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NOTES AND CORRESPONDENCE

A Short Term Seismic Hazard Assessment in Christchurch, New Zealand, After the M 7.1, 4 September 2010 Darfield Earthquake: An Application of a Smoothing Kernel and Rate-and-State Friction Model

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ABSTRACT

The M_w 6.3, 21 February 2011 Christchurch, New Zealand, earthquake is regarded as an aftershock of the M 7.1, 4 September 2010 Darfield earthquake. However, it caused severe damage in the downtown Christchurch. Such a circumstance points out the importance of an aftershock sequence in seismic hazard evaluation and suggests the re-evaluation of a seismic hazard immediately after a large earthquake occurrence. For this purpose, we propose a probabilistic seismic hazard assessment (PSHA), which takes the disturbance of a short-term seismicity rate into account and can be easily applied in comparison with the classical PSHA. In our approach, the treatment of the background seismicity rate is the same as in the zoneless approach, which considers a bandwidth function as a smoothing Kernel in neighboring region of earthquakes. The rate-and-state friction model imparted by the Coulomb stress change of large earthquakes is used to calculate the fault-interaction-based disturbance in seismicity rate for PSHA. We apply this approach to evaluate the seismic hazard in Christchurch after the occurrence of the M 7.1, 4 September 2010 Darfield earthquake. Results show an increase of seismic hazards due to the stress increase in the region around the rupture plane, which extended to Christchurch. This provides a suitable basis for the application of a time-dependent PSHA using updating earthquake information.

Key words: PSHA, Smoothing Kernel function, Coulomb stress change, Rate-and-state friction model, Christchurch

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1. INTRODUCTION

The city of Christchurch is the largest city on the South Island of New Zealand and is the second-largest urban area in the country. Since few active faults in its vicinity were identified formerly (Stirling et al. 2002), previous studies (Smith and Berryman 1986; Stirling et al. 1998, 2002, 2008) concluded a low seismic hazard. Surprisingly, the M 7.1, 4 September 2010 Darfield earthquake, 40 km west of Christchurch, caused the largest peak ground acceleration (PGA) of 0.3 g in Christchurch as recorded by GeoNet (http://www.geonet.org.nz/earthquake/historic-earthquakes/top-nz/quake-13.html). On February 21st, 2011, the M_w 6.3 Christchurch earthquake took place 40 km away from the epicenter of the Darfield earthquake. According to the spatial and temporal relations, the Christchurch earthquake can be thought of as an aftershock in the Darfield sequence. However, a larger PGA of 1.88 g was recorded than that of the mainshock in downtown Christchurch due to the characteristics of the earthquake, such as, close proximity to the city, directivity, high fault strength, a slapdown phase, and hanging wall effect. The Darfield sequence case explores the importance of aftershocks to seismic hazard evaluation.

As demonstrated by the Darfield sequence, it is necessary to re-evaluate the seismic hazard immediately after a

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large earthquake. However, up to the present, none of the PSHA approaches which have been proposed fully fit for this purpose. For example, the classical PSHA approach (Cornell 1968; McGuire 1976) requires the definition of seismic sources, such as the geometry of each seismic source zone, maximum possible magnitudes, and recurrence time of earthquakes. Based on this approach, the evaluation of seismic hazard requires some subjective judgment that is usually different for various studies. The process is time-consuming. Further, in order to evaluate the recurrence time in the form of the Gutenberg-Richter law, only characteristic events are considered; thus, seismic hazards resulting from aftershock sequences cannot be evaluated through this approach.

In consideration of the complicated application of the classical PSHA approach, two zoneless approaches were developed by Frankel (1995) and Woo (1996). These approaches present the background seismicity density rate simply through smoothing Kernels; in other words, the tectonic constraints are not incorporated. However, they do not consider the short-term seismicity rate disturbance. It is difficult to illustrate the distribution of an aftershock sequence accurately.

In order to evaluate the seismicity rate disturbance by the latest large earthquakes, a seismicity rate model with a time-dependent feature should be considered. At present, some of the pure statistical or physical prevision models, which fulfill the requirement, have been proposed: STEP (Short-term Earthquake Probability, http://earthquake.usgs.gov/eqcenter/step/), EEPAS (Every Earthquake a Precursor According to Scale, Rhoades and Gerstenberger 2009), PPE (proximity to past earthquakes, Jackson and Kagan 1999), ETAS (time-space epidemic type aftershock sequence model, Kagan and Knopoff 1981), and rate-and-state friction model (Dieterich 1994).

