Red GNSS del Centro Sismológico Nacional de Chile, aplicaciones a terremotos

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Geodetic Applications for Earthquake Studies
Motivation:

GNSS network from CSN (> 130)

Task 1
Install, operate and maintain a GNSS network to develop applications for seismology

See http://gps.csn.uchile.cl
Motivation: Acceleration and displacement of EQ
Motivation:

Task 2

Estimate moment magnitude and slip distribution of earthquake, ASAP!!, with displacement from GNSS observations.
Motivation: earthquakes

Illapel 2015

Iquique 2014

(Leyton et al. 2018)

Estimation of Mw from PGD

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GNSS application

www.csn.uchile.cl
Abstract  Fast and reliable characterization of earthquakes provides valuable information to the population, even reducing the effects of strong shaking produced by them. In this study, we explore the minimum time required to estimate the magnitude for subduction earthquakes. Using traditional P-wave earthquake early warning parameters and considering a progressively increasing time window, we are able to estimate magnitude for subduction earthquakes $\sim 30$ s from the origin time (with an average residual of $0.05 \pm 0.28$). However, estimations for larger events ($M_w \geq 7.5$) present larger errors (average residual of $0.70 \pm 0.30$). We complement our data with Global Navigation Satellite System observations for these events, enabling magnitude estimations $\sim 70$ s from the origin time (average residual of $0.42 \pm 0.41$). We propose that rapid estimations of magnitude should consider, initially, P-waves in a progressively increasing time window, and complemented with GNSS data, for large events.

Plain Language Summary  Fast and reliable magnitude estimation of earthquakes enables the preparation of the public to reduce its impact. Here we test known methods to rapidly estimate the magnitude of subduction earthquakes. We found encouraging results, taking a few tens of seconds to provide reliable values. However, results for larger events tend to underestimate the real magnitude. Hence, we propose the combination with other sources of information, such as Global Positioning System, that are able to resolve these larger events.

1. Introduction  Recent advances in communication and automatic processing of seismic data have enabled fast and reliable earthquake source estimation, improving the rapid response of public and private agencies as well as the general public (Kanamori, 2005; Satriano et al., 2011). Indeed, fast estimations of the location, magnitude, and expected ground motions are the basis of the present Earthquake Early Warning Systems (EEWS) aimed to prevent losses produced by earthquakes (Colombelli et al., 2013). It has been shown that a robust estimation can be analyzed in the near field, given the prompt arrival of the seismic waves, recording only the second portion of the shaking, after the first few seconds that do not provide reliable information. However, for larger events, magnitude 7.5 and above, these estimates become less reliable (average residual of $0.42 \pm 0.41$). We propose that rapid estimations of magnitude should consider, initially, $P$-waves in a progressively increasing time window, and complemented with GNSS data, for large events.

Moreover, the main principle in usual EEWS is that the information from few seconds of the P-wave can provide information regarding the magnitude and location of an earthquake (Allen & Kanamori, 2003), and given that these waves travel faster than the potentially destructive waves, this can provide an actionable warning to the population to reduce the impact of shaking (Colombelli & Zollo, 2016). However, there always will be a trade-off between the warning time and the reliability of the information: larger time windows should enable better knowledge of the event, while giving less time to prepare for its impact; this concept has lead to a general use of continuous updates in EEWS (Colombelli et al., 2012, 2015; Satriano et al., 2011). Moreover, Minson et al. (2018) using simple seismological relations, discussed the minimum time required to estimate the possibility of having strong ground shaking due to an earthquake: they showed that there is a limit given by the required time for the earthquake to evolve into a large event.

Indeed, a key aspect that remains controversial is whether a few seconds of the P-wave can predict the earthquake’s size over a wide range of magnitudes: some authors suggest that an initial rupture will develop into a large earthquake only if it has enough fracture energy to break across several heterogeneities (Olson & Allen, 2005). In this case, the Deterministic model, the final seismic moment is determined by the initial rupture (Ellsworth & Benisa, 1995; Zollo et al., 2006). However, as pointed out by Rydelek & Horiuchi (2006), it is not clear by which mechanism the information between these heterogeneities is transmitted across large
Magnitude and slips distribution

1.- Physic model e.g. Okada (1985)
2.- discretization of contact
3.- Inversion method

Physic model: (Okada, 1985)

Assumptions
- Semi space geometry
- Homogenous media
- Elastic linear response

SLAB1 (Hayes et al.2012)

Estados de información
≡ Estimación bayesiana en este caso

\[ p(x|d) = \frac{p(x)p(d|x)}{p(d)} \]


It should work with just one station!!!

