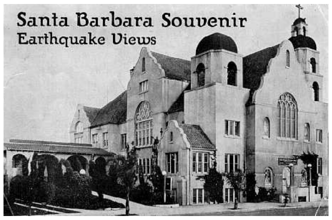

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ESTIMATION OF SLIP SCENARIOS FOR MEGATHRUST EARTHQUAKES: A CASE STUDY FOR PERU

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ABSTRACT

The recent 2011 Tohoku-oki earthquake occurred in a region where giant megathrust earthquakes were not expected. This earthquake proved the difficulty to assess seismic hazard mainly based on information from historical earthquakes. In this study we propose a methodology to estimate the slip distribution of megathrust earthquakes based on a model of interseismic coupling (ISC) distribution in subduction margins as well as information of historical earthquakes, and apply the method to the Central Andes region in Peru. The slip model obtained from geodetic data represents the large scale features of asperities within the megathrust, which is appropriate for simulation of long period waves and tsunami modelling. For the simulation of a broadband strong ground motion it becomes necessary to introduce small scale complexities to the source slip to be able to simulate high frequency ground motions. To achieve this purpose we propose a "broadband" source model in which large scale features of the model are constructed from our geodetic scenario slip, and the small scale heterogeneities are obtained from a spatially correlated random slip model. The good agreement between the power spectral density (PSD) of our geodetic slip model, and the PSD of a slip model of the 2010 Maule earthquake, suggests that our methodology can be appropriate to typify megathrust earthquakes.

INTRODUCTION

Recent mega-earthquakes in Sumatra (2004), Chile (2010) and Japan (2011) have highlighted the enormous hazard associated with these giant subduction events. In particular the 2010 Tohoku-oki earthquake proved the difficulty to assess seismic hazard mainly based on information from historical earthquakes. Due to the limited span of earthquake catalogues, other source of information such as geological or geodetic data might be considered for hazard assessment of future mega-earthquakes. In recent years the development of GPS and SAR interferometry is making possible to measure the strain build up associated with plate convergence in many earthquake prone regions around the world (Chlieh et al., 2008, Hashimoto et al. 2009, and Perfettini et al. 2010). Recent studies have suggested that subducting plates are either locked or creeping aseismically, and that a patchwork of locked or coupled regions during the interseismic period may be related with asperities of earthquakes (Moreno et al. 2010). In this study we propose a methodology for seismic hazard estimation of megathrust earthquakes based on a model of interseismic coupling (ISC) distribution of subduction zones as well as information of historical earthquakes, and apply the method to the Central Andes region in Peru.

Central Andes in Peru is a very active seismic region characterized by the fast subduction of the Nazca plate beneath the South

