012), that is not presenting the highest risk for Japan, China or Haiti, respectively. This caused extensive discussions related to current probabilistic seismic hazard assessments (e.g., Frankel, 2013; Geller, 2011; Gülkan, 2013; Hanks et al., 2012; Iervolino, 2013; Kerr, 2011; Kossobokov and Nekrasova, 2012; Stein et al., 2011, 2012; Stirling, 2012; Wong, 2013; Wyss and Rosset, 2013). One of the main conclusions, which can be derived from the discussion, is that the location and magnitude of future extreme[1] seismic events are still poorly known.

An extreme seismic event is a key manifestation of the lithosphere dynamics exhibiting non-linear system behavior and evolving from stability to a catastrophe over space and time (e.g., Keilis-Borok, 1990; Turcotte, 1999). Driven primarily by thermal convection in the mantle, lithosphere plates are involved in relative movement resulting in stress–strain localization and in subsequent earthquakes (e.g., Ismail-Zadeh et al., 2008). The lithosphere presents a hierarchy of blocks, where the largest blocks are the major tectonic plates. The blocks are separated by less rigid boundary zones by a factor of 10–100 thinner than the corresponding blocks (Keilis-Borok et al., 2001). The blocks and faults interact and move relatively to each other under control of lithosphere dynamics. These movements are realized through formation and subsequent healing of failures on surfaces where displacements are discontinuous as defects, slips, fractures, and faults (e.g., Ben-Zion, 2008; Rice and Ben-Zion, 1996). About a million earthquakes with magnitude greater than two are registered each year; about a thousand of them are large enough to be felt; about a hundred earthquakes cause damage, and once in a few decades an extreme seismic event occurs. The extreme events are rare (statistically speaking, they are located in the tail of the frequency–magnitude relationship) and their reoccurrence time is uncertain. Meanwhile

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[1] An extreme seismic event is defined here as an earthquake, which magnitude is above a threshold value near the upper end of the range of observed magnitudes.

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these events are most dangerous in terms of the impact on society, which is not always prepared to cope with them as evidenced by giant earthquakes (e.g., Ismail-Zadeh and Takeuchi, 2007; Cutter et al., 2015).

Seismic hazard assessment (SHA) in terms of strong ground motion parameters is based on the information about the features of earthquake ground motion excitation, seismic wave propagation (attenuation), and the regional site effect, and combines the results of seismological, geomorphological, geological, tectonic and geodynamic investigations. Two principal methods are used in seismic hazard assessment: deterministic and probabilistic. Deterministic (or scenario-based) SHA models use specified earthquake scenarios and analyze the attenuation of seismic energy with distance from this hypothetical (or historical) earthquake's hypocenter to determine the level of ground motion at a particular site. The ground motion calculations capture the effects of the local site conditions and use the available knowledge on earthquake sources and wave propagation processes. The drawback of the deterministic models is that the occurrence/frequency of the ground motion is not addressed. Probabilistic SHA (PSHA) determines the total frequency of exceeding various levels of ground motion during a specified period of time (Cornell, 1968; McGuire, 2004). The PSHA results are used in seismic hazard mapping, development of design codes, retrofit design, and financial planning of earthquake losses (e.g. Gülkan, 2013; McGuire, 2001, 2004).

Besides peculiarities of ground motion excitation and propagation, the following elements are essential in seismic hazard assessment: (i) the seismic sources, on which future earthquakes are likely to occur; (ii) the size of the possible earthquakes and the frequency, with which an earthquake is likely to occur on each source; and (iii) the distance and orientation of each source with respect to the site. The data about these elements come from instrumentally recorded earthquakes (the most reliable data source) as well as from historical records of large earthquakes, geological investigations, and geodetic measurements (e.g., Ader et al., 2012). Despite the importance of the information on historical seismicity, the data rely on reports of felt ground motions or patterns of damage, and the earthquake intensity is to be restored from these data (sometimes with significant uncertainties). Moreover the historical information is sparse in space and time, and the derivation of the magnitude, depth and quantitative characteristics of the source of the past seismic events is difficult (if not impossible). Also historical seismicity provides a little information on the future occurrences of earthquake on a fault.

Earthquakes are associated with specific faults, and large events can leave some tracks in geological records (e.g., fault scarp, displacement of soil/rock sediments at near surface depths). Although the geological indicators of large seismic events are quite important, sometimes it is difficult to reconstruct the magnitude and source location of the events from the geological data. Fault slip rates, earthquake magnitude and reoccurrence can be inferred from geological markers of fault dynamics. Average fault slip rates can be derived from cumulative displacement along the fault (calculated from displaced geological or geomorphic features) if the estimated age of the deformed soil/rocks is determined, and the rates are reliable considering that strain accumulation and release over the time period have been uniform. The fault slip rates based on geological markers differ sometimes significantly from those based on geodetic and satellite radar interferometry observations, e.g., at major faults in the Tibet–Himalayan region (Ismail-Zadeh et al., 2007).