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GNSS application

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Magnitude with pick ground displacement

\[
\log(\text{PGD}) = A + B \cdot M_w + C \cdot M_w \cdot \log(R).
\]

Crowell et al. 2013, Melgar et al. 2015
Example 1: Maule Mw8.8 2010

$M_w = 8.83$

$u_{max} = 14.58 \text{ m}$

$M_0 = 2.186 \times 10^{22} \text{ Nm}$
Example 2: Valparaiso Mw 6.9 2017

\[ M_w = 7.06 \]
\[ u_{max} = 0.75 \text{ m} \]
\[ M_0 = 4.874 \times 10^{19} \text{ Nm} \]

\[ M_w = 6.82 \]
\[ X_i = X_0 + V(t_i - t_0) + \Sigma_r \]

\[ X_i = X_0 + V(t_i - t_0) + C_s + P_s + S + T + SL + e \]

Bevis and Brown 2014
Bedford and Bevis 2018
\[ X_i = X_0 + V(t_i - t_0) + \Sigma_r \]

\[ X_i = X_0 + V(t_i - t_0) + C_s + P_s + S + T + SL + e \]

Solutions from different AC

(Báez and Moreno, 2020, in preparation)
Between these stations suggests a high degree of locking in the Chiloé area since at least the year 2009. The area has not been affected by the Maule megathrust earthquake. The large landward velocity gradient andGUAF (Figures 2d and 2e) show no significant variation after the 2010 earthquake, suggesting that this adjustment in mantle viscoelastic relaxation following the 1960 earthquake. Blue star denotes the epicenter of Chiloé earthquake.

After the 2010 Maule megathrust earthquake in central Chile, continuously recording seismological instruments offer an increase in the degree of interseismic plate locking. On the other hand, sites MELK have been triggered by the deep intraslab 2005 event followed by precursory seismic activity (SSE) (Fig. 4), but no substantial coseismic slip occurred 2 days later (Fig. 2 and figs. S6 and S7).

The overall decadal velocity field before the 2010 Maule earthquake. GPS vectors have been corrected by removing the 1 April 2014 Iquique earthquake. The linear velocity trend of ESQU reduced to 0.72 ± 0.12 mm/yr, probably due to a complex readjustment in mantle viscoelastic relaxation following the 1960 earthquake. Blue star denotes the epicenter of Chiloé earthquake. The seismic swarms detected since 2008 occurred in the LCZ (Fig. 1). Whereas precursory seismic swarms associated with the 2010 Maule earthquake, the final foreshock sequence as in the preslip model of nucleation (Ida, 1972).

Together with the fact that the 1985 Valparaiso earthquake (Mw 8.1 event) and the 2010 Maule earthquake (Mw 8.8 event) were preceded by precursory seismic activity (SSE); in particular, the 1985 Valparaiso earthquake (Mw 8.5) was followed by a series of over 600 precursory foreshocks. Ground deformation associated with these events was deeper than that of the March precursors that occurred 2 days later (Fig. 2 and figs. S6 and S7).

The slip distribution of nucleation phase. (a) East–west daily GPS solution for TRPD – CTPC – ROB1 GPS stations; in Figure S3 we show the time series of TRPD, CTPC, and ROB1 GPS stations. The colored arrows are the real GPS vector data, and the transparent arrows are the simulated GPS vectors. The 1 April 2014 Iquique earthquake started the 10.1002/2017GL074133

The maximum slip associated with these events now, either the magnitude of these SSEs was too small or they were too shallow to have been detected. The strike–slip type of the mainshock, whereas the black dotted lines in Figure 3. Motion of coastal GPS stations preceding the Iquique earthquake.

The 1960 Valparaiso earthquake (Mw 8.1 event) was followed by a series of over 600 precursory foreshocks. The 2010 Maule earthquake (Mw 8.8 event) was preceded by precursory seismic activity (SSE); in particular, the 1985 Valparaiso earthquake (Mw 8.5) and the 2010 Maule earthquake (Mw 8.8). Immediately after the 2010 Maule earthquake, the 1960 Valparaiso earthquake (Mw 8.1 event) was followed by a series of over 600 precursory foreshocks. The 2010 Maule earthquake (Mw 8.8 event) was preceded by precursory seismic activity (SSE); in particular, the 1985 Valparaiso earthquake (Mw 8.5) was followed by a series of over 600 precursory foreshocks.

