Low-parametric modeling of Mw8.3 Illapel 2015, Chile earthquake

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Abstract

The Mw 8.3 (GCMT) Illapel megathrust earthquake is investigated. The objective is to find out which features of the previously published rupture scenarios can be resolved using a regional strong-motion network and source models with few parameters only. Low-frequency waveforms (<0.05 Hz), at nine stations (Centro Sismológico Nacional, Chile - CSN), are subjected to modeling. Various representations of the source are used: (i) Multiple-point-source models based either on iterative deconvolution or simultaneous inversion of source pairs, (ii) Models of circular and elliptical uniform-slip patches, employing synthetic and empirical Green's functions, respectively. This variety of methods provides consistent results. The earthquake appears to be a segmented rupture progressing from an early (deep) moment release to a later (shallow) one, towards the NW. The source models of slip-uniform patches synchronously suggest a low rupture speed 1-2 km/s. Despite different data sets and methods, this estimate of rupture speed is consistent with independent publications. As for ambiguity in literature regarding depth and timing of the rupture, our paper clearly prefers the models including a ~20-30 s delay of the shallow moment release compared to the initial deep one. The strong-motion data set and low-parametric models proved to be competitive with more sophisticated approaches. This result implies a need to improve regional accelerometer networks in South America, which might eventually help in resolving source process of possible future large events, e.g. in Patagonia.

Key words: Illapel earthquake, Chile; Low-frequency modeling; Multiple-point-source models; Empirical Green's functions.

Introduction

An Mw8.3 (Illapel) earthquake occurred on September 16, 2015 in central Chile, causing significant strong ground motions, most likely due to a combined effect of rupturing a deep (~30 km) and shallow (~15 km) slip patch, respectively, thus indicating an along-dip segmentation of the megathrust (Melgar et al., 2016). Relatively little attention has been paid to seismic source investigations with strong-motion acceleration data, freely accessible from CSN. Although previously published papers show several common features, some aspects of the quantitative source models, such as, for example, position of the main slip patches remain ambiguous. Therefore, the objective of this work is to develop low-parametric models of the Illapel earthquake, helping to answer specific questions like this: (i) Was most of the seismic moment released in a single patch, situated close to surface, northwest of the epicenter, or also in a deeper patch situated closer to the epicenter (hence also closer to the locus of the high-frequency radiation identified by the backprojection techniques)? (ii) If two patches represent a correct source model, then what was the timing of the two moment-release episodes? In order to accomplish these goals we choose a low-parametric modeling (ISOLA multiple-point source (MPS) modeling) as a suitable tool for the Illapel earthquake. Wishing to get some insight into the source complexity we use near stations. At the same time, being interested in a robust model of the source complexity, we use the lowest frequencies enabling deterministic modeling. To further validate our MPS results, we also apply the empirical Green's function technique for calculating apparent source functions and inverting them into finite source models composed of slip-uniform elliptical patches.

Materials and Methods

ISOLA multiple-point-source (MPS) modeling. ISOLA code (Sokos and Zahradník, 2013) is used for inverting regional full-wave seismograms for single- and multiple-point source models. The point source contributions are called subevents, representing points of moment release at different times with associated moment tensors. In this work subevents are calculated by the *Joint inversion of source pairs* method (Zahradník and Sokos, 2014) by non-negative least squares (NNLS). In this method each solution consists of a pair of subevents and this representation is suitable if the studied earthquake seems to be basically composed of one or two dominant subevents.

Equivalent uniform-patch method (EUP). consists in a uniform patch (i.e. the patch with homogeneous slip), representing the simplest finite-fault model. The patch is an improved equivalent of a previously identified MPS model. This method is a simplified version of the Multiple Finite-Extent method (MuFEx) (Gallovič and Zahradník, 2012). The model is parameterized by the patch radius and rupture velocity, and it is discretized.

Two-patch finite-source EGF modeling. This technique is based on Empirical Green's Functions (EGF) representing a well-established seismological tool (Plicka and Zahradník, 2002; Roumelioti et al., 2009). Using EGF, the apparent source time functions (ASTFs) are calculated similarly as explained in Zahradník and Sokos (2014). Finally, the ASTFs are inverted into a model of two elliptical patches of uniform slip (Vallée and Bouchon, 2004). The model parameters are as follows: (i) Position of the centers, the axes lengths and the slip values of two ellipses. (ii) Constant speed of rupture propagating radially from hypocenter.

Data and basic earthquake parameters. Strong-motion acceleration records of the Illapel main shock, recorded at nine stations, are modeled in the present paper. The epicentral distances range from 130 to 260 km. The stations records represent part of the CSN collection from which we eliminated those stations situated close to each other. For Empirical Green's Functions (EGF) modeling the CSN records of an aftershock are also used. We used earthquake locations from CSN and the Global Centroid Moment Tensor solution (GCMT), for fixed mechanism inversions.

Velocity model. The strong-motion data are inverted using a 1D velocity model. The velocity model was provided by CSN and it is relevant for the zone between 26° S and 34° S (Pardo et al., 2002).

