Development of calibrated tsunami evacuation models through real-world collected data: The case study of Coquimbo-La Serena, Chile

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Abstract. Evacuation is considered the most important and effective method to save human lives in case of a tsunami. In recent years, significant efforts have been carried out to examine evacuation through computer-based models; nevertheless, challenges remain on examining the accuracy of these models in simulating real-world populations’ behavior. Along these lines, this paper uses a large call detail records (CDR) database to examine populations’ behaviors during a Mw 6.7 earthquake and tsunami evacuation in Coquimbo-La Serena, Chile, on January 19, 2019, and compare its outcomes with an agent-based model for the same case study. Results show partial correspondences between the model and the real-world data. While cell phone users’ rapid response to the emergency resembles the model’s assumption of rapid departures (alongside the rough evacuation direction), the evacuation rate of people in vulnerable areas significantly differs from the ‘total compliance’ (i.e. 100% evacuation rate) assumption of the model, which might lead to large human casualties in case of a real emergency.

1. Introduction

In the case of near-field tsunami events, evacuation is considered the most important and effective method to save human lives. In recent decades, significant efforts have been carried out to examine tsunami evacuation, particularly using increasingly complex computer-based models, e.g. agent-based, genetic algorithms, GIS, distinct/discrete element method, and system dynamic approaches [1]. Challenges remain, however, on examining the accuracy of these models in simulating real-world populations’ behavior during emergencies, given the inherent difficulties in
collecting relevant data about it. Two methods for achieving this are post-disaster questionnaire surveys (e.g. [2]) and analysis of surveillance or closed circuit television video cameras [3]. In addition to this, recent research efforts (e.g. [4–7]) have proposed to use mobile call details records (CDRs) to assess human mobility and behaviors during disasters. These are data logs generated by telecom companies to capture details related to the calls and internet connections made through their networks. As each connection is made on a specific time through the closest Base Transceiver Station (BTS), with a well-known spatial location and service area, CDRs can be used to trace back cell phone users’ moves.

In this paper, we applied a CDR database (from the largest mobile phone company in Chile, with roughly 28% of market share) as a framework to examine and calibrate the outcomes of an agent-based model for tsunami evacuation. As a case study we use the urban area of Coquimbo-La Serena, Chile, which was struck by a Mw 6.7 earthquake on January 19, 2019 (at 22:32 local time). While it did not provoke a tsunami, the quake prompted a large evacuation after a warning was released by the Chilean Emergency Management Agency (ONEMI) at 22:34 and subsequently cancelled at 22:57. Coquimbo-La Serena is an important destination for Chilean and international tourists, and the emergency occurred in the height of summer. This implied that during the earthquake the city was hosting a large floating population, with limited knowledge of evacuation procedures.

We first develop a tsunami inundation scenario and an agent-based model (e.g. [8]) for examining evacuation in the study area. Then, we analyze the evacuees’ real-world behavior as collected from the CDR database of Coquimbo-La Serena (for a period of study between 22:00 and 24:00, local time, on January 19, 2019). Lastly, we compare both outcomes and deliver conclusions and paths for future work.

2. Study area
The Coquimbo-La Serena area (29°54’ S, 71°15’ W) is a coastal touristic location 400 km north of the Chilean capital Santiago. While its foundational site (year 1544) was located 2 km inland, during the 19th century a port site was established 10 km southwest, and in the last decades the city has intensively developed its 12-km long and tsunami-exposed waterfront, through high-rise apartment buildings and touristic facilities like hotels, restaurants and a casino. We established a study area according the Chilean Emergency Management Office (ONEMI) definition of evacuation zones (see Figure 1). The recent census data (2017) shows a population of about 47,500 in this study area, which nonetheless can increase up to roughly 172,000 in certain times during the peak of the summer season. Coquimbo-La Serena is in an earthquake-prone territory, which has been affected (since the 16th century, when the Spanish conquerors arrived) by tens of destructive seismic events (the last of which occurred in 2015). In turn, documented near-field tsunamis occurred in 1849, 1922, 1943 and 2015. The 2015 event seriously affected the port area of Coquimbo, with 11 deaths and large material damages, although no losses were recorded in La Serena. See Figure 1.
3. Agent-based model and inundation scenario

