

Speeding up Tsunami Forecasting to boost Tsunami Warning in Chile

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Abstract. Despite the occurrence of several large earthquakes during the last decade, Chile continues to have a great tsunami-genic potential. This arises as a consequence of the large amount of strain accumulated along a subduction zone that runs parallel to its long coast, and a distance from the trench to the coast of no more than 100 km. These conditions make it difficult to implement real-time tsunami forecasting. Chile issues local tsunami warnings based on preliminary estimations of the hypocenter location and magnitude of the seismic sources, combined with a database of pre-computed tsunami scenarios. Finite fault modeling, however, does not provide an estimation of the slip distribution before the first tsunami wave arrival, so all pre-computed tsunami scenarios assume a uniform slip distribution. We implemented a processing scheme that minimizes this time gap by assuming an elliptical slip distribution, thereby not having to wait for the more time consuming finite fault model computations. We then solve the linear shallow water equations to obtain a rapid estimation of the run-up distribution in the near field. Our results show that our linear method captures most of the complexity of the run-up heights in terms of shape and amplitude when compared with a fully non-linear tsunami model. In addition, we can estimate the run-up distribution in quasi-real-time as soon as the results of seismic finite fault modeling become available.

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1 Introduction

For decades, countries exposed to coastal inundation have done a lot of work to develop their tsunami warning systems (Doi, 2003; Wächter et al., 2012). Most tsunamis are generated by large subduction earthquakes and landslides, which owing to the characteristics of the tsunami source process, places a real-time tsunami forecast out of reach. Regular earthquakes follow a scaling law that links their energy release (seismic moment) to their duration (Ide et al, 2007). For instance, a regular 8.5 Mw earthquake can last for about 2 minutes, whereas we can consider tsunami generation quasi-instantaneous after the source origin time. This implies that a robust tsunami warning system must integrate several systems that monitor different potential triggers such as earthquakes and volcanoes, among others. In the case of tsunamis generated by subduction earthquakes is essential to detect and characterize the seismic source. At present, the W-phase moment tensor is the preferred method for

characterizing large earthquakes in Chile (Riquelme et al, 2016, 2018), as it allows to obtain a moment tensor solution within 5 minutes. It is well-known, however, that tsunami heights are very sensitive to the spatial slip distribution of the seismic source (Geist, 2002; Ruiz et al., 2015). Even after having a finite fault model, the simulation of the tsunami propagation can take several hours depending on the desired level of resolution. This is the reason why the tsunami forecasts of many of the current warning systems are based on pre-computed scenarios. Chile and Japan use this methodology for that purpose (https://www.jma.go.jp/jma/en/News/lists/tsunamisystem2006mar.pdf). This methodology, however, ignores the complexity of the seismic source and resolves only for uniform slip models. We propose a methodology applicable to near-field tsunamis triggered by earthquakes that complements the monitoring systems in operation, and helps make better decisions during and after an emergency alert.

10 2 Methodology

We can separate this problem into three main parts: 1) the estimation of a seismic source model, 2) the generation of initial conditions, and 3) the corresponding tsunami simulation. We define a computation domain around the earthquake source and the coastal areas in the near field. We use the SRTM15 bathymetric data with 15 arcsec of resolution, based on the STM30 (Becker et al.,2009).

15 The core idea consists in trading off some accuracy to gain speed. Within the context of earthquake tsunamis generated in the near field we want to know the places with the maximum inundation, the extension of the inundation until it decreases to 0.5 to 1 m, and the average run-up. Our model does not aim at computing a detailed inundation map with the best possible accuracy, but rather to provide a fast estimate of the main area prone to inundation relying on the W-phase CMT, currently considered one of the fastest and more accurate methods to characterize the source of large earthquake (Kanamori and Rivera, 20 2008).

2.1 Slip Distribution Model

Once a W-phase solution provides a characterization of an earthquake we use an elliptical slip distribution (Dmowska and Rice,1986) over a region determined with the scaling laws obtained by Blaser et al. (2010). This serves as a preliminary estimation while seismic waves are still traveling, and later finite fault solutions are computed. This in turn allows to model the 25 near field tsunami for every finite fault model update.

2.2 Tsunami Modeling Initial Conditions

Despite evidence of influence of the source time components in the tsunami generation process, for speed purposes we model a static seafloor deformation induced by a non-uniform slip distribution that includes the horizontal components, as suggested in Tanioka and Satake (1996). This is obtained by applying the Okada equations (Okada, 1985).