Frequency range. The usable frequency range is determined by the quality of the velocity model, the epicentral distances and the noise. After several preliminary tests we decided to use the frequency range 0.01-0.05 Hz and/or sub-ranges.

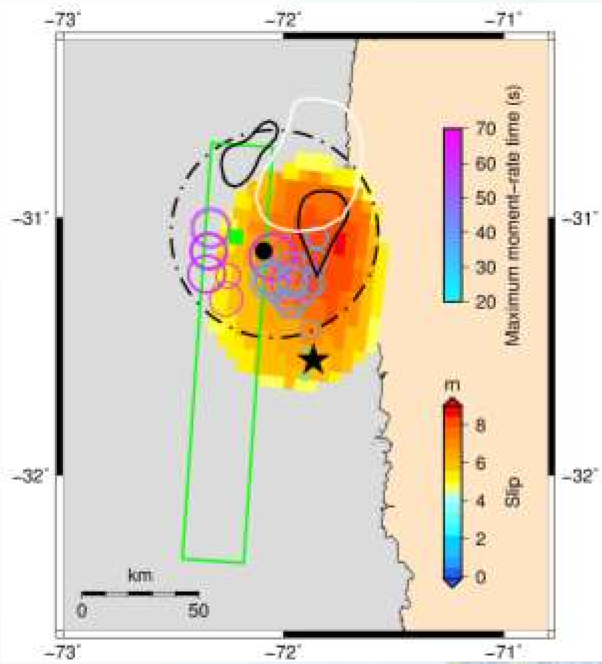

Figure 1. The colored background is the distribution of the mean slip (> 4.5 m) in the best EGF models. The small colored circles are the best pair solutions calculated by NNLS (circles are color-coded according to their moment release time, while their radius scale with scalar moment). The dot-dashed circular uniform patch is the model obtained by EUP method, keeping fixed the focal mechanisms (GCMT). For comparison, solutions by other authors are also included. The black and white irregular curves are contours of the maximum slip (~7 m) from Melgar et al. (2016) and Ye et al. (2016), respectively. The green rectangle and the small green square represent the USGS finite model. The GCMT centroid is plotted by a black dot, CSN epicenter by a star. This figure was created using Generic Mapping Tools.

Results and Discussion

Results are shown in Table 1 and Figure 1.

In the joint inversion of source pairs (NNLS), the best solutions in terms of variation reduction (VR) of waveform fitting show an initial deep episode followed after ~30 s by a shallow one, suggesting a temporal rupture progression in the up-dip direction and, slightly less clearly, towards the NW. According to the size of subevents, the two episodes may have released a comparable amount of the seismic moment.

Representing the source by a single circular patch of uniform slip (EUP) a good waveform fit in terms of VR is obtained prescribing radius R=50 km, rupture velocity Vr=2 km/s and placing the patch center close to the GCMT centroid. The center position was obtained by an iterative deconvolution method (results in Bollini et al., submitted in 2016). This model only slightly underestimates the GCMT magnitude (Mw8.3).

Using EGF method, we confirm position of the main slip region and validate the low rupture speed (1.5-2.0 km/s).

To make a comparison with published results, we focus on the most comprehensive papers. Melgar et al. (2016) reported two major slip episodes, which evolved with the same ~30 s delay of the shallow moment-release episode compared to the deep one. Ye et al. (2016) obtained results characterized by a single patch. Despite different data sets and methods, our estimate of the low rupture speed is consistent with these (and other) independent studies. Moreover, as shown in Fig. 1, the main slip region identified by our methods comprises the significant slip contours of the mentioned papers. The key point is that our low-parametric models, obtained with regional strong motion stations, are in reasonable agreement with the other, more complex studies.

Table 1. Summary of the results using three methods and three different frequency ranges

Method	Freq. range (Hz)	Source model	Mw	VR	Slip (m)	Rupture speed (km/s)
EUP	0.01-0.02	Single circular patch	8.2	0.77	5.6	2
NNLS	0.02-0.05	2-points	8.3 (fixed)	0.55	-	-
EGF	0.03-0.5 *)	Two elliptical patches	8.3 (fixed)	-	8.6 **)	1.6

*) The range used in the calculation of apparent source time function.
**) Maximum slip value of the mean model in Fig. 1.

Conclusions

Our results show that using limited data (9 strong-motion records at regional distances) and low parametric models (2-points NNLS models, single uniform slip patch, and 2-elliptical patch models) we were able to retrieve the same gross features of the rupture process as in the previously published papers, based on more abundant data and multi-parameter inversions. By gross features we mean position of the main rupture area, direction of rupture propagation and rupture velocity. In particular, segmentation of the source process into the early (deep) and later (shallow) episode, indicated at low frequencies in some of the published papers only, was unanimously detected, too. These results represent a strong motivation for improving regional accelerometer networks in South America, which might help to resolve source process of possible future large events, e.g. in Patagonia.

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