frontiers in Earth Science

ORIGINAL RESEARCH
published: 24 December 2021
doi: 10.3389/feart.2021.744193

Assessment of Top-Down Design of Tsunami Evacuation Strategies Based on Drill and Modelled Data

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Tsunami evacuation drills are helpful tools aimed at reinforcing procedures and practices to reduce disaster risk, especially for vulnerable populations like school-age children. While the predictive value of evacuation drill data has been pointed out, challenges exist in enhancing the scientific examination of this information, with the final aim of improving proactive preparedness and scenario-based evacuation strategies. We address this gap by delivering a mixed-method approach that combines ground-collected data and tsunami and evacuation computer-based modelling, using as a case study the evacuation drill performance of four K-12 schools in the cities of Valparaíso and Viña del Mar, Chile. Our main objective was to critically assess the efficacy of the drill-based evacuation procedures of the schools by comparing them in the light of a likely worst-case tsunami scenario (based on historical data from the 1730 event) in these areas. Our findings show that, although a large number of evacuees from the schools could rapidly achieve evacuation to safe locations, complete evacuation (that is, 100% of evacuees reaching the shelter) is only achievable if the Evacuation Onset Times (i.e. the time, relative to the earthquake, of the first evacuee departing from the school) are shorter than demanding threshold values (between 4 and 14 min), as the result of the tsunami's short arrival time and rapid inland penetration. Hence, we suggest complementing existing national-level protocols with a more detailed, case-by-case management approach, comprising a more precise tsunami inundation modelling and a focus on the characteristics of each of the schools (relative to the student body composition such as age and others, the staff, and the geomorphological conditions of its location). Moreover, we suggest that tsunami evacuation drills in Chile pose significant research opportunities yet to be fully grasped.

Keywords: tsunami, evacuation, agent-based modelling, schools, drills

OPEN ACCESS

Edited by:
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Reviewed by:
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Hermann Marc Fritz, Georgia Institute of Technology, United States

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Specialty section:
This article was submitted to Geohazards and Georisks, a section of the journal Frontiers in Earth Science

Received: 19 July 2021
Accepted: 29 November 2021
Published: 24 December 2021

Citation:
León J, Catalán PA and Gubler A (2021) Assessment of Top-Down Design of Tsunami Evacuation Strategies Based on Drill and Modelled Data. Front. Earth Sci. 9:744193. doi: 10.3389/feart.2021.744193

INTRODUCTION

In tsunami-prone countries, timely evacuation is the most important and effective method to save human lives (Shuto, 2005). This is especially relevant in countries where the lag time between tsunami generation and first arrival can be as short as less than 10 min (Fritz and Kalligeris, 2008; Williamson and Newman, 2019). This has been evidenced in Chile, where recent earthquakes in Pisagua (2014) and Illapel (2015) triggered tsunamis with arrival times shorter than 15 min (Catalán et al., 2015; Aránguiz et al., 2016). These short times severely constrain the response of the population exposed to this hazard, where school-age children (i.e., persons aged 18 and younger) are particularly vulnerable, due to several reasons. It has been shown that very young populations have higher mortality rates in tsunamis as the result of difficulties related to reduced mobility and low pedestrian velocity that compromise their evacuation capacities (Birkmann et al., 2010; González-Riancho et al., 2015; Yun and Hamada, 2015; Latcharote et al., 2018). Buchmüller and Weidmann (2006) estimated that kids age five and under walk at an average speed of roughly 0.6 (meters/second), which is less than 40% of that of a person in his/her late teens. Additionally, Peek (2008), under a broader disaster-related perspective, points out that infants and young children are physically vulnerable to disasters due to their dependence on adults. On the other hand, older children and adolescents (while also at risk for injury or death) can also develop behavioural, psychological, and emotional issues during and after a disaster.