2.3 Tsunami Modeling

The last part of this methodology is the estimation of the tsunami heights along the coast. Usually, tsunami modeling involves complex codes to solve the fully coupled non-linear shallow water equations. Depending on the domain size and resolution, a full tsunami simulation run can take several hours, which makes real-time forecast nearly impossible. To overcome this limitation, we solve the linear shallow water equations with a forward finite difference scheme. The propagation inside the domain is governed by the second order PDE with initial conditions:

where $\eta(x,y,t)$ denote the water surface, g the acceleration of gravity, $h(x,y)$ the bathymetry, and $\eta_0(x,y)$ the initial condition. In the open boundaries we set a radiation condition (Reid and Bodine, 1968), whereas in the solid boundaries (coasts) we impose full reflection in a vertical wall placed at an isobath of 100 m, before reaching the non-linear zone. Here, a Neumann boundary condition is applied: $\frac{\partial \eta}{\partial n}$ where \hat{n} denotes the exterior unit normal vector. The linear method (LM) allows to obtain a quicker estimation than a full tsunami code since second-order terms are disregarded while still accounting for the same main features. In addition, this approach does not require to compute the velocity field, an added benefit that makes the computation programs even faster. Each simulation is compared to its corresponding full linear water shallow water equation propagation. We use the JAGURS code (Baba et al., 2014) written in Fortran90 using parallel arrays via OpenMP and OpenMP + MPI. This code is based on the classical finite difference method of Satake (2002). For each scenario, we run the simulation for the equivalent of two hours of tsunami travel time to obtain the main features of the runup distributions despite the fact that later amplification of edge waves and resonance effects can occur.

3 Implementation and Benchmarking

To evaluate the performance of our approach, we modeled nearly all the great tsunamis of the last two decades. Most of them were already tested with an analytical approach in (Riquelme et al, 2015). The details of the propagation and runup distribution of the 12 events tested are presented in the supporting information. For these examples we used the finite fault models provided by the USGS (Hayes, 2017), as they have proven to be operationally robust for real time operations in the context of global monitoring. All the computations were performed in a Dell Precision 7920, with two Intel Xeon Gold 6136 processors, each with 12 physical cores, for a total of 24 physical cores, and 2 threads each. For each time iteration, the domain is divided into 48 subdomains that are computed in different threads, for a parallel array (Fig. 1). To compute the tsunami initial condition, the Okada equations were implemented in the C programming language using threading, together with the finite difference scheme for the LM. The C code uses the pthread library to define a C data structure containing a pthread, and then calls a function that sends each grid subdomain to threads running in different cores for computation. This method is as reliable as any other linear scheme method, as it solves the same equations. The only significant difference is in the threads distribution for time optimization. When a thread finishes, it computes for a certain time step and it joins with the others in order to avoid miscomputations. For instance, on the system used to run our computations for a regular grid of 4 million points with a FFM of 300 subfaults, the vertical and horizontal seafloor displacements can be calculated almost instantly (less than 5 seconds), and two hours of tsunami wave propagation for the 2011 Tohoku, Japan earthquake can be solved in 60 seconds.

4 Discussion of Computational Results

All 12 tsunamigenic earthquakes listed in Table 1 occurred in different subduction zones around the world and had moment magnitudes between 7.7 to 9.1. Among them the 2011 Tohoku, Japan, and 2010 Maule, Chile earthquakes had the largest magnitudes. All these events had a thrust fault mechanism, except for the Samoa event in 2009, which had a normal fault mechanism. Both the 1992 Mw 7.7 Nicaragua earthquake, and the 2006 Mw 7.6 Java earthquake classify as tsunami (slow) earthquakes. The length (L) of the causative faults varies from 150 to 500 km, while the range of the peak displacements at the source varies from 3 to 40 meters. This variety aims at testing our approach with as many earthquakes and as many source features as possible:

1. The 1992 Mw 7.7 Nicaragua tsunami earthquake
- 10 2. The 2001 Mw 8.4 Southern Perú earthquake³.
3. The 2003 Mw 8.3 Hokkaido earthquake
4. The 2006 Mw 7.6 Java, Indonesia earthquake
5. The 2007 Mw 8.1 Solomon Islands earthquake
6. The 2007 Mw 8.0 Pisco, Perú earthquake
- 15 7. The 2009 Mw 8.1 Samoa Islands Region earthquake
8. The 2010 Mw 8.8 Maule earthquake
9. The 2011 Mw 9.0 Tohoku earthquake
10. The 2012 Mw 7.8 British Columbia earthquake
11. The 2014 Mw 8.2 Iquique, Chile earthquake
- 20 12. The 2015 Mw 8.3 Illapel, Chile earthquake

For each event we apply the methodology previously described, and use the W-phase centroid moment tensor, a scaling law, and a elliptic slip distribution to define the first source. Then, the linear and non-linear tsunami simulations are performed. The resulting run-up distributions are decomposed along latitude and longitude in order to compare both models. The same procedure is repeated, this time considering a FFM solution instead. Table 1 shows the correlation between the runup distributions obtained with the JAGURS code (non-linear method) and the method presented in this paper (linear method). Table 2 summarizes the CPU times in seconds for different stages of the process for each simulation. There is a high degree of agreement within a short time. Detailed figures showing the results for the 24 simulations are provided in the supplementary material, where maximum amplitudes, runup distribution, and field measurements are listed.

