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Probabilistic characterization of seismic ground deformation due to tectonic fault movements

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ABSTRACT

Tectonic ground deformations in the near-fault region cause major damage to buildings and infrastructure. To characterize ground deformation demands on structures, a novel stochastic approach to evaluate the ground deformations of tectonic origin is developed by combining probabilistic models of earthquake source parameters, synthetic earthquake slip models, and Okada equations for calculating the deformation field due to a fault movement. The output of the method is the probability distribution of ground deformations at a single location or differential ground deformations between two locations. The derived probabilistic models can be employed as input to advanced structural models and analyses. The method is illustrated for the 16 April 2016 Kumamoto earthquake in Japan. By comparing simulated ground deformations with observed deformations at multiple sites, a set of refined source models is first derived and then used to investigate the detailed earthquake characteristics of the event and to develop probability distributions of tectonic ground deformations at target sites.

1. Introduction

Movement of a fault triggers various effects on the ground, such as strong shaking and permanent deformation, and causes major destruction to buildings and infrastructure. In a near-fault region, both strong shaking and permanent ground deformation are strongly influenced by the characteristics of the fault movement, such as type of faulting (strike-slip, normal, and reverse) and slip distribution of earthquake rupture. The near-fault ground motions generate so-called killer-pulses [1] and are particularly damaging to structures [2]. Whereas careful seismic design considerations are needed when linear civil structures are subjected to large tectonic deformations [3–5]. On occasion, fault rupture reaches the ground surface and differential movement of the ground can be in the order of several meters to several tens of meters, depending on the earthquake characteristics, local site conditions, and various other factors, including earthquake-triggered settlement and sliding of soil [6,7]. Generally, the effects of the fault movement appear over extended areas along a fault with distributed ground deformation [4,8].

Predicting seismic ground deformations due to an earthquake has been conventionally carried out using empirical ground motion models [9]. Empirical ground motion models evaluate the amplitude of peak ground displacement as a function of earthquake magnitude, source-to-site distance, and site condition. Uncertainty of the estimation is characterized by a so-called logarithmic standard deviation (or sigma). However, such conventional methods are faced with two difficulties. Firstly, in the near-fault region, estimating permanent ground deformations from observed accelerograms is not a simple task; careful baseline correction of the acceleration data is of critical importance [10,11]. Secondly, observed ground motion data are scarce in the near-fault region and the number of ground motion data that are usable for developing empirical ground motion models decreases drastically with longer spectral periods of ground motion intensity measures [12]. Moreover, empirical ground motion models cannot be applied directly to evaluate ground deformations at multiple nearby locations simultaneously, because spatial correlation models of ground deformations are not usually available [13]. In other words, conventional prediction models have been derived for a single site and spatial dependence of the seismic effects, which is important in evaluating differential ground deformations at two locations, is not fully characterized.

In light of preceding limitations of current tools for predicting spatially distributed ground deformation fields, it is necessary to develop an alternative approach. One way is to implement so-called Okada equations [14] to analytically compute ground deformations due to tectonic fault movements in an elastic half-space. Despite simplicity, Okada equations have been employed in various fields, including geodesy, volcanology, and tsunami modeling [15,16]. An important advantage of using Okada formulae is that the spatial field of ground deformations can be simulated and thus can be used for evaluating differential ground deformations between two locations. Input

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information of Okada equations is an earthquake rupture model that is defined in terms of source parameters, such as fault geometry and slip distribution. For a given earthquake scenario (e.g. earthquake magnitude and faulting type), source parameters can be estimated using empirical scaling relationships [17–22]. To capture the uncertainty of earthquake rupture, a stochastic synthesis method of earthquake slip distribution [23–25] can be adopted. It is highlighted that accounting for variability of earthquake slip is particularly important for evaluating near-fault ground motions and deformations. The requirements for capturing uncertainties of both geometrical parameters and earthquake slip distributions narrow the choice of applicable scaling relationships into those by [22]. This is because other equations are mainly focused upon geometrical parameters only, while the relationships developed by [22] are applicable to earthquake source parameters that specify the key features of slip heterogeneity over a fault plane.

This study develops a novel approach to characterize the ground deformations of tectonic origin probabilistically. Key components of the integrated method include: (i) probabilistic models of earthquake source parameters [22], (ii) stochastic synthesis of earthquake slip [25], and (iii) Okada equations [14,16] for calculating the deformation field due to a fault movement. The output of the method is the probability distribution of ground deformations at a single location or the probability distribution of differential ground deformations between two locations. The derived probabilistic models can be employed as input to advanced structural models and analyses (e.g. reliability analysis of a bridge subjected to differential ground deformations). In this study, the method is illustrated by focusing on the 16 April 2016 Kumamoto earthquake in Japan. This earthquake registered the moment magnitude (M_w) of 7.0 and was of a right-lateral strike-slip type. It struck rural areas of Kumamoto Prefecture in Kyushu Island of Japan and caused major destruction to buildings and infrastructure in the near-fault region [26]. Notably, the surface rupture was observed at many locations with horizontal dislocations exceeding 2 m at several locations [8,27]. Furthermore, for this event, several inverted source models have been developed [28,29], and geophysical observations, such as strong motion data [26], GPS deformation [30], and InSAR satellite images [8,31], are available. In the main part of the results of this study, numerous stochastic slip distributions having heterogeneous slips are generated based on the scaling relationships and stochastic synthesis method to identify a set of earthquake slip distributions with a better fit with near-fault GPS observations and strong motion data than the uniform-slip source model developed by the Geospatial Institute of Japan (GSI). The refined set of the source models can be used to develop the probability distribution of tectonic ground deformations at sites of interest. Finally, in a case-study application, sites near the Aso Bridge, which had collapsed due to the Kumamoto earthquake, will be focused upon, noting that the Aso Bridge is very near (within 0.1 km) from the fault rupture observed in the post-earthquake fieldwork [26,27] and from the fault strike of the causative Futagawa Fault. The illustration of the methodology will be followed by key conclusions from this study.