One widely established way to strengthen preparedness is to conduct evacuation drills to reinforce procedures and practice (UNESCO/IOC, 2020). However, tsunami evacuation drills are frequently criticized for their limited participation levels and other aspects, including the need to halt daily activities, the possible creation of unpleasant feelings in residents and tourists, and the impossibility of reflecting the real state of stress of the evacuees (Mas et al., 2013; Poulos et al., 2018; Sun and Yamori, 2018). Nevertheless, they can be a useful tool to reduce the population's vulnerability. They allow to test the feasibility of the tsunami evacuation plans and highlight possible flaws (Mas et al., 2013), and also to familiarize exposed populations with the hazard, therefore contributing to timely evacuations and less human casualties (Løvholt et al., 2019). Moreover, they do appear to contribute to reducing evacuation times (Vásquez et al., 2018). In consequence, pupils and staff from schools in floodable areas are required to participate in training as a well-established disaster prevention education activity. Furthermore, drills aim at developing "the practical attitude and ability of children for safe evacuations and the willingness to act for the safety of other people, groups, and communities at home and in the community, at the time of disaster" (Oka et al., 2020, p.279). In tsunami-exposed countries like Chile, the authorities periodically carry-on evacuation exercises, some of them exclusively aimed at educational institutions.

School drills also offer research opportunities. They comprise, for instance, active research to grasp non-experts' perceptions and actions, with the final aim of improving proactive preparedness and scenario-based evacuation strategies (Nakano et al., 2020; Sun, 2020). Also, Vásquez et al. (2018) examined a tsunami drill in Iquique, Chile, to unveil a range of issues that might impact the actual evacuation behaviour during an emergency, such as the information provided by the families of the pupils, which in some cases could be contradictory with the school evacuation plan. Poulos et al. (2018) used a training tsunami drill of a K-12 (kindergarten to 12th grade) school in Iquique, Chile, to validate an agent-based evacuation model of the buildings of the school, using video analysis of the actual behaviour of the pupils during the exercise. Oka et al. (2020) point out that while children tend to participate passively in evacuation drills, real disaster response evacuation requires active and practical decision-making. Therefore, they suggest using Information and Communication Technology Equipment (ICTE), specifically tablets equipped with planar maps and street view applications, to increase the effectiveness of in-classroom training for subsequent street evacuation.

The above studies focused on subjective assessments or specific data sources. On the other hand, Sun and Yamori (2018) underline the predictive value of evacuation drill data. However, they also point out that there is a lack of scientific examination of this information, which could be enhanced through information technologies, including Global Positioning Systems (GPS) and simulation models. These technologies can also help people to understand and manage tsunami risk information effectively. Nevertheless, integration between information technologies and tsunami evacuation drills is scarce (Sun and Yamori, 2018). For instance, challenges remain on using these technologies to critically assess the actual significance of tsunami evacuation drills as a disaster prevention strategy, given different hazard scenarios. This gap is crucial in schools, where particularly vulnerable people gather and spend several hours a day. Therefore, this paper aims at providing a significant contribution to this research area by delivering a mixed-method approach that combines fieldwork data and tsunami and evacuation computer-based modelling. We used as case study the evacuation drill performance of a group of K-12 schools in the cities of Valparaíso (33°02′50″ S, 71°36′46″ W) and Viña del Mar (33°00′55″ S, 71°33′00″ W), Chile. Our main objective was to critically assess the efficacy of the drill-based evacuation procedures of these schools, by comparing them in the light of a likely worst-case tsunami scenario (based on historical data from the 1730 event) in these areas. In turn, these findings might support an evidence-based review and enhancement of current disaster risk policies and emergency response practices not only in these two cities, but also in other Chilean, South American and global tsunami-prone communities.

The article is structured as follows. **Section 2** introduces the methodology, including the examined evacuation drill and schools, and describes the modelling approaches. **Section 3** delivers the research outcomes, which we discuss in **section 4**. Lastly, **section 5** addresses the main conclusions of the paper.