Since this study does not aim at a comparison of the PSHA results by different approaches, we restrict ourselves and apply only one assessment tool. For a short-term seismicity rate disturbance, we consider the physics-based rate-and-state friction model since we can not only describe the earthquake empirically, but also delve into the physical mechanisms that drive it. The treatment of the background seismicity rate follows the zoneless approach by Woo (1996). We apply this approach to evaluate seismic hazard in Christchurch after the 2010 Darfield earthquake. The change of seismic hazard potential in Christchurch will be discussed in this study.

2. METHODOLOGY AND RESULTS

The background seismicity density rate, short-term seismicity rate change, and ground motion prediction equation (GMPE) are important factors in PSHA. Here, we will demonstrate how we evaluate the background seismicity density rate acquired by a Kernel function and seismic catalog, short-term seismicity rate change model by the rate-and-state friction model, and seismic hazard assessment by introducing path effect and site amplification through GMPEs. Correspondingly, an application for the Christchurch region will be presented.

2.1 Background Seismicity Rate

The first step of our approach is to build up a data set of the background seismicity density rate. The estimation of a seismicity density rate follows the zoneless approach offered by Woo (1996). It is based on the Kernel function [Eq. (3) by Chan et al. (2010)] defined by Vere-Jones (1992). The Kernel function is a function of the bandwidth function, in form of *c*- and *d*-values [Eq. (4) by Chan et al. (2010)], which is defined as the distance between two events as an exponential function of magnitude. By counting contribution of each earthquake in a complete catalog, the background seismicity density rate can be determined.

The GeoNet earthquake catalog (http://magma.geonet.org.nz/resources/quakesearch/) from 1846 to 2010 is used in this study and provides a list of events from both historical and instrumental records. We calculated the magnitudes of completeness (M_c) for different time periods using the ZMAP program (Wiemer 2001). We found that the M_c between 1840 - 1939, 1940 - 1975, and after 1976 are 6.0, 4.0, and 3.0, respectively. The *c*- and *d*-values in the bandwidth function are 0.0659 and 1.0362, respectively, which are acquired through regression from the earthquake catalog. Accordingly, we generate the background seismicity density rate (Fig. 1a), which shows a high seismicity density rate in the northwestern corner of the study region due to the Alpine fault, which is a transform boundary between the Pacific Plate and the Indo-Australian Plate. Near the rupture plane of the Darfield mainshock as well as the epicenter of the Christchurch earthquake, the background rates are relatively low. Such a background rate cannot properly explain the behavior of the Darfield sequence. Thus, more consideration for the short-term seismicity rate disturbance imparted by the Darfield mainshock is required.

2.2 Short-Term Seismicity Rate Change

In this study, the short-term seismicity rate change is constructed using the rate-and-state friction model (Dieterich 1994) and implementing the change of Coulomb failure stress (ΔCFS) factor. For the purpose of the ΔCFS calculation immediately after a large earthquake, it is desirable to suggest simplest and most reliable strategy. Thus, we follow the two assumptions for the ΔCFS calculation proposed by Catalli and Chan (2012): (1) the maximum ΔCFS within the seismogenic zone; (2) and, the ΔCFS resolved on spatially variable receiver faults.