The average fault slip rates can be constrained by the displacement of a segment of the fault for an individual rupture event measured during geological (paleoseismic) field studies. However, there are significant uncertainties in assessments of maximum displacement of a fault or its segments (e.g., Cluff and Cluff, 1984; Swan et al., 1980). Also, in many cases it is impossible to ensure whether historical seismic activity characterizes the fault activities through geological time, unless clear evidence of the sizes of past large earthquakes is available from paleoseismic studies.

There are two approaches to evaluate a maximum magnitude ($M_{\max}$) of an earthquake at a given fault: deterministic and probabilistic. The deterministic approach is based on the empirical relationships between magnitude and various tectonic and fault parameters (e.g., Wells and Coppersmith, 1994; Wyss, 1979) or the strain rate/the rate of seismic-moment release (e.g., Field et al., 1999; Stein and Hanks, 1998). In the probabilistic approach, $M_{\max}$ is estimated from earthquake catalogs using some statistical estimation procedures (e.g., Holschneider et al., 2011; Kijko, 2004; Kijko and Sellevoll, 1989, 1992; Main, 1996; Pisarenko et al., 1996, 2008). Each method for $M_{\max}$ assessment has some limitations including heterogeneities in the quality of the empirical data, completeness of data set, possible inconsistency of data representing different tectonic environments. $M_{\max}$ is unstable with respect to minor variations in earthquake catalogs and, in particular, for use with incomplete regional catalogs. Uncertainties in measured magnitudes influence the b-value in the frequency–magnitude relationship. Furthermore, it is essentially impossible to infer statistically the maximum possible earthquake magnitude in a region in terms of alternative testing with sufficient confidence from an earthquake catalog alone (Holschneider et al., 2014). Therefore, uncertainties associated with the maximum magnitude may significantly influence seismic hazard estimates (e.g., Knopoff and Kagan, 1977; Rhoades and Dowrick, 2000).

Knowledge about the reoccurrence interval between large earthquakes is also important for seismic hazard analysis. The reoccurrence time can be calculated from fault slip-rate and displacement during each event (e.g., Idriss and Archuleta, 2007; Molnar, 1979). Paleoseismic (e.g., Bollinger et al., 2014; Sapkota et al., 2013) and archeological (e.g., Marco, 2008) studies can provide additional (independent) information on the reoccurrence time. However, as the record of instrumental and historical seismicity in many earthquake-prone regions of the world is too short compared to the average recurrence time of large earthquakes, the estimates of the reoccurrence times of extreme events (based only on the catalogs) have significant uncertainties. Moreover, a practical use of the average reoccurrence interval is limited as large events may occur earlier than the time expected from a simple averaging of reoccurrence times between a few extreme events ever observed at a fault. Although time-dependent occurrence models give some estimates on the probability of occurrence of large events in some future time window, significant uncertainties do not allow determining reliably the time of the next large event.

The probabilistic seismic hazard assessments, which are based only on instrumentally recorded seismic observations and a few historical large events, have a disadvantage because these observations cover a much shorter time interval compared to the duration of the tectonic processes responsible for earthquake generation (e.g., Bilham, 2013; Soloviev and Ismail-Zadeh, 2003). Numerical modeling of realistic seismogenic processes allows generating catalogues of synthetic earthquakes covering relatively long time intervals and, therefore, providing a basis for estimates of the parameters of the earthquake occurrences and the ground shaking.

For example, the earthquakes simulated in the Sunda arc region (prior the giant seismic events happened in 2004 and 2005 in the region) showed a considerable deviation of the frequency–magnitude curve in the range of magnitudes from 8 to 9+ with respect to that for observed earthquakes. Moreover, two areas of giant earthquakes have been identified in the eastern part of the Sunda arc and in its northwestern part, where the Aceh–Sumatra M9.3 earthquake occurred in 2004 (Soloviev and Ismail-Zadeh, 2003). Simulated seismicity in the San Jacinto fault zone, California, showed the events with larger magnitude than those included in the short instrumental record. The hazard associated with the large earthquakes on the fault increases significantly, if the simulated seismicity is taken into account (Zöller and Ben-Zion, 2014).

The principal aim of this paper is to assimilate the records of simulated large seismic events into the PSHA together with observed