MATERIALS AND METHODS

The Tsunami Evacuation Drill on September 5, 2019

The Valparaíso region in Chile (where the city of the same name and Viña del Mar are located) is an earthquake- and tsunami-prone territory, struck by destructive near field earthquakes in 1,575, 1,647, 1730, 1822, 1906 and 1985 (Lomnitz, 2004). Among these, the July 8, 1730, Mw 9.1–9.3 event triggered a destructive tsunami (Carvajal et al., 2017). Klein et al. (2017) suggest that the persistent 300 years long gap between mega-earthquakes in this area might be filled soon by a large seismic event, which in turn could trigger another destructive tsunami. Since 2010, the local branch of the Chilean Emergency Management Agency (OREMI and ONEMI, respectively, by their Spanish acronym: Oficina Nacional de Emergencia del Ministerio del Interior y Seguridad Pública) carries out disaster prevention in this region, comprising recurrent tsunami evacuation drills, aimed at fostering a self-care and prevention culture across the population (ONEMI, 2014a). This approach is part of the risk management strategy ruled by the National Civil Protection Plan, passed on March 2002 by the Chilean government, which establishes general guidelines that are applied nationwide with little local variations, if any. Recently, drills have been conducted in the Valparaíso region one each year in 2012, 2013 and 2016. ONEMI enacted the latest training exercise on September 5, 2019, at 11:30 AM. As in the rest of the country, this emphasis on evacuation aims at fostering community-based education and awareness, the importance of which was demonstrated during the 2010 tsunami, where the tsunami arrived before official warnings reaching the population (Fritz et al., 2011).

Nearly 207,060 people and roughly 200 schools from 19 municipalities participated in this recent drill (ONEMI, 2019). Prior to it, an information campaign through the written and internet media informed the population about the drill's date, but the exact timing was not announced beforehand, except notifying it would occur during morning time. To trigger the evacuation, ONEMI sent a text emergency announcement to smartphones which resembled the newly implemented (in this region) SAE (Sistema de Alerta de Emergencia/Emergency Alert System) messaging system. At the same time, coastal klaxon alarms (where available) sounded. The population used demarcated evacuation routes to access previously designated safe assembly areas, each located at an elevation of at least 30 m a.s.l. These were open-space shelters which could accommodate numerous people, who could reach them by following the street network on foot. Most of these locations had been defined several years prior by the local emergency management departments (with ONEMI's support) using as reference the official tsunami charts developed by the Chilean Navy Agency (SHOA, 2012), which are based on a deterministic hazard assessment using the historical scenario of 1730, albeit with its prior estimated magnitude of Mw 8.8. The magnitude has been updated recently to Mw 9.1–9.3 by Carvajal et al. (2017).

Collecting Drill Data From Schools

During the 1730 Great Valparaíso Earthquake and Tsunami Commemoration (July 8, 2019, 2 months prior to the drill), tsunami awareness seminars were given by local scientists at several schools (Zamora et al., 2020). We chose four of these schools for analysis during the evacuation drill according to their exposure, giving greater weights to highly tsunami-exposed areas in lowlands. Two of them are in Valparaíso: Escuela Grecia (G) and Liceo Matilde Brandau de Ross (MB), and two in Viña del Mar: Colegio María Auxiliadora (MA) and Colegio República de Colombia (RC). These schools are located at 500, 200, 800, and 800 m from the coastline, with elevations of roughly 6, 4.5, 6, and 7.5 m.a.s.l (respectively). Moreover, according to our tsunami flood model explained in **section 2.3**, the expected inundation depth at these schools' locations could be as high as 1.1, 2.9, 3.6, and 3.4 m, respectively (see **Figure 1**). To assess the performances of the schools during the drill, we assigned at least two examiners to each of them. One was in charge of tracking and recording (using video cameras and GPS devices) the trajectory of the first evacuee (henceforth called "head") belonging to the first evacuation group of pupils, from the school gate to the designated safe assembly area. Concurrently, the other examiner did the same with the last pupil of the closing group (henceforth called "tail"). In addition, before leaving with the back of the group, we recorded the departure time of each pupil to assess the evacuation rates. We analysed this GPS data in Google Earth Pro and QGIS systems to establish the performance metrics of each school, required as inputs for an agent-based model (described in **section 2.3**).