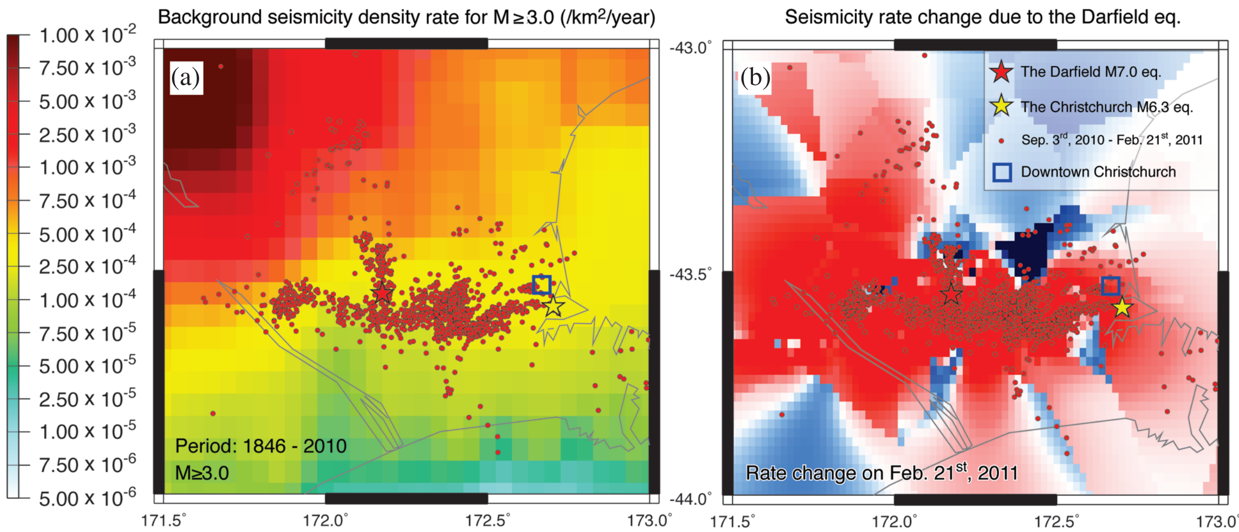

Fig. 1. (a) Distribution of the background seismicity density rate for M ≥ 3.0 acquired from the catalog dating from 1846 to the 2010 Darfield earthquake. (b) Distribution of the short-term seismicity rate change right before the Christchurch earthquake according to the rate-and-state friction model imparted by the Darfield earthquake.

To calculate the ΔCFS for the Darfield earthquake, we consider the spatial slip dislocation model acquired by G. Hayes (http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010atbj/finite_fault.php), inverted from teleseismic broadband waveforms. The model is defined by 416 slip patches with a variable rake on an E-W striking near-vertical plane. In this study, a fixed effective friction coefficient is assumed to be 0.4 follows previous studies (Chan and Ma 2004; Ma et al. 2005; Chan and Stein 2009). According to the focal depths of the earthquakes in this region, the seismogenic zone is assumed to be at a depth of between 0 and 20 km. We assume a spatially variable receiver fault for each calculation cell according to the nearest reference focal mechanism from the GeoNET CMT catalog. The ΔCFS imparted by the Darfield earthquake shows that the stress is enhanced in a region around the ruptured plane and extended to Christchurch, where there are many consequent earthquakes include the Christchurch earthquake (Fig. 2). In the region where stress is reduced, by contrast, few events took place.

In order to quantify the impact of ΔCFS on the seismicity rate, we introduce the rate-and-state friction model presented by Dieterich (1994). In this study, $A\sigma$, a parameter set of the rate-and-state friction model, is assumed to be 0.4 bars, which is in accordance with physically reasonable ranges found by many authors and applied in different regions (Toda and Stein 2002; Toda et al. 2005; Catalli et al. 2008). The duration of aftershock sequences is assumed to be a function of the mainshock magnitude as proposed by Burkhard and Grünthal (2009) and Grünthal et al. (2009).

Through the rate-and-state friction model (Fig. 1b), seismicity rate change can be quantified that rate increases in the region where ΔCFS is enhanced and vice versa (Fig. 2). This rate change model shows a good agreement with the distribution of the Darfield sequence. This result emphasizes the importance of a short-term rate change in seismic hazard assessment. Accordingly, we evaluate the PSHA in Christchurch based on both the background seismicity density rate and short-term rate change and then judge the modification of the seismic hazard after the Darfield earthquake.

2.3 PSHA in Christchurch

A PSHA requires, with respect to the use of GMPE, a consideration of the differences of attenuation behaviors for path and site effects. Since this study does not intend to consider the full epistemic uncertainties usually contained in a PSHA, we restrict ourselves and apply one GMPE for describing crustal wave propagation. The GMPE by Abrahamson and Silva (1997) is used due to adequate congruency attenuation behavior in New Zealand (McVerry et al. 2000).

The seismic hazard in Christchurch prior to the 2010 Darfield earthquake and 2011 Christchurch earthquake are compared and represented as the response spectrum for the probability of 2.1‰ (Fig. 3). Inferred from the background seismicity density rate (Fig. 1a), the resulting spectrum represents a low hazard due to infrequent seismicity activity near Christchurch before 2010 (the grey dashed line in Fig. 3). Taking the short-term seismicity rate perturbation imparted by the Darfield earthquake (Fig. 1b) into consideration, the seismic hazard right before the Christchurch earthquake is evaluated (black solid line in Fig. 3). Compared with those inferred from the background hazard, a significant higher hazard is found especially for the shorter

