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Preliminary probabilistic seismic hazard assessment for the Kingdom of Saudi Arabia based on combined areal source model: Monte Carlo approach and sensitivity analyses

Hani Mahmoud Zahran [a], Vladimir Sokolov [a,*], Salah El-Hadidiy Youssef [a,b], Wael Wassel Alraddadi [a]

[a] National Center for Earthquakes and Volcanoes, Saudi Geological Survey, P.O. Box 54141, Jeddah 21514, Saudi Arabia
[b] National Research Institute for Astronomy and Geophysics, Helwan, Cairo, Egypt

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ABSTRACT

We create and test a framework for probabilistic seismic hazard assessment for the Kingdom of Saudi Arabia using Monte Carlo simulation, recently developed models of seismic source zones and modern ground-motion prediction equations (GMPE). A generalized seismic source model containing 43 zones has been compiled and seven GMPEs were selected. The assessment was performed on the basis of 100 synthetic seismic sub-catalogs with duration 10,000 years each. The hazard curves were calculated for the nodes of $0.25^\circ \times 0.25^\circ$ grid and the hazard maps were created in terms of PGA, PGV and seismic intensity for rock sites. Preliminary sensitivity analysis was performed to determine the importance of the input parameters and the level of uncertainty introduced by the parameters. The developed framework and the results of PSHA provide a benchmark for the comprehensive seismic hazard and seismic risk analysis and up-to-date seismic hazard maps for the Kingdom of Saudi Arabia.

1. Introduction

Saudi Arabia has experienced considerable earthquakes in the past [12–15,61]. However the number of documented large earthquakes in the Arabian Peninsula is low due to sparsity of population. The seismotectonic setting around Saudi Arabia suggests that large earthquakes can occur along the Red Sea rift zones, Arabian Gulf and Zagros belt [4,6,8,39,40,45,60,64,66,78,79,82]. Design of buildings and structures in earthquake prone regions, seismic risk estimation and management, and insurance business require information related to expected seismic effect; the expected effect should be expressed in terms of earthquake ground-motion parameters, such as seismic intensity, peak amplitudes of ground motion, pseudo-spectral acceleration (PSA) and ground-motion time histories. The specification of engineering (or design) ground-motion parameters is the goal of seismic hazard analysis (SHA). It involves the quantitative estimation of ground shaking hazard at a particular site taking into account characteristics of potentially dangerous earthquakes around the site. The relation between deterministic and probabilistic approaches for SHA is a subject of much controversy [3,23,29,47–51,83] (see also discussion in EOS, 2003, 2004, 2005). The choice of approach depends on (a) the final goal: how and where to expect to use the result, and (b) the parameters of seismicity or likelihood of the worst-case event. Seismic hazard mapping, development of design codes, retrofit design, and financial planning of earthquake losses require mostly probabilistic seismic hazard assessment (PSHA) especially in the case of low-seismicity areas.

Several studies have been carried out to evaluate the seismic hazard for different regions of the Arabian Peninsula. The earliest study for the Kingdom of Saudi Arabia (KSA) was performed by Thenhaus et al. [80], in which peak ground acceleration (PGA) and velocity (PGV) were estimated for stiff soil and for 10% probability of being exceeded in 100 years using several ground motion prediction equations (GMPE). Al Haddad et al. [8,9] used these ground-motion models to estimate PGA for 10% of being exceeded in 50 years and suggested seismic zonation map for KSA to be used as a basis for seismic design. Seismic hazard for particular areas in KSA and the neighboring countries was analyzed by Deif et al. [36] (Sinai Peninsula and Gulf of Aqaba area, PGA and spectral acceleration for rock sites, single GMPE); Deif et al. [37] (area of construction of Makkah–Madinah high-speed rail, PGA and spectral acceleration for rock sites, consideration of several GMPEs in logic tree scheme); Osman [56] (Makkah area, rock sites, single

* Corresponding author. Tel.: +966 12 619 5000x2672.
E-mail address: sokolov.v@sgs.org.sa (V. Sokolov).

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GMPE); Al-Malki and Al-Amri [11] (southwestern part of KSA, PGA and spectral acceleration were estimated for bedrock and sedimentary rock sites on the basis of semi-theoretical ground-motion models obtained by stochastic simulation); Al-Arifi et al. [7] (northwestern part of KSA, PGA and spectral acceleration for rock sites, single GMPE).

Seismic hazard for the territory of United Arab Emirates (UAE) was analyzed by Abdalla and Al-Homoud [1,2] in terms of PGA for rock sites. Khan et al. [46] considered also spectral acceleration at different natural periods and used several ground-motion prediction equations in a logic tree scheme showing results of deaggregation for major cities. Sicbjornsson and Elnashai [67] performed PSHA for stiff soil for Dubai in terms of PGA and uniform hazard response spectra. Mohindra et al. [53] analyzed seismic hazard (PGA and macroseismic intensity) for Yemen and considered local soil conditions through amplification coefficients.

Probabilistic seismic hazard assessment for Arabian Peninsula was performed by Pascucci et al. [59], in which PGA and spectral acceleration at rock sites were estimated for particular cities. Uncertainties in seismic sources characteristics (earthquake recurrence, maximum magnitude) and ground motion models were incorporated using a logic-tree framework. Aldama-Bustos et al. [10] estimated seismic hazard in terms of uniform hazard spectra for rock sites in the cities of Abu Dhabi, Dubai and Ra's Al Khaymah in the UAE and showed results of deaggregation.