The location of the four examined schools and their target routes are shown in **Figure 1A**. **Table 1** shows the collected data during the drill, including the counted evacuees (i.e. number of pupils involved in the exercise), the time lapse between the departure of the head and tail pupils, the total evacuation time, the total distance, and the average evacuation speed, for five different cases. We measured the first four of these according to the percentage of completion of the evacuation trajectory: 25% (v1), 50% (v2), 75% (v3) and 100% (v4). Similarly, we calculated the fifth evacuation speed (v5) as the ratio between the accumulated distance and the accumulated time, from the start until the DEM slope reached 3° (i.e. the threshold where the gradients of the routes become significantly steeper, as shown by **Figure 2**). The objective of this approach was to assess the fluctuating impact of the terrain slope on pedestrian evacuation speeds, as shown by Tobler's basic hiking function (1993). Hence, we used speeds v1 to v5 as inputs for the evacuation model explained in **section 2.3**.

It is also noticeable (as shown in **Figure 1B** and **Figure 1E**) that in MB and RC schools the head and tail pupils took different evacuation routes. Additionally, **Figure 2** shows the gradients of the measured paths of the head pupils in Valparaíso and Viña del Mar, which reveal that final destinations were located farther above the 30 m elevation contour. **Figure 3** shows the number and percentage of departed pupils after ONEMI issued the evacuation warning. In the four examined schools, the first counted persons began to evacuate roughly one or 2 minutes following the warning. The lapse between the head and tail pupils varies from 3 min (MB school, 267 pupils counted) to 5 min and 40 s (MA school, 826 pupils counted).

Agent-Based and Tsunami Flood Model

We aimed to accurately simulate the evacuation trajectories of each school to support subsequent integration with tsunami inundation scenarios. To do this, we further adapted the agent-based model developed by Arikawa (2015) and extensively described in León et al. (2020). This model couples a dynamic bottom-up evacuation simulation of the population (where each individual is represented by an 'agent') with a single tsunami inundation scenario. Using as inputs the initial positions of the agents, their assigned evacuation routes and their walking speeds (which in our simulation can be affected by the terrain