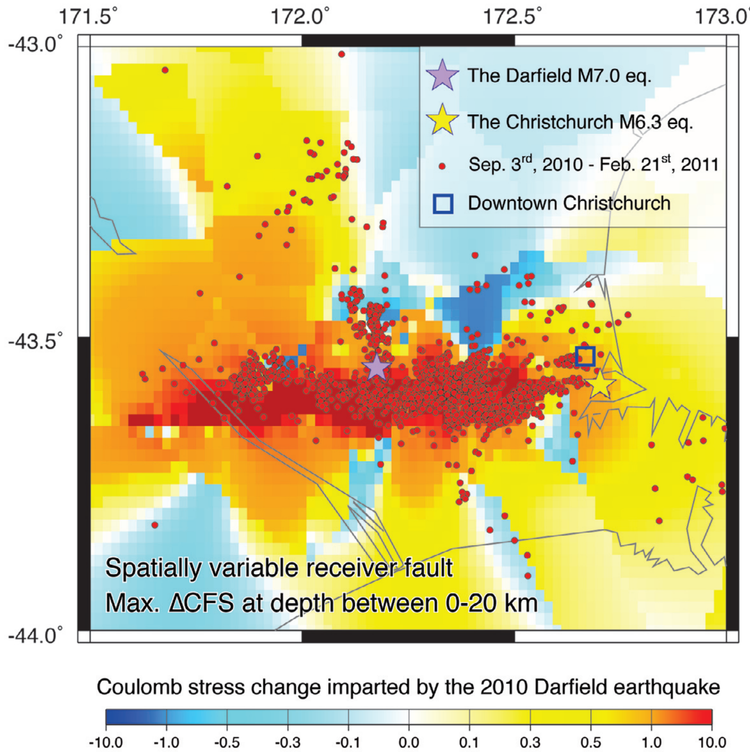

Fig. 2. The Maximum Coulomb stress change imparted by the Darfield coseismic slip among the seismogenic zone. The stress is resolved on spatially variable receiver faults, which is assumed to be the nearest reference focal mechanism from the GeoNET CMT catalog.

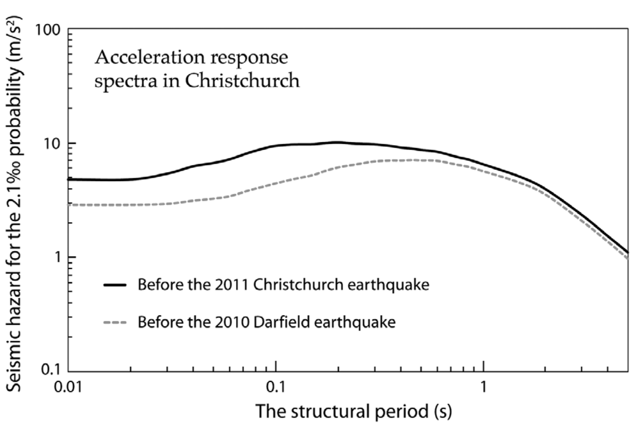

Fig. 3. The response spectrum in Christchurch for the probability of 2.1‰ as a function of structural period before the Darfield earthquake (grey dashed line) and right before the Christchurch earthquake (black solid line).

structural period. Note that more than twice the acceleration is expected during the structural period in between the 0.05 and 0.12 seconds. Figure 4 shows the seismic hazard curves before and after the 2010 Darfield earthquake. Obviously, after the 2010 Darfield earthquake the seismic hazard is higher than before. Results show that the probability of exceedance as a function of ground motion level in Christchurch prior to the 2010 Darfield and the 2011 Christchurch earthquakes. It is worth noting that more than twice the acceleration is expected for a probability of 10%.

The 2010 Darfield earthquake is the only large event ever recorded in the Christchurch region. Due to lack of reliable information on background seismicity, it is difficult to propose a long-term seismic hazard map. Thus, it is important to consider time-dependency for the application of PSHA in this region. By considering short-term seismicity rate perturbation by previous events, our methodology may fit the requirement.

3. DISCUSSION

3.1 Comparison to the Classical PSHA Approach

Application of the classical PSHA approaches by Cornell (1968) and McGuire (1976) requires a knowledge of the properties of seismic source zones, which is acquired by some subjective judgments that may be different for various studies. The process is laborious. Here, only the earthquake catalog is the input for the background seismicity rate in our approach. Despite the use of few considerations, the method denotes similar hazards as those evaluations revealed by the classical approach. We obtain the seismic hazard of 3 m s^{-2} for a short structural period (> 0.06 second). This result is similar as those by previous studies (Smith and Berryman 1986; Stirling et al. 1998, 2002). In addition, the seismic hazard of 6 m s^{-2} for the structural period of 0.2 second is also similar as the result by Stirling et al. (2002).