1168 | September 2014

The relation among small, large and mega-earthquakes in central Chile
Moreno M., Cisternas M., Báez, J.C., Ortega F., Melnick D., FONDECYT Nº 1181479
Investigation the feedback between megathrust eq. and continental plate faulting: Consequences for seismic hazard in Metropolitan Chile

Moreno et al., 2018
Transitory decoupling before Pisagua 2014 EQ

Schurr et al., 2014
Abstract

Megathrust earthquakes are responsible for some of the most devastating natural disasters\(^1\). To better understand the physical mechanisms of earthquake generation, subduction zones worldwide are continuously monitored with geophysical instrumentation. One key strategy is to install stations that record signals from Global Navigation Satellite Systems\(^2,^3\) (GNSS), enabling us to track the non-steady surface motion of the subducting and overriding plates before, during and after the largest events\(^4,^5,^6\). Here we use a recently developed trajectory modelling approach\(^7\) that is designed to isolate secular tectonic motions from the daily GNSS time series to show that the 2010 Maule, Chile (moment magnitude 8.8) and 2011 Tohoku-o-ki, Japan (moment magnitude 9.0) earthquakes were preceded by reversals of 4–8 millimetres in surface displacement that lasted several months and spanned thousands of kilometres. Modelling of the surface displacement reversal that occurred before the Tohoku-o-ki earthquake suggests an initial slow slip followed by a sudden pulldown of the Philippine Sea slab so rapid that it caused a viscoelastic rebound across the whole of Japan. Therefore, to understand better when large earthquakes are imminent, we must consider not only the evolution of plate interface frictional processes but also the dynamic boundary conditions from deeper subduction processes, such as sudden densification of metastable slab.
Proyecto "Precursor"
Hacia la comprensión de la deformación sísmica transitoria a precursora en Chile

**L1: Observational line, focused on providing displacement time series from spatial geodesy data (GNSS and SAR), and from seismicity catalogs**

InSAR time-series Central Chile

Displacements 2016-2019

Seismicity 2014-2018
Mapa sin título
Escribe una descripción para tu mapa.
Four years before the eruption, a cluster of earthquakes was observed in the region, but of smaller amplitude (Buenos Aires graben inside its bounding structures (Fig. 3a)). In fact, only 36 hours of continuous GNSS data obtained from an east-dipping reverse fault directly observed was not possible until 21 May.

On 30 April, some large volcano-tectonic earthquakes were recorded, but the earthquake activity increased on 1 May with several subplinian columns, the largest of which occurred on 2 May with the eruption beginning. The observed GPS vectors during the first subplinian eruption which began approximately on 2 to 4 May were defined by visual inspection and correspond to incipient volcanic inflation. However, no systematic patterns of inflation were observed. Displacements are relative to the South American craton; for processing details see Section 3.2. Black dots indicate GPS sites, note different colour scales. The eruptive vent is marked by a star.

In the case of interferograms 2011-07/2011-10 and 2011-05/2011-06, results of the comparison between measured and predicted displacement vectors are shown in Fig. 4. The eruptive vent is marked by a star.

**Table 1**

<table>
<thead>
<tr>
<th>Location (UTM 18S)</th>
<th>Depth [m]</th>
<th>Volume [km$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>735 000 m E, 5 513 000 m N</td>
<td>5500</td>
<td>4250</td>
</tr>
<tr>
<td>9000 m E, 4 000 m N</td>
<td>6250</td>
<td>139</td>
</tr>
<tr>
<td>14 000 m E, 5 500 m N</td>
<td>6250</td>
<td>139</td>
</tr>
</tbody>
</table>

Interferogram 2011-06/2011-07, 30 d, Mogi model

- **LINC**
  - **E**
    - 2011-06/2011-07: 0.062 m, 0.030 m, 0.023 m
  - **N**
    - 2011-06/2011-07: 0.047 m, 0.030 m, 0.023 m

- **Piña et al., 2009, Andean Geology**

- **Novoa et al., 2019, EPSL**

**Figure 4.** Location (UTM 18S) Depth [m] Volume [km$^3$] LINC is well reproduced by the prediction of the Mogi sources.
The Helmert transformation does not work in Chile, even the use of velocities to transform epochs, due to deformation and earthquakes.
Final Remarks

• We developed an integrated system to obtain moment magnitude and slip distributions with GNSS observations;

• Next step will be to include intraplate and fault system EQ and also a combination between displacement from GNSS and data from accelerometers to characterize large EQ;

• We generate high-quality observations, which are available in an ftp for the use of the general public. We also keep the observations of the IGS stations in Chile;

• We participate in several multidisciplinary research project, national and international, to better understand the seismic cycle in Chile and, a relation between faults system and earthquakes.

https://scholar.google.com/citations?user=TeLKryYAAAAJ&hl=es
Thank you for your attention!