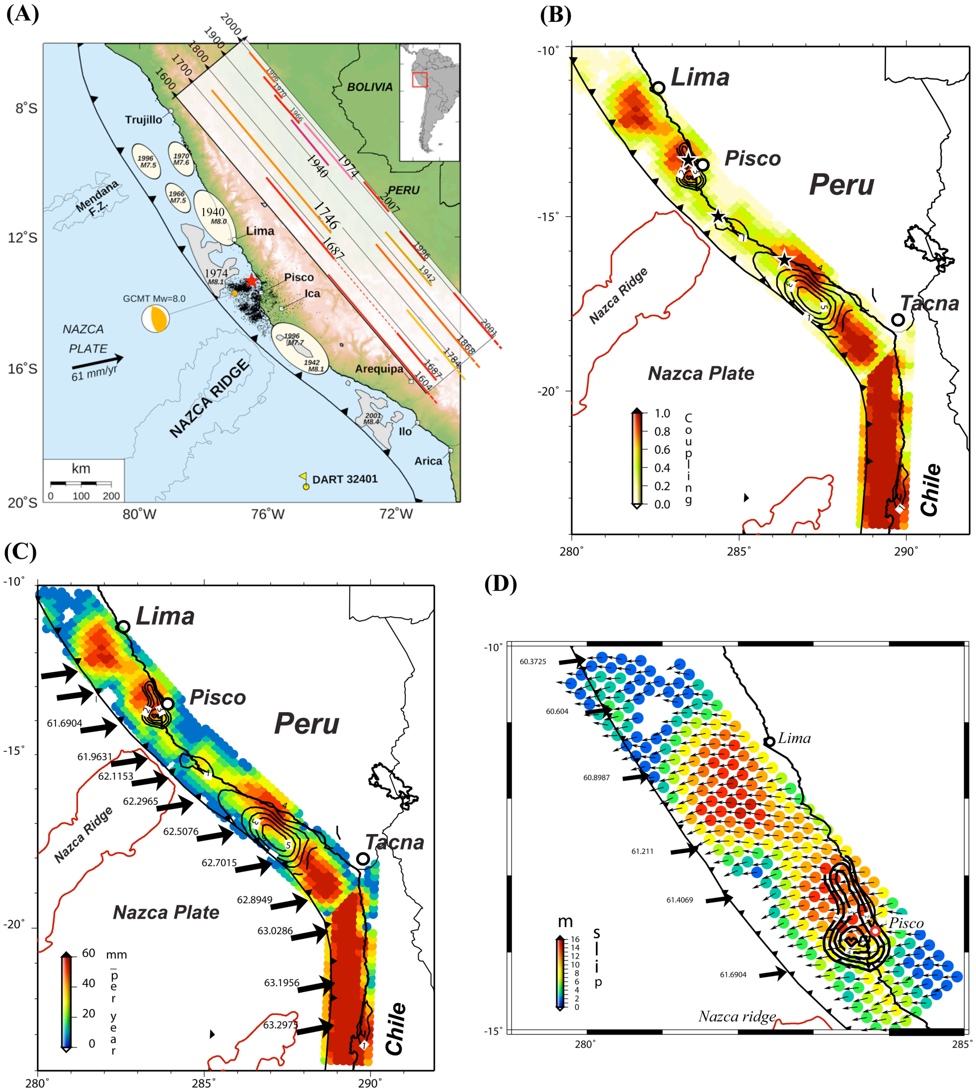

Fig. 1. A) Historical earthquakes along the Nazca subduction zone in Peru (Sladen et al. 2010). B) Interseismic seismic coupling (ISC) model in Peru and northern Chile obtained from geodetic measurements. C) Slip deficit rate model in Peru and northern Chile . D) Slip distribution of a scenario earthquake for the subduction zone off-Lima, obtained by combining the slip deficit rate in (C) with an interseismic period of 265 years since the 1746 earthquake. The slip contours of the 2007 Pisco earthquake is displayed in figures B,C and D.

American Plate (Figure 1A). Seismic activity in Peru can be divided in two regions located North or South of the Nazca ridge (15^{o}S). The ridge is coincident with a region of low coupling, where the Nazca plate is believed to subduct aseismically (Perfettini et al. 2010), and therefore may act as a geometrical barrier for earthquakes located North and South of the ridge. Central Peru, North of the Nazca ridge, has been repeatedly affected by large earthquakes such as the 28 October 1746 which is reportedly the worst earthquake Lima has experienced since its foundation. Intensity reports as well as a tsunami record suggest a moment magnitude of ~8.8 for this earthquake (Dorbath et al. 1990). The 1746 earthquake was followed by a long period of quiescence until a sequence of magnitude 7-8 earthquakes in the 20th century starting with the 1940 earthquake up to the M8.1 Pisco earthquake in 2007 (Sladen et al., 2010) (Figure 1A). We use this information combined with an interseismic coupling model of Central Andes to elaborate a scenario for a megathrust earthquake that could likely affect the Lima metropolitan region.