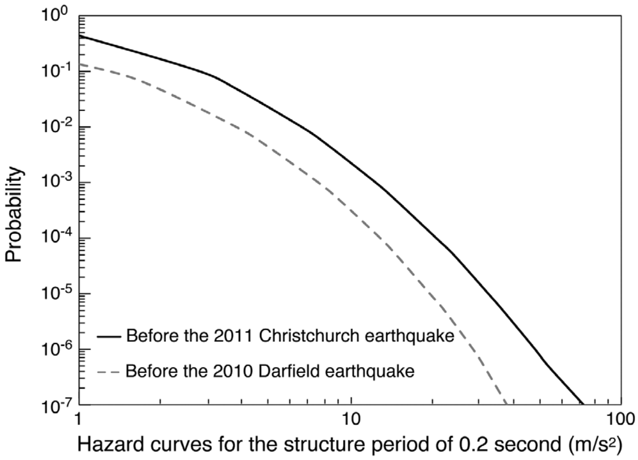

Fig. 4. The probability of exceedance as a function of hazard curves for the structural period of 0.2 seconds before the Darfield earthquake (grey dashed line) and right before the Christchurch earthquake (black solid line).

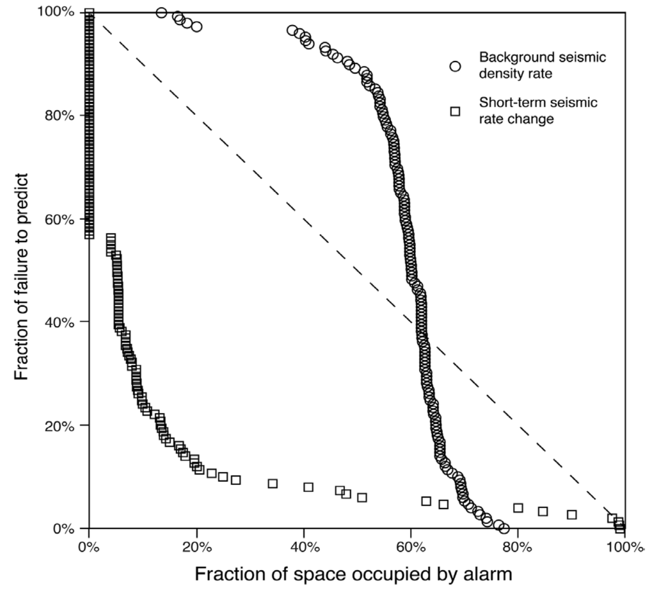

Fig. 5. Molchan diagram investigating the correlation between seismicity density rate models and the seismicity observation between occurrence of the Darfield and Christchurch earthquakes. Circles represent the correlation with the background seismicity density rate; rectangles represent the correlation with the short-term seismicity rate change according to the rate-and-state friction model.

3.2 Feasibility of Seismicity Rate Models

An accurate seismicity density rate plays a key factor in obtaining a reliable PSHA. In this study, we introduce the background seismicity density rate and the short-term rate change. To validate their feasibility statistically, we compare them with the distribution of earthquakes in the period in between the 2010 Darfield and the 2011 Christchurch earthquakes using the Molchan diagram. This diagram was first proposed by Molchan (1990, 1991) and is described in detail by Chan et al. (2010). The result from the Molchan diagram shows that the behavior of the Darfield sequence cannot be described accurately by the background seismicity density rate (circles in Fig. 5). The background seismicity density rate model implies a higher rate on the Hope Fault in the north-western study region due to the Alpine fault; conversely, there is a lower earthquake potential near the rupture plane of the Darfield mainshock (Fig. 1a). As outlined, the short-term rate change represents a significantly better correlation in the plot of the Molchan diagram (rectangles in Fig. 5). In this situation, 94% of the Darfield sequence occurred within the top 50% seismicity rate increase region.

4. CONCLUSIONS

For the classical PSHA approach (Cornell 1968; McGuire 1976), some assumptions and information for seismic source zones are required. To obtain such information is highly subjective and time-consuming. Thus, following seismic hazards as a result of a large earthquake cannot be evaluated rapidly. In this study, we introduced a zoneless approach and a rate-and-state friction model to evaluate PSHA imparted by background seismicity rate and short-term rate change, respectively. For our approach using minor model assumptions, our method provides a suitable basis for this need. The concept of near real-time and updating seismic hazard assessment will be a benefit to society in the future.

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