5 Application of the Method to Complement Tsunami Warning: The 2015 Illapel Earthquake Case Study

On 16 September, 2017 an 8.3 Mw earthquake occurred in the Coquimbo region, Chile (Melgar et al., 2016; Fuentes et al., 2017). The characteristics of this event made it an ideal case study for tsunami generation. The national agencies implemented the established protocols for evacuating the whole Chilean coast, even the more distant insular territories (SNAM, bulletin 1, 5 Sept. 16th, 23:02 UTC). Such decisions have to be made within minutes of origin time. In general, an accurate prediction of the tsunami run-up heights requires a precise image of the seismic source, which at present is not available within 5 minutes or more for real-time after adding the tsunami simulation times. Nevertheless, we can come close to a quasi-real-time approach by triggering a first estimation assuming an elliptical slip distribution. This only take a few seconds, and can at present be done instead of searching a pre-computed database of scenarios that are usually restricted. For monitoring purposes, the results 10 can be updated everytime a seismic source imaging is received, for both, the near field (at 15 arcsec) and regional field (at 60 arcsec). All this information is summarized in a color-coded map following the official coding used by the Chilean institutions (Melgar et al.,2016). Color coded maps are self-explanatory, which makes them easy to interpret (Figs. 2 and 3). Each region can then be rapidly assigned a color linked to an specific evacuation protocol. All the simulations were performed for two hours of tsunami propagation where the main energy content plays a key role on the inundation process. Figure 4 illustrates 15 the normalized energy rate that generates the runup history along the coast, showing that the majority of the global energy is concentrated within the first hour. We can also observe that the first estimation obtained for an elliptical fault predicts the same levels of inundation as the full finite fault model in the near field, while we can observe minor differences in the regional field. This makes sense since finite fault model results become available during the tsunami monitoring stage, when time is not as critical as in the very first minutes after origin time. For completeness, we computed the travel time isochrones across the 20 Pacific Basin (Fig. 5). These computations use a dense set of rays following Sandanbata et al. (2018), which allows to include dispersive effects. We have also included the effect of the earth elasticity as shown in An and Liu (2016). This kind of maps can be computed instantly together with the very first estimation of the moment tensor and then update them.

6 Conclusions

In this study we propose a method that disregards the fine complexity of the seismic source while using fine bathymetric data 25 and a set of simplified equations to model more than 80% of the runups with enough accuracy for tsunami warning purposes up to 20 times faster. Our method also aims at rapidly predicting the spatial distribution of the run-ups using some simplifications in the tsunami equations. Despite lacking the mathematical rigorosity that we would otherwise prefer, the method we propose is not inexact within the context of an emergency response system that needs to trigger actions that can potentially save lives and reduce economic losses after the occurrence of a large earthquake. Taking into account the results of our study we can list 30 the following as the most noteworthy results:

1. Although other tsunami warning centers use linear theory as part of their operations, for instance at the PTWC (<http://unesdoc.unesco.org>), in this study we have combined it with the use of more complex sources and faster algorithms to generate a unique and simple product easy to interpret.
2. The non-complexity of the adopted source does not seem to significantly affect the results of a fast run-up estimation for emergency response purposes. By computing different levels of tsunami hazard in near-real time we estimate more accurately the extent of the area potentially affected by the tsunami, the maximum level of inundation, and how many people will be exposed to this hazard along the Chilean coast.
3. Using the methodology of Sandabata et al. it is possible to instantaneously calculate the tsunami arrival times from sources generated in the far field with enough accuracy. This can also be done via tsunami modeling, but at the expense of longer computation times.
4. When compared to other tsunami modeling codes such as JAGURS, results obtained from our method match more than 80% of the predicted runup for 15 arcsec bathymetry while obtaining the results at least 20 times faster.
5. The simple method proposed in this study provides a fast, reliable, and intuitive characterization of the tsunami threat, which in turn allows disaster mitigation agencies to take appropriate action.

15 *Code availability.* TEXT

Data availability. TEXT

Code and data availability. TEXT

Sample availability. TEXT

Video supplement. TEXT

Appendix A

A1

Author contributions. TEXT

Competing interests. TEXT

5 *Disclaimer.* TEXT

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References

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REFERENCE 2