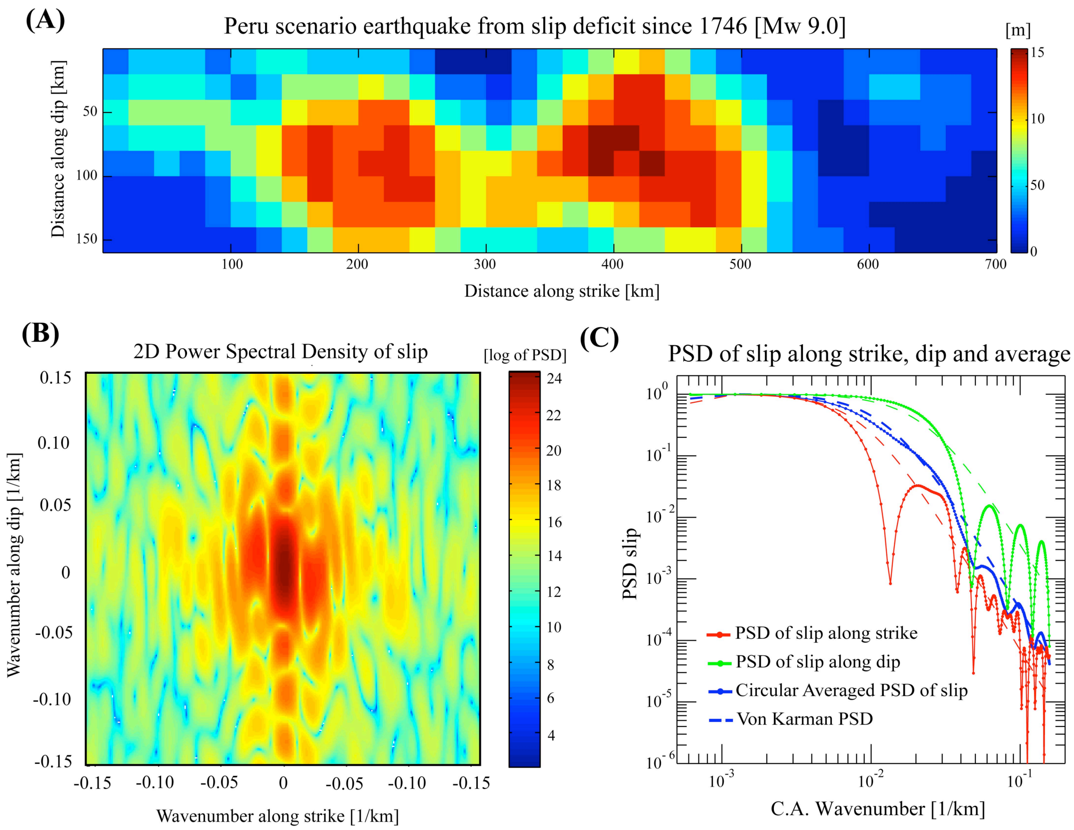

Fig.2 A) Slip distribution of the Lima scenario earthquake B) 2D power spectral density (PSD) distribution along strike and dip. C) PSD along strike (red line) and dip (green line). The solid blue line corresponds to a circular averaged PSD and the dashed blue line to the fit of a Von Karman PSD to this average.

INTERSEISMIC COUPLING (ISC) AND SCENARIO EARTHQUAKE

Interseismic seismic rates in Peru and Chile were obtained by inverting velocities from GPS campaigns at 87 sites surveyed from the period 1993 to 2003 (Chlieh et al. 2010 submitted). These data include sea floor deformations measurements obtained off-shore Lima city from a combination of GPS receivers and acoustic transponders (Gagnon et al. 2005). The model for interseismic coupling (ISC) is based on the assumption that convergence between the Nazca and South American plates is accommodated along the megathrust, as well as at the sub-andean thrust-belt region, to account for the fraction of plate convergence that is accommodated by back-arc shortening (Chlieh et al. 2010 submitted). The inversion of geodetic measurements to obtain a heterogeneous ISC was performed using a slab geometry with a dip of 15^{o} for the Central Peru segment, 20^{o} for Southern Peru segment and 18^{o} for Northern Chile segment, and was subdivided into cells of 20km x 20km. In each cell the coefficient of coupling is allowed to vary from 0 to 1. The results of ISC indicate the existence of two strongly coupled regions, the first one off-shore Lima and the second one off-shore Pisco city (Figure 1B). Figure 1C shows the slip deficit rate, obtained by multiplying the ISC by an average long term slip rate imposed by plate convergence. Assuming an interseismic period of 265 years since the last megathrust earthquake that stroke Central Andes in 1746, up to 2010, we obtained a slip deficit equivalent to an earthquake with a moment magnitude of 9.0 (Figure 1D). For this model we neglected the 20th century sequence of events from 1940 up to 2007, due to large uncertainty in their sources models and also to obtain the worse scenario for a megathrust rupture in Central Andes.