The conventional Cornell-McGuire approach [32,52] has been applied in almost all aforementioned studies, and the results were not suitable for seismic loss analysis for extended portfolios (cities) and spatially distributed structures (lifelines), because the conventional PSHA does not allow consideration of ground-motion correlation [24,52]. In this study we present a framework and results of tentative "current-state" PSHA analysis performed for KSA using the Monte Carlo approach. The Monte Carlo technique is a flexible and rigorous tool to characterize various uncertainties in the assessment and, at the same, it is extendable to earthquake engineering applications such as probabilistic seismic loss analysis (for examples, see Refs. [17,19]). The Monte Carlo technique is the only possible way to analyze multiple-location hazard, i.e. ground motion occurring simultaneously in several points during a particular earthquake. The analysis is very important for assessment of damage, loss and seismic risk for spatially distributed structures (lifelines, critical elements of network, important objects, urban areas, etc.) [24,35,42,43,58,71–73]. We considered recently developed models of seismic source zones for the Arabian Peninsula and surrounding regions, and modern ground-motion prediction equations. We performed preliminary sensitivity analysis to determine the importance of input parameters (seismic zonation, maximum and minimum considered magnitudes, local site conditions) and the level of uncertainty introduced to the results by the parameters. Previous PSHA studies for the region did not contain such analysis.

2. Probabilistic seismic hazard assessment – the method

In probabilistic seismic hazard analysis, seismic hazard is defined as the annual frequency of exceedance γ of different levels of ground motion. In other words, the annual frequency γ, with which ground motion parameter A exceeds a specific value A_0 at a specific site, i.e. $\gamma\,[A > A_0]$, is estimated. The return period (or more precisely "the mean return period") T_γ is defined as the reciprocal of the annual frequency of exceedance, i.e. $T_\gamma = 1/\gamma$. The term "return period" is more frequently used in seismic hazard assessments than the term "annual frequency of exceedance" due to convenience and usability. For the Poisson occurrence of earthquakes in time, the probability of observing at least one exceedance of the given ground motion level A_0 in time interval t, i.e. $P_t[A > A_0]$, is related to annual frequency γ as:

$$P_t\ [A > A_0 \,|\, t] = 1 - \exp(-\gamma[A > A_0] \times t) \tag{1}$$

For $t = 1$ year and small enough value $\gamma[A > A_0]$, the annual probability of at least one exceedance is numerically almost equal to the annual frequency of exceedance. Note, however, that these quantities have different dimensions. Thus, a PSHA result is represented by the frequency of exceedance, the probability of exceedance, and the return period. A plot showing the calculated annual frequencies of exceedance or the annual probabilities of exceedance for different levels of ground motion parameter is referred to as "hazard curve".

The hazard is estimated at a particular site taking into account characteristics (location, size and occurrence frequencies) of all potentially dangerous earthquakes around the site. The most important applications of PSHA results include seismic hazard mapping, development of design codes, retrofit design, and financial planning of earthquake losses [51].

The design seismic action is associated with a reference probability of exceedance $P_{te}\ [A > A_0]$ during finite time period te (the exposure period). Assuming a Poisson process for the ground motion occurrence, the reference probability is related to the annual frequency of exceedance γ and the exposure time as:

$$P_{te}\ [A > A_0] = 1 - \exp(-\gamma[A > A_0] \times te) \tag{2}$$

The correspondent reference return period is defined as:

$$T(A > A_0) = -te/\ln(1 - P_{te}[A > A_0]) \tag{3}$$

Several design levels may be defined in seismic codes. For example, if the ordinary structure (OS) is designed and constructed to withstand the design seismic action without local or global collapse, the recommended values for reference probability P_{OS} are 10% (0.1) in a 50-year exposure period of engineering interest, the correspondent return period is $T_{OS} = 475$ years, and the annual frequency of exceedance is hence $\boldsymbol{\gamma_{OS}} = 0.002105$. Note that for essential or hazardous facilities (EHF) the collapse prevention requirement may correspond to $P_{EHF} = 2\%$ (0.02) in a 50-year exposure period of engineering interest, the return period $T_{EHF} = 2475$ years, and the annual frequency of exceedance is $\boldsymbol{\gamma_{OS}} = 0.000404$. The reference probability 2% in a 50-year exposure period is also applied for ordinary structures in low-seismicity regions. For safely critical facilities (SCF, e.g. nuclear and defense-related facilities) $P_{NCR\_SFC} = 0.5\%$ (0.005) in a 50-year exposure period (or 1% in 100-year) and return period $T_{NCR\_SFC} = 9475$ years. The adopted probability level is related to regional seismicity and historical progress of seismic design requirements.

2.1. Monte-Carlo approach for probabilistic seismic hazard assessment

In recent decades, Monte Carlo simulation is frequently used in PSHA as an alternative to conventional numerical integration (so-called Cornell-McGuire PSHA) [17,19,38,54,55,71,84]. The calculation steps are straightforward and intuitive: simulating earthquake location, generating earthquake magnitude and fault dimensions, and then estimating ground motion parameters for given earthquake characteristics. Simple statistical data analysis is carried out next to develop seismic hazard curves. Through multiple repetitions of this process, additional uncertainties regarding different source models, uncertain maximum magnitude and parameters of the Gutenberg–Richter relationships and choice of GMPEs can be easily incorporated by treatment of epistemic and aleatory uncertainties as being equivalent. In numerical integration, by contrast,