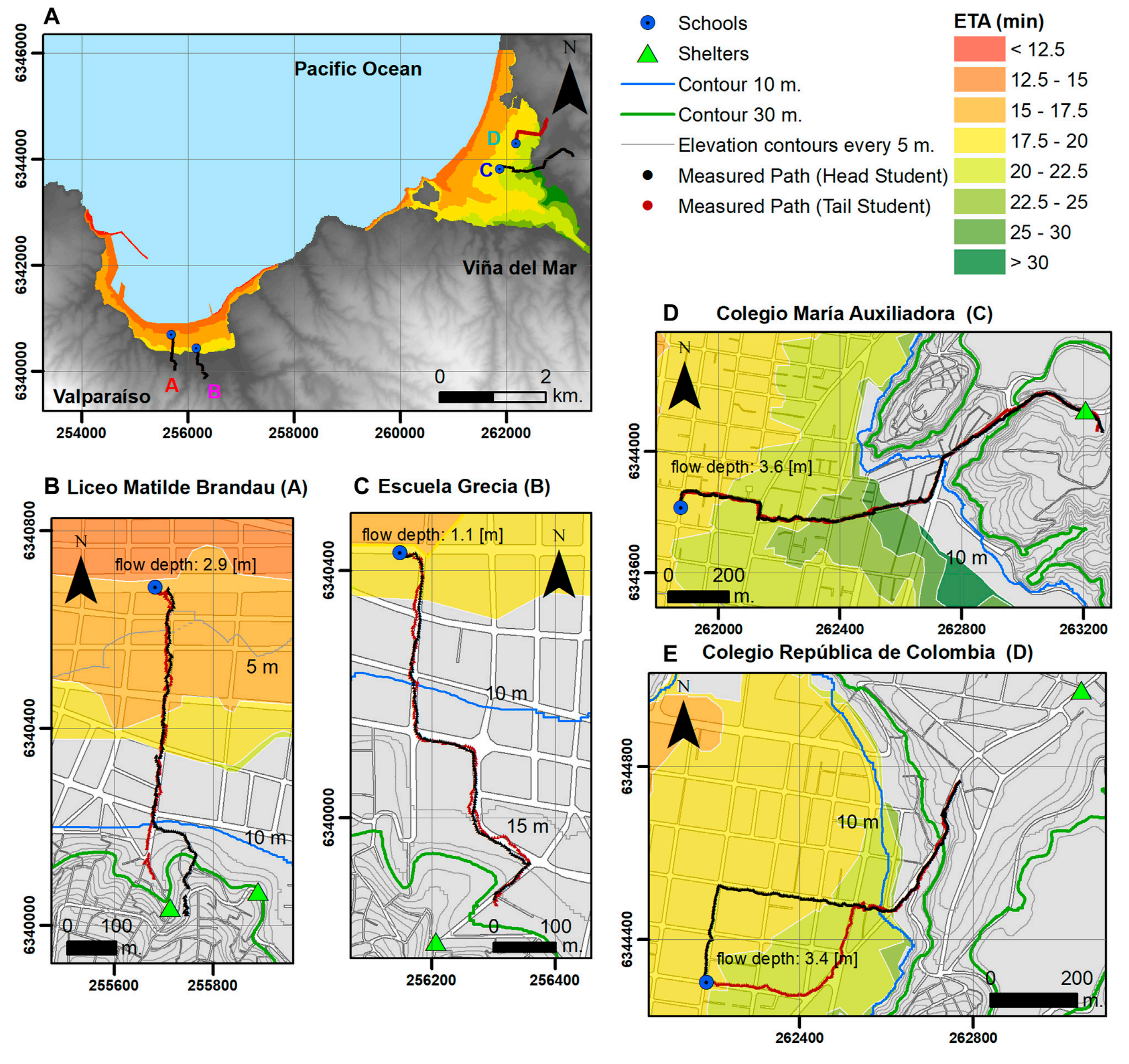

FIGURE 1 | Study areas in Valparaíso and Viña del Mar, including the estimated tsunami inundation area and arrival time, and the location of the four examined schools, their estimated inundation depths and their evacuation routes.

slope), the model updates at each time step (1 s) the agents' locations. Then, it compares these with the inundation data to update the agents' status: 1) moving (i.e., alive but not yet in the shelter) 2) affected (i.e., reached by the water), and 3) escaped (i.e., alive in the shelter).

To validate this model usefulness to simulate each school's performance, first we developed two separate evacuation sub-models for every school, simulating only the head and tail pupils, respectively. For each sub-model, the input data included the evacuation route (with real-world street width and terrain slope) and evacuation speeds v1 to v5 (measured with GPS during the drill), which we examined with and without the impact of terrain slope on them. Then, we used QGIS and MATLAB to spatialize and display each sub-model's outputs and compare them with real-world data. Results showed good agreement (see **Figure 4**), allowing us to subsequently use the agent-based model to simulate the whole group of pupils' evacuations for each examined school, in case of a catastrophic tsunami scenario.

Using the drill GPS-collected data as input, we modelled a range of evacuation scenarios for each school, comprising all the pupils (agents). We considered two routing options, head and tail, and five possible pedestrian speeds (v1 to v5). We also considered varying Evacuation Onset Times (EOT), from 0 to 20 min. These indicate the time, relative to the earthquake, of the first evacuee

TABLE 1 | Synthesis of examined schools in Valparaíso (G and MB) and Viña del Mar (MA and RC).

Name	City	Location	Number of pupils involved in the evacuation drill	Examined pupil	Average evacuation speed/25% of the trajectory (m/s)	Average evacuation speed/50% of the trajectory (m/s)	Average evacuation speed/75% of the trajectory (m/s)	Average evacuation speed/100% of the trajectory (m/s)	Average evacuation speed/3° slope limit (m/s)	Total evacuation time (sec.)	Total distance (m)	Time lapse between head and tail pupil (sec.)
Escuela Grecia	Valparaíso	33°02′50″ S, 71°36′40″ W	267	Head	1.31	1.25	1.37	1.34	1.35	553	742.0	192
				Tail	1.31	1.23	1.2	0.99	1.18	808	803.7	
Liceo Matilde Brandau de Ross	Valparaíso	33°02′41″ S, 71°37′00″ W	267	Head	1.44	1.49	1.42	1.14	1.48	720	821.9	180
				Tail	1.42	1.33	1.35	1.15	1.2	614	705.0	
Colegio María Auxiliadora	Viña del Mar	33°01′06″ S, 71°32′59″ W	826	Head	1.39	1.37	1.35	1.25	1.40	1,465	1837.5	340
				Tail	1.09	1.17	1.17	1.11	1.16	1,543	1718.4	
Colegio República de Colombia	Viña del Mar	33°00′49″ S, 71°32′46″ W	606	Head	1.02	0.95	0.92	0.85	0.94	1,239	1,055.0	338
				Tail	1.39	1.19	1.01	0.94	1.07	1,051	987.2	

