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Probabilistic seismic hazard analysis (PSHA) for Ethiopia and the neighboring region

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ABSTRACT

Seismic hazard calculation is carried out for the Horn of Africa region (0°–20° N and 30°–50°E) based on the probabilistic seismic hazard analysis (PSHA) method. The earthquakes catalogue data obtained from different sources were compiled, homogenized to M_w magnitude scale and declustered to remove the dependent events as required by Poisson earthquake source model. The seismotectonic map of the study area that avails from recent studies is used for area sources zonation. For assessing the seismic hazard, the study area was divided into small grids of size 0.5° × 0.5°, and the hazard parameters were calculated at the center of each of these grid cells by considering contributions from all seismic sources. Peak Ground Acceleration (PGA) corresponding to 10% and 2% probability of exceedance in 50 years were calculated for all the grid points using generic rock site with Vs = 760 m/s. Obtained values vary from 0.0 to 0.18 g and 0.0–0.35 g for 475 and 2475 return periods, respectively. The corresponding contour maps showing the spatial variation of PGA values for the two return periods are presented here. Uniform hazard response spectrum (UHRS) for 10% and 2% probability of exceedance in 50 years and hazard curves for PGA and 0.2 s spectral acceleration (Sa) all at rock site are developed for the city of Addis Ababa.

The hazard map of this study corresponding to the 475 return periods has already been used to update and produce the 3rd generation building code of Ethiopia.

1. Introduction

The Afar Depression hosts a diffused triple junction where the Red Sea, Gulf of Aden and the East African divergent plate boundaries meet. Rifting along the Red Sea, Gulf of Aden and the East African Rift initiated around 29 Ma, apparently following weakening of the Nubia, Somalia and Arabia continental lithosphere (Fig. 1) caused by the Afar plume (e.g. McQuarrie et al., 2003; Garfunkel and Beyth, 2006). Crustal accretion at the three divergent plate boundaries typically occurs via episodic dike intrusions and magma dynamics manifested through earthquake occurrence and volcanic eruptions (Wright et al., 2006; Ayele et al., 2007, 2009; Keir et al., 2009; Ebinger et al., 2010). The Arabian plate is moving away from Nubia in a northeast direction in the Red Sea at a rate varying between 5.6 and 14 mm/yr along the strike of the rift (McClusky et al., 2009). Current estimates for spreading rates in the East African rift reach 6 ± 1.5 mm/yr near the northernmost part in the Ethiopian rift (Chu and Gordon, 1999). The two oceanic rifts can be categorized as ultraslow spreading ridges from their characteristics and rate of opening (Dick et al., 2003). The notable transition from oceanic to continental prototype on dry land, in this part of the Afro-Arabian rift system makes the region a unique and natural ocean-ridge laboratory for earth scientists. This area is characterized by pronounced volcanism, which greatly influences the tectonics and geodynamics of the region that has vast environmental and social implications. The ongoing volcanic activity and earthquake hazard in Ethiopia and surrounding region poses threats to the local populations and the relatively fast growing infrastructure. However, this threat has not been given due attention, mainly because governments and concerned stakeholders give high priority to other natural hazards like drought and food security issues. In addition, the region has never experienced disastrous earthquake damage in the recent past.

Earthquakes have attracted human curiosity since ancient times, but the scientific study of earth tremors is a fairly recent attempt. Instrumental recordings of earthquakes were not made until the last quarter of the nineteenth century, and the primary mechanism

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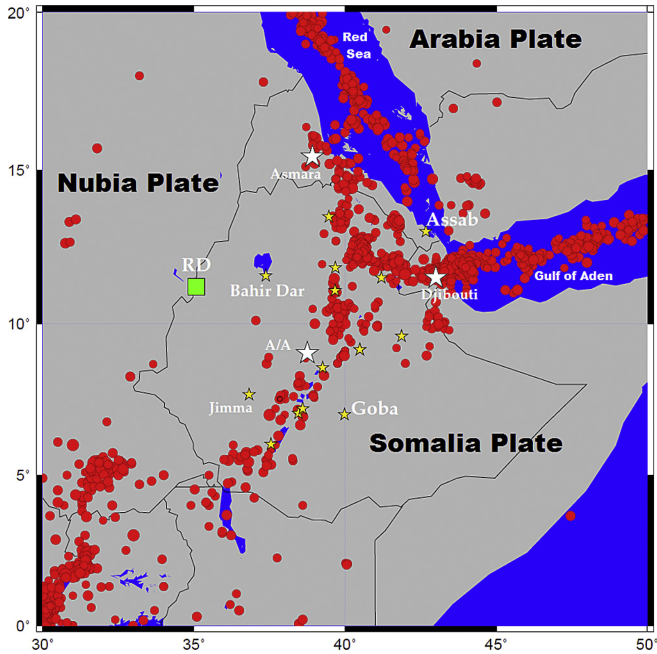

Fig. 1. Seismicity of the Horn of Africa region for the period from 1900 to 2012. The red spots are locations of earthquakes from the clustered catalogue where size of the circle is proportional with magnitude. The white stars show locations of capital cities in the region (A/A is to mean Addis Ababa) while the yellow stars show major towns in Ethiopia. There is an unintended overlap between urban centers and location of major earthquakes as most towns emerged from villages that developed over the years along the fertile rift valley for agriculture. The green square shows the location of the GERDP (Great Ethiopian Renaissance Dam Project) site.