We developed an ad-hoc tsunami flood model using the Multi-layered Static Dynamics Model (STOC-ML) [9], using seismic parameters provided by Carvajal et al. [10], as the best-known worst seismic scenario for Central Chile, according to the 1730 event. This was an estimated Mw 9.1–9.3 earthquake with a 600–800-km long rupture, involving average slip amounts of 10–14 m. The numerical simulation used four nested grids, with a 1512; 216; 24 and 6-meter spatial resolution for each of them, and the tsunami simulation time was 45 minutes. The expected maximum inundation depth is roughly 12 meters, while the first tsunami wave arrives at the coast around 20 minutes after the earthquake. For the agent-based evacuation analysis we used a modified PARI-AGENT model [11] (which allows dynamic coupling of evacuation and inundation parameters), to include: (1) the impact of the slope on the evacuees’ speed, according to Tobler’s exponential hiking function [12]; (2) a Rayleigh probabilistic distribution of departure times for evacuees; and (3) a routine to assign each agent with...
an evacuation speed, according to its age [13], which required to probabilistically define a certain age for each agent, based on the study area’s population pyramid from the 2017 Census. Other two parameters for the agents included (4) a random-walk parameter that introduces a random fluctuation up to 10º on the evacuation direction; and (5) a crowd potential parameter that makes the agent tend to follow the direction in which other evacuees are moving, stochastically assigned (with a probability of 0.5) to each agent.

We examined a worst-case scenario population distribution as an extrapolation of the CDR data (considering a market share of 27.6% of our providing telecom company). For computation reasons, we split the study area in 4 evacuation zones (see Figure 1). Agents were randomly distributed within each zone’s public space. From every location, the model calculated the optimal route to its closest shelter (from a total number of 34, as established by ONEMI) using the A* algorithm [14]. Two different mean departing times were tested: 3 and 8 minutes. While the former represents an ideal evacuation scenario in which most of the population departs immediately after the end of the tsunamigenic earthquake, the latter implies a likely scenario in which people tend to wait for an official warning to be issued to evacuate (based in the historical data from the Chilean tsunami emergencies of Iquique (2014), Coquimbo (2015) and Valparaiso (2017)). At each time step, the model compared the agent’s new position with the inundation data; with this information the agent’s status was updated to: (1) moving (i.e., alive), (2) dead (i.e., reached by the water) and (3) escaped (i.e. alive in the shelter). The calculation stopped after 3,600 seconds (60 minutes). We carried out 10 simulation rounds for each evacuation zone and population scenario. Table 1 and Figure 2 summarize the results.

Table 1. Summary of the outcomes from the agent-based model, for a worst-case evacuation scenario.

| Zone | Population | Average departure time (min) | Average evacuee status after t=60 min (n) | Average evacuee status after t=60 min (%) |
|------|------------|-----------------------------|------------------------------------------|------------------------------------------|
|      |            |                             | Escaped | Moving | Dead | Escaped | Moving | Dead |
| 1    | 32,244     | 3                           | 32,238.2 | 0.0    | 5.8  | 99.98   | 0.0    | 0.02 |
|      |            | 8                           | 32104.4  | 0.0    | 139.6 | 99.57   | 0.0    | 0.43 |
| 2    | 34,758     | 3                           | 34,694.6  | 30.8   | 32.6  | 99.82   | 0.09   | 0.09 |
|      |            | 8                           | 34,031.8  | 81.0   | 645.2 | 97.91   | 0.23   | 1.86 |
| 3    | 33,189     | 3                           | 32,981.7  | 136.3  | 71.0  | 99.38   | 0.41   | 0.21 |
|      |            | 8                           | 32,511.5  | 217.9  | 459.6 | 97.96   | 0.66   | 1.38 |
| 4    | 13,562     | 3                           | 13,307.1  | 222.6  | 32.3  | 98.12   | 1.64   | 0.24 |
|      |            | 8                           | 13,056.6  | 303.9  | 201.5 | 96.27   | 2.24   | 1.49 |
Figure 2. Summary of the outcomes from the agent-based model, for a worst-case evacuation scenario.