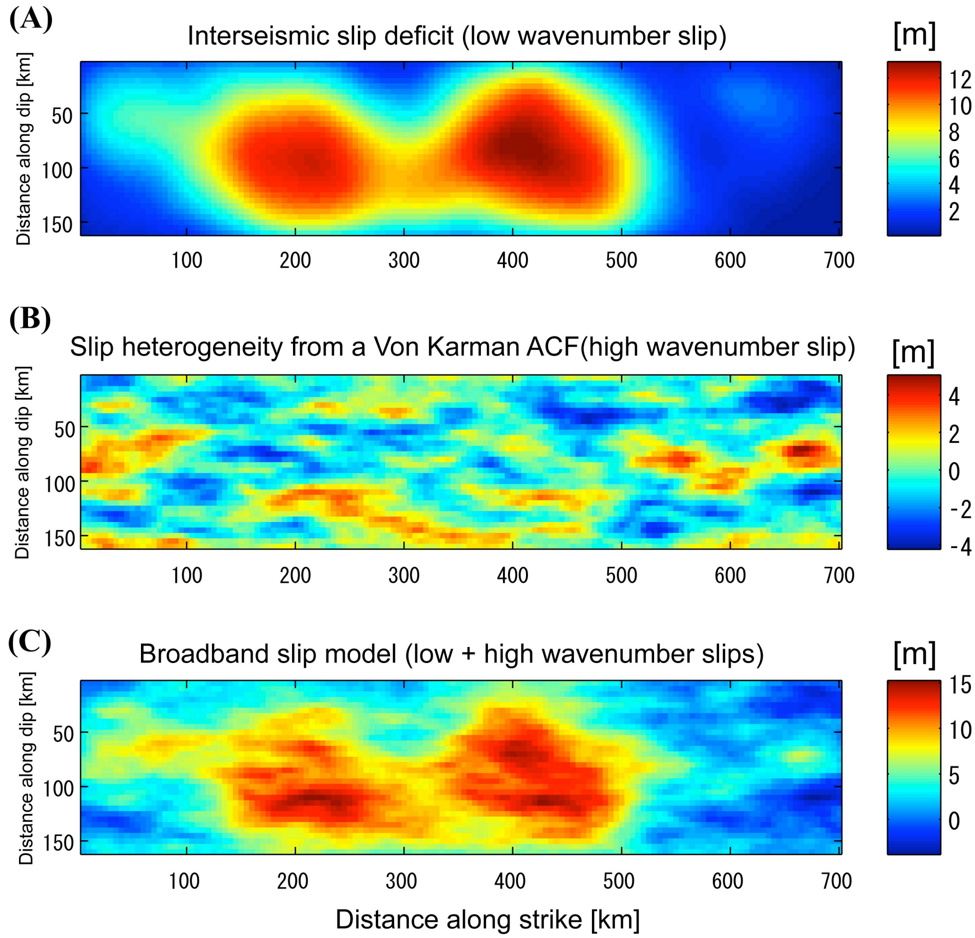

Fig. 3 A) Low wave number filtered scenario slip in Figure 2A. B) High wave number slip from the Von Karman PSD function in Figure 2C. C) Broadband slip obtained by adding low and high wave number slips in A and B.