departing from the school. After this, the departure rate of the other agents is the one shown in **Figure 3**. Lastly, we also tested the model with and without considering the impact of terrain slope on evacuation speeds.

The Chilean coast is exposed to catastrophic, large-scale tsunamis, as it occurred in the 1960 Valdivia and 2010 Maule events (triggered by Mw 9.2 and Mw 8.8 earthquakes, respectively) (Fujii and Satake, 2012). In line with this possibility, we coupled each of the school evacuation simulations with a worst-case known tsunami inundation scenario for the Valparaíso-Viña del Mar area (similar to the 1730 Great Valparaíso Earthquake and Tsunami), as described in León et al. (2019) (whose inundation area is shown by the estimated arrival times (ETA) in **Figure 1A**). This scenario, developed in the Storm Surge and Tsunami Simulator in Oceans and Coastal Areas (STOC) simulator (Tomita et al., 2006), used as an initial condition an Mw 9.1–9.3 earthquake offshore Valparaíso (Carvajal et al., 2017). The model shows that the tsunami arrives at the coast in roughly 12.5 min after the earthquake occurs, reaching the MB and G schools in 15 and 17 min, respectively, while MA and RC schools are flooded in 19 min. In Valparaíso, the waters penetrate inland up to 750 m, while in Viña del Mar the maximum inland penetration reaches approximately 800 m in the urban area and 3 km along the Marga-marga Creek. See **Figure 1** (a).

The coupled inundation-evacuation model allowed us to estimate the feasibility of the drill-based evacuation procedures to escape the incoming tsunami, as it delivered a time-dependent count of moving, affected, and escaped agents.

RESULTS

Figure 5 and **Figure 6** show a synthesis of the temporal evolution of the escaped and affected agents, combining (for the head and tail routing scenarios) the results of 10 simulations (i.e. five evacuation speeds and two cases: with and without considering the impact of the terrain slope on them), for different EOTs. Overall, in the case of short EOTs (2–4 min, which imply an almost immediate departure after the earthquake has finished), if the performance of each school is like its drill head pupil, it is possible to rapidly achieve complete evacuation (that is, 100% of evacuees reach the shelter). This means that, after the first agent has arrived at its safe destination, it takes roughly another 5, 10, 12 and 15 min (in the case of G, MA, MB and RC schools, respectively) to complete the evacuation process. In the case of performances like the tail pupils, for these same EOTs, evacuation completion takes longer in the case of G school (around 7.5 min), while RC school maintains the same 15 min and MB school reduces to 5 min (probably due to the change to a shorter route, see **Figure 1B** and **Table 1**). MA school, in turn, can reach only up to roughly 58% of escaped agents, as the rest would be reached by the incoming tsunami.

If EOTs extend, it becomes progressively hard to achieve full evacuation. For instance, it is also interesting to see in **Figure 5** and **Figure 6** that EOTs above 14 min might rapidly lead to 100% of affected evacuees, for both the head and tail routing options. In