2. Estimating tectonic ground deformation through stochastic earthquake source modeling

2.1. Methodology

A procedure to evaluate the probabilistic characteristics of tectonic ground deformations due to an earthquake is developed in this section. The method is comprised of four steps: (i) definition of an earthquake scenario, (ii) stochastic synthesis of earthquake source models for the specified scenario, (iii) estimation of ground deformations at locations of interest, and (iv) post-processing of ground deformation results. A computational procedure is based on Monte Carlo simulation and is illustrated in Fig. 1. The main idea of the method is straightforward. For a specified target scenario (i.e. step (i)), numerous earthquake sources are generated stochastically based on seismological theories and models (i.e. step (ii)) and corresponding ground deformation fields are evaluated using Okada formulae (i.e. step (iii)). By adopting a subset of synthesized source models and deformation fields according to some acceptance criteria, probabilistic distributions of ground deformations can be characterized (i.e. step (iv)).

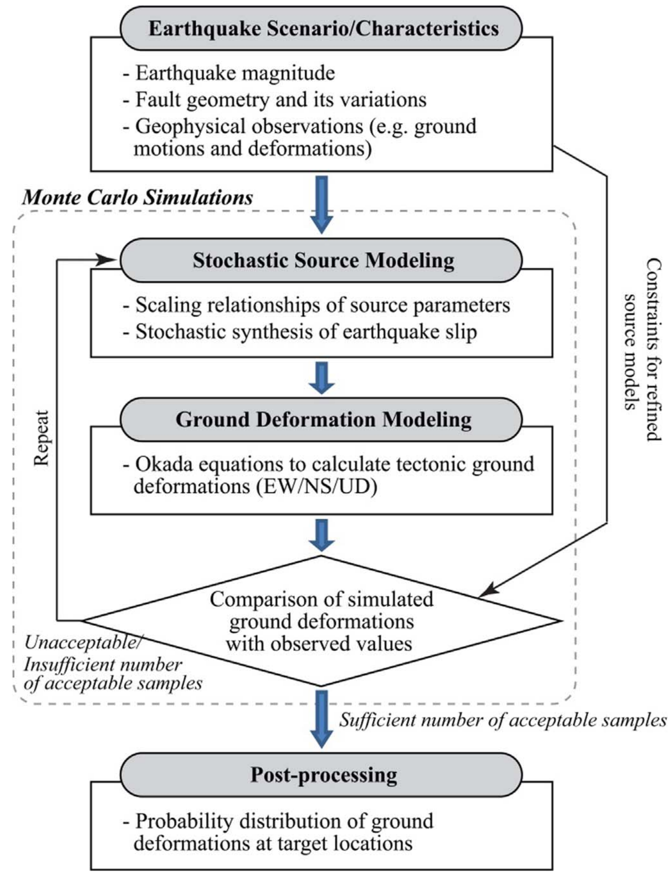

Fig. 1. Stochastic earthquake source modeling procedure for estimating tectonic ground deformations.

It is important to highlight that two types of investigations can be carried out using the stochastic procedure for estimating tectonic ground deformations outlined in Fig. 1. One way is to apply to a general forecasting situation, while the other is to apply to a retrospective case study. The former is applicable to situations where general seismological/geological information is available to define an earthquake scenario of interest but without specific observations. In this case, simulated stochastic sources and resulting ground deformations (i.e. steps (ii) and (iii)) are constrained on existing geological and seismological models (e.g. fault geometry based on regional geological and geomorphological investigations and scaling relationships of earthquake source parameters). For the latter case, when geophysical (field) observations are available for a specific earthquake, predictions based on the stochastic source models can be refined by comparing model predictions with the observations; source models that produce poor match with the observations may be discarded, while many more models that are in closer agreement with the observations can be generated. The selection criterion can be determined based on existing (crude/preliminary) benchmark earthquake source models and some other seismological and geological information. Essentially, the latter approach is equivalent to seismic source inversion [32]. From the perspective of inverse problems, the proposed method attempts to find a set of refined source models, rather than a single best model [33,34], that produce better predictions of geophysical quantities of interest. A search mechanism of the proposed method differs from conventional gradient-based methods