SLIP SCENARIO EARTHQUAKE

The source model of the scenario earthquake has a maximum slip of approximately 15 m, the source dimensions are 700 km along strike and 160 km along dip, and the grid spacing is 20 km (Figure 2A). The moment magnitude, calculated using a rigidity of 53.6GPa is 9.0. The rigidity was obtained as an average at the scenario source region from the velocity model of Hartzell and Langer (1993). The fault model spans an area from the Nazca ridge, sligthly South of the Pisco earthquake source, up to 9.6S in the North, which corresponds to a region where the Mendana fracture (a possible geometrical barrier for a northern fault rupture propagation) is located.

The slip model obtained from the geodetic data is characterized by a smooth distribution of asperities (Figure 2A). This model is appropriate for the simulation of long period seismic waves as well as for tsunami modelling due to the large grid spacing employed in the model. However for the simulation of a broadband strong ground motion it becomes necessary to introduce small scale complexities to the source slip to be able to simulate high frequency ground motions. To achieve this purpose we propose a "broadband" source model in which large scale features of the model are constructed from our geodetic scenario slip (GSS), and the small scale heterogeneities are obtained from a spatially correlated random slip model. We apply the procedure of Mai and Beroza (2002) to obtain the parameters that characterize the power spectrum of our GSS, such as the corner wave number and correlation lengths along strike and dip, and use these values to generate a slip distribution at high wavenumbers. The 2D power spectral density (PSD) of GSS is displayed in Figure 2B. In Figure 2C we show the normalized PSD of slip along strike (red solid line) and along dip (green solid line), as well as a circular averaged PSD of GSS (blue solid line). We fitted a Von Karman PSD to the observed spectra as follows:

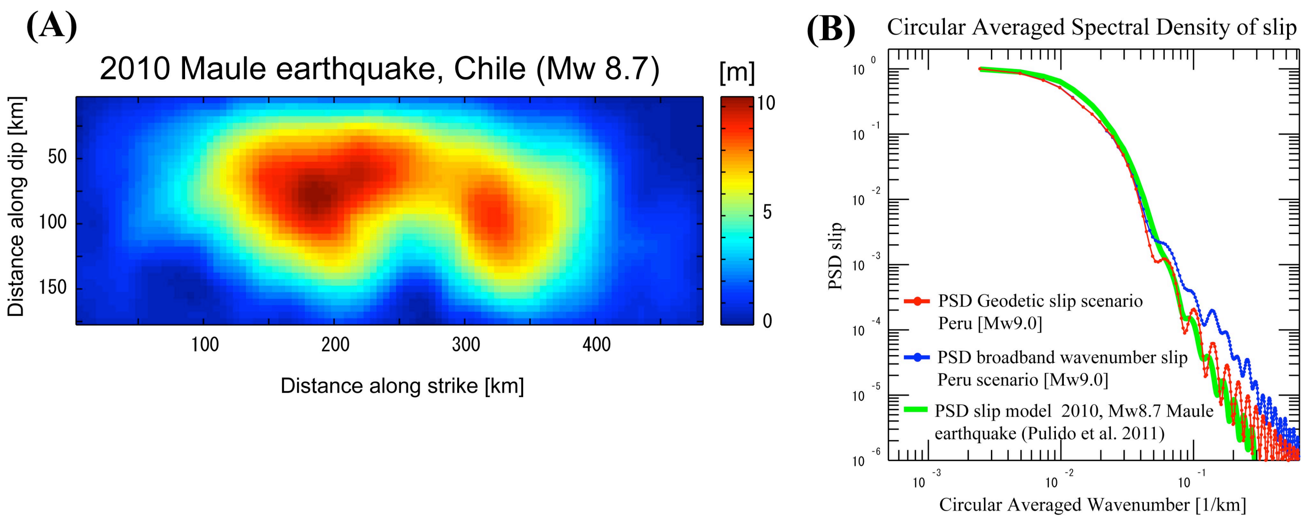

Fig. 4 A) Slip distribution of the 201/02/27 Maule earthquake (Chile) (Pulido et al. 2011). B) Circular averaged PSD (CPSD) of the Maule earthquake slip as well as CPSD of broadband wavnumber slip and GSS.