for the generation of seismic waves, the release of accumulated strain by sudden slippage on a fault, was not widely recognized until the beginning of the twentieth century. The rise of earthquake science during the last hundred years illustrates how the field has progressed through a deep interplay among the disciplines of geology, physics, and engineering and yet we are unable to save the lives of thousands of victims during tremendous earthquake destruction where China is leading the death toll by over a million for the time period 1900 to 2016 (https://www.statista.com). Earthquakes also destroy massive and expensive infrastructures of nations that nearly paralyze the economy where Haiti is a case in point during the 2010 earthquake of magnitude 7.0 M_W (DesRoches et al., 2011). We expect the worst in the years to come as the repeat times of large magnitude earthquakes are longer than the time coverage of instrumental earthquake catalogue. Historical earthquake catalogue and earthquake geology are assisting to date in bridging data gaps and making earthquake catalogues longer but the global coverage is sparse for several reasons.

Though at times earthquake hazard maps made with reasonable estimate fail (Stein et al., 2012), they are the solution to advise decision makers and investors so as to erect earthquake resistant structures with fair balance between cost and safety. Building earthquake hazard models is a process that evolves through time with the addition of more data and improved techniques. Model inputs come from earthquake catalogues, fault maps, ground motion prediction equations and slip rates (which can be estimated geodetically or from earthquake geology). Our knowledge in all these parameters is limited in scope and is even less accurate in developing countries. Due to these limitations, hazard maps often depend crucially on the authors' preconceptions, which can lead to significant over prediction or under prediction of hazards. Probably, no other branch of engineering has to deal with as much uncertainly as earthquake engineering, e.g. recurrence of earthquakes, intensity of earthquakes, ground motion features, soil effects, topographic effects, structural properties, nonlinear dynamic behavior of structures, etc. On the other hand, the earthquake occurrence process is more complicated than the models assume which shows lack of comprehensive understanding of the complex earth processes.

The Tohoku (Japan) earthquake of March 2011 is the recent classic surprise for well prepared Japan (for mitigating earthquake risk) and the world at large where a magnitude 9.0 earthquake offshore generated a huge tsunami that overtopped sea walls, causing over 19,000 deaths and at least $200 billion damage (Normile, 2012; Stein et al., 2012), including crippling nuclear power plants. Therefore there is no perfect earthquake hazard model even in the technologically advanced nations (Stein et al., 2012). The vulnerability to earthquake risk is even higher in developing countries which was well demonstrated by the classic examples of the 2010 earthquakes in Chile and Haiti. Countries that lie along the East African rift will not be an exception and there is a fear that destructive earthquakes may hit the fast growing cities located near the rift margins in Africa. With all these challenges, one has to produce and update the hazard model once every few years and hopefully use the updated maps to revisit building codes. For example, Ethiopia is one of the fastest growing countries in sub-Saharan Africa where the capital Addis Ababa is overwhelmed by a construction boom. However, the 2nd building code is over 20 years old and considerable earthquake activity has occurred ever since which is not considered in the current effort of erecting earthquake resistant structures. On top of the massive construction underway in the capital, Addis Ababa hosts the African Union (AU) headquarters and several other United Nations (UN) organizations. Therefore, moderate seismic activity corroborated by poor awareness makes the city risk level high. This demands a regular update of the seismic hazard map and building code of the country, which also applies for many others in the region.

Gouin (1976) produced the first seismic hazard map of Ethiopia using a probabilistic approach which served as a basis for developing the first building code of Ethiopia, ESCP-1:1983. Since the production of that map, quite a large number of destructive earthquakes occurred in the country causing damage both to property and human life. Consequently, Kebede and Asfaw (1996) revised the map and their results were used as an input into the second building code of the country, EBCS-8:1995. Kebede and Van Eck (1997) revisited the seismic hazard analysis for Ethiopia and neighboring countries with no much difference from Kebede and Asfaw (1996) both in approach and results but included spectral responses for some economically important cities and towns in the region. Both analyses by Kebede and Asfaw (1996) and Kebede and Van Eck (1997) were conducted for 100 years return period (i.e. 39.35% of being exceeded in 50 years), which is not the normal practice in building code revisions. In addition M_o (threshold magnitude) and b-values were assumed to be constant in all the 8 zones considered. Another probabilistic seismic hazard assessment for the sub-Saharan Africa was conducted by Midzi et al. (1999) for 10% probability of exceedance in 50 years but the source models are smoothed for regional scale, lacking detail compared to previous studies (Kebede and Asfaw, 1996; Kebede and Van Eck, 1997). All conducted studies in the region so far preferred to use the Poisson earthquake source model but proper catalogue declustering was not done with any one of the known algorithms which resulted in overestimation of the activity rate λ and hence the PGA (Peak Ground Acceleration) values.

A new probabilistic seismic hazard analysis has therefore been undertaken in this study to determine seismic ground motion parameters for seismic design of facilities located in the Horn of Africa