4. CDR data
We received a CDR database comprising 3,766,026 records of calls and internet connections made by 67,585 different users through a network of 56 BTS located in the study area, during a study period between 22:00 and 24:00 (local time) on January 19, 2019. From this database we sampled 40,042 users that made their first connection between 22:00 and 22:30, with the purpose of examining their evacuation behavior after the earthquake that occurred at 22:32. We conducted two levels of analysis. The first was an aggregated study based on the BTS locations (identified as either safe or vulnerable, according to our study area) within each evacuation zone. This analysis summarized every 5 minutes the number and percentage of users connected to safe or vulnerable BTS (see Table 2 and Figure 3).
Figure 3. % of users in safe and vulnerable areas, for each evacuation zone, according to CDR data.

Table 2. Total number and % of users in safe and vulnerable areas, according to CDR data.

| Time  | Vulnerable users (n) | Safe users (n) | TOTAL (n) | Vulnerable users (%) | Safe users (%) | TOTAL (%) |
|-------|----------------------|----------------|-----------|----------------------|----------------|-----------|
| 22:00 | 14,705               | 6,001          | 20,706    | 71.02                | 28.98          | 100       |
| 22:05 | 14,270               | 5,990          | 20,260    | 70.43                | 29.57          | 100       |
| 22:10 | 13,860               | 6,156          | 20,016    | 69.24                | 30.76          | 100       |
| 22:15 | 13,787               | 5,690          | 19,477    | 70.79                | 29.21          | 100       |
| 22:20 | 13,367               | 5,724          | 19,091    | 70.02                | 29.98          | 100       |
| 22:25 | 13,469               | 5,659          | 19,128    | 70.42                | 29.58          | 100       |
| 22:30 | 13,406               | 5,546          | 18,952    | 70.74                | 29.26          | 100       |
| 22:35 | 37,339               | 23,203         | 60,542    | 61.67                | 38.33          | 100       |
| 22:40 | 35,695               | 22,131         | 57,826    | 61.73                | 38.27          | 100       |
| 22:45 | 29,268               | 21,075         | 50,343    | 58.14                | 41.86          | 100       |
| 22:50 | 25,182               | 20,427         | 45,609    | 55.21                | 44.79          | 100       |
| 22:55 | 22,619               | 19,646         | 42,265    | 53.52                | 46.48          | 100       |
| 23:00 | 22,551               | 17,741         | 40,292    | 55.97                | 44.03          | 100       |
| 23:05 | 21,679               | 14,278         | 35,957    | 60.29                | 39.71          | 100       |
| 23:10 | 20,794               | 13,103         | 33,897    | 61.34                | 38.66          | 100       |
| 23:15 | 20,240               | 12,344         | 32,584    | 62.12                | 37.88          | 100       |
| 23:20 | 18,957               | 11,785         | 30,742    | 61.66                | 38.34          | 100       |
| 23:25 | 17,191               | 11,395         | 28,586    | 60.14                | 39.86          | 100       |
| 23:30 | 17,809               | 10,807         | 28,616    | 62.23                | 37.77          | 100       |
The second CDR study was an aggregated analysis based on the users’ change (or not) of position (i.e. BTS location) during the study period. Its main findings are listed below:

- 32,807 users out of 40,042 (81.93%) moved during the examined time interval (22:00-24:00).
- A ‘departure interval’ can be studied between 22:32 and 22:57 (while the former is the time of the earthquake, the latter is when the tsunami warning was cancelled). During this interval, 25,968 users moved (64.85% of 40,042). Of these, 19,404 users (48.46% of 40,042, and 74.72% of 25,968) finished up in safe zones.
- During the ‘return interval’ between 22:58 and 24:00, 24,004 users moved (59.95% of 40,042). Of these, 17,800 (44.45% of 40,042, and 74.15% of 24,004) remained in safe zones at the end. 5,210 (13.76% and 22.95%, respectively) moved from safe to vulnerable areas.
- During the ‘departure interval’, three of top-origin BTS (numbers 34, 24, 2 and 52, see Figure 1) are in vulnerable areas. Number 2 is out of the study area. Numbers 34 and 24 are roughly 500 and 100 meters away from the coastline, respectively. In line with this, top-destination BTS (52, 9, 33, 18 and 2) are in safe areas.
- Users that did not move are concentrated in BTS n° 52, 2, 53 and 22, out of the vulnerable areas.
- During the ‘departure interval’, 25,968 moving users spent (on average) 6.02 minutes to move between antennas, while during the ‘return interval’ 24,004 moving users spent (on average) 14.79 minutes to do this.
- Large numbers of people began evacuation as soon as the earthquake occurred and returned promptly after the warning was cancelled. Figure 4 shows that the users’ first changes of position are largely concentrated in the initial minutes of both examined intervals.

**Users’ first change of position**

![Departure interval (22:32 - 22:57)](image1)

![Return interval (22:58 - 24:00)](image2)

**Figure 4.** Numbers of users according to their first change of position, for a departure and a return interval.
Figure 5. Comparison between the CDR data and the outcomes from the agent-based model, for evacuation zones S1 and S3.

5. Comparison of the results of agent-based model and CDR data analysis

The analysis of the real-world CDR data delivered some interesting insights for a critical review of the agent-based model and their assumptions. To this end, in Figure 5 we overlaid the outcomes of the CDR analysis and the model. We removed from the analysis the evacuation zone 4, as its lack of BTS might lead to comparatively divergent data, as shown in Figure 3.

- The ‘total compliance’ (i.e. 100% evacuation rate) scenario assumed by the agent-based model did not have a fully realistic correspondence with the emergency of January 19, 2019. During the ‘departure interval’ roughly 65% of the users moved (evacuated?), while around 49% finished up in safe zones. In this respect, Kubisch et al. [15] reported an evacuation rate of 72.1% during the 2010 tsunami in Talcahuano, which was likely influenced by the strong intensity of the Mw 8.8 earthquake. In the case of the 2011 Great East Japan Earthquake and Tsunami, Fraser et al. [16] reported an evacuation rate of 66.4% in Kamaishi City, while Makinoshima et al. [17] showed that in Kesennuma City 90% of the residents started their evacuation before the arrival of the first devastating tsunami.
- During the initial 3 minutes of the event, rapid population response (+16.5% in the number of users in safe areas) exceeds the evacuation rate as predicted by the agent-based model (with an average departure time of 3 min) (+12.5%), as shown in Figure 5.
- The cancellation of the tsunami warning (at 22:57) approximately matches the required time for evacuation of coastline locations, which might take up to 25 minutes to reach safe areas located 2 km away (considering a standard average pedestrian speed of 1.34 m/s [18]. These two factors could explain why the growth of users in safe areas almost immediately began to slow and then stopped around that time. In line with this, the agent-based model (with an average departure time of 3 minutes) for evacuation zone 3 shows that after 25 minutes of walk roughly 80% of the agents have reached a shelter.
- In a first analysis, top origin and destination BTS show that evacuees’ main choices of evacuation direction tend to follow the logical coastland-hinterland track. While the number and location of BTS in the study area does not allow a more accurate representation of the users’
displacements, future work could be focused in a smaller sub-sample of these with larger number of connections, to enhance tracking of their movements.

- Results shown above could help the development of calibrated agent-based models, with more realistic assumptions about the evacuees’ behaviors (e.g. limited evacuation rates). In turn, these models could help to examine the consequences of a worst-case tsunami scenario if these behaviors are not properly managed before a future severe emergency.

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