$$P(k_s, k_d) = \frac{k_s k_d}{\left[1 + a_s^2 k_s^2 + a_d^2 k_d^2\right]^{H+1}}$$

Where k_s and k_d are wave numbers along strike and dip, a_s and a_d are the autocorrelation distances along strike and dip, and H the Hurst exponent defining the spectral decay. Our fit yielded an a_s value of 110 km^{-1}, an a_d value of 40 km^{-1}, and H equal to 1 (dashed lines in Figure 2C). We generated a correlated random slip model for a source area corresponding to our GSS model using a Von Karman PSD with the aforementioned parameters, and assuming a grid spacing of 5 km. In order to combine the low and high wave number slips we selected a crossover wave number (k_{cross}) equal to 0.05 km^{-1} which is about 5 times the corner wave number of GSS. We interpolated the GSS to a grid size of 5 km and apply a low pass filter for wavenumbers smaller than k_{cross} (Figure 3A). The high wave number slip is obtained by applying a high pass filter to the correlated random slip for wave numbers larger than k_{cross} (Figure 3B). Finally the broadband wave number slip is obtained by adding the low and high wave number slips (Figure 3C).

In Figure 4B we compare the PSD of our GSS (red line), with the PSD of broadband slip obtained in this study (blue line). We can observe that the addition of small scale heterogeneities to the GSS significantly enrich the energy content of PSD of slip at high wavenumbers (blue line). This feature will contribute to the source high frequency radiation for strong ground motion simulations.
For a comparison we also plot the PSD of a slip model of the 2010 Maule earthquake obtained from inversion of long period teleseismic data (Figure 4A, and Figure 4B) (Pulido et al. 2011). We can observe a good agreement between the PSD of the slip model of the Maule earthquake and the PSD of our GSS for Peru, which suggests that slip models based on geodetic measurements as well as information of historical earthquakes can be appropriate to typify future megathrust earthquakes.

DISCUSSION AND CONCLUSIONS

We have developed a methodology for the estimation of slip scenarios for a future megathrust earthquake originated from the convergence between the Nazca plate and the South American plate. This methodology is based on estimations of interseismic coupling at the megathrust obtained from space geodesy measurements as well as information of historical earthquakes.
Estimation of scenario earthquakes for megathrust earthquakes have been traditionally approached using information on historical earthquakes. This methodology might be appropriate for regions where recurrence of large earthquakes is well know, like in the Tokai, Tonankai, and Nankai regions in Japan, which are characterized by a short recurrence period of approximately 150 years. Information on intensity distribution of historical earthquakes in the last 500 years in this region has been used to delineate asperities of earthquakes with magnitudes greater than 8 (Central Disaster Prevention Council of Japan, 2003). This information has been used for estimation of scenario earthquakes and strong motion simulation for future earthquakes to strike West Japan (Sekiguchi et al. 2006). On the other hand the recent Tohoku-oki earthquake in East Japan, reached a magnitude of 9 which was not expected for this region, as magnitude of historical earthquakes there had not exceeded M8.1 (Earthquake Research Committee, 1999). Due to the limited

span of earthquake catalogues, the supplementary use of other source of information such as geological or geodetic data as proposed in the present study might be helpful for hazard assessment of future mega-earthquakes. In this study we propose a methodology to construct the slip distribution for megathrust earthquakes that characterize the asperity distribution at plate boundary regions from geodetic measurements, and incorporate small scale slip heterogeneities that are appropriate for broadband strong motion simulations. The good agreement between the PSD of our geodetic slip with the PSD of the M8.7 Maule earthquake suggests that our methodology is appropriate to characterize megathrust earthquakes.

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