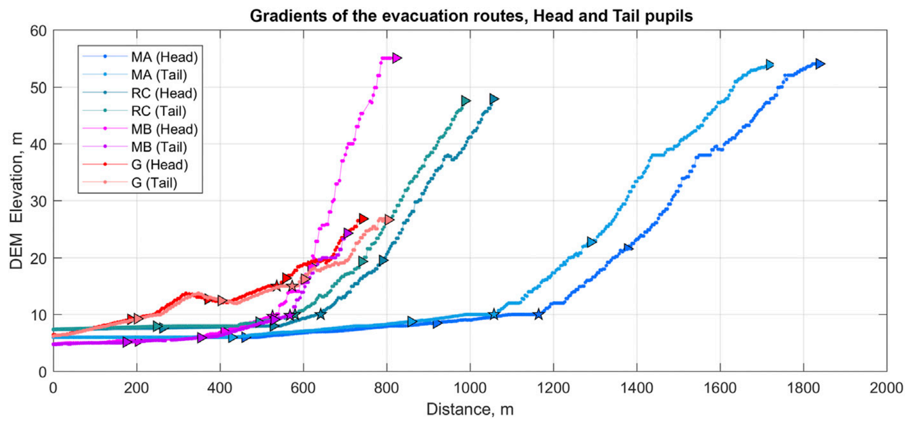

FIGURE 2 | Gradients of the evacuation routes of the four examined schools.

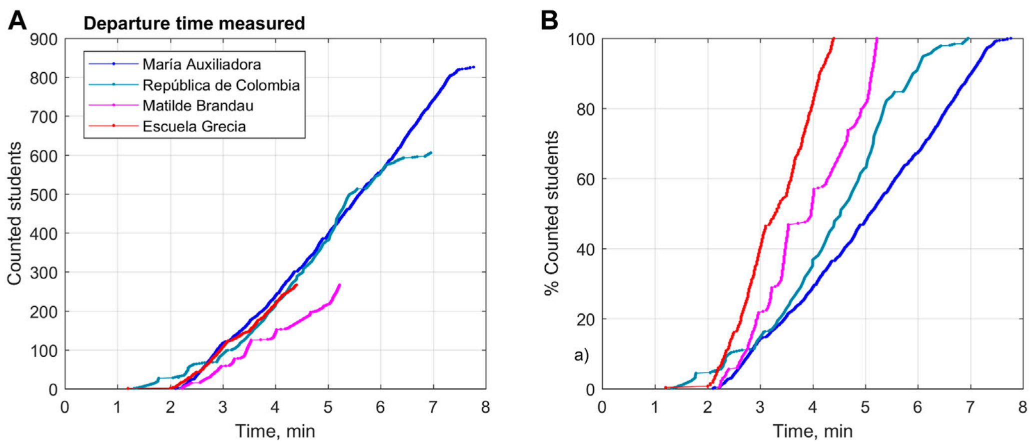

FIGURE 3 | Departure time of the four examined schools.

this respect, as **Figure 7** and **Figure 8** show, full evacuation can only be achieved if the schools begin to evacuate no more than 14 (G), 10 (MB), 8 (MA) and 3 min (RC) after the quake, respectively. If evacuation begins after that, the percentage of affected evacuees rapidly increases according to every added minute of delayed departure, for example to roughly 30 and 75% in the case of G school (tail route). This case might not be significantly dependent on the examined evacuation speed, as it shows little dispersion on the rate of affected evacuees. On the contrary, the percentage of affected agents in RC school (tail route case) varies between 5 and 80%, with an average of 50% (EOT = 9 min).

Critically, there is a threshold time beyond which 100% of evacuees will be affected: 17–18 min for G school, 14–15 min for MB school, 15 min for MA school, and 11–14 min for RC school. These large percentages of affected evacuees are the outcome of the short arrival time and rapid inland penetration of the tsunami: 12.5 min and 15–20 min to reach the school sites. These results depend on the school location, relative to the coastline and the shelter, and the topography (see **Figure 1A**). For instance, MB and G schools in Valparaíso are similarly close to the 30 m elevation contour (around 800 m, which facilitates rapid access to safe high ground), but MB trajectories face a steeper topography on the last section (up to 20%), and it is also closer to the coastline, which means that it can be reached earlier by the tsunami. In contrast, MA and RC schools (especially the latter) ought to traverse long distances (roughly 1,000 and 600 m, respectively) without any significant elevation gain. During these sections of their trajectories, their elevations remain below 10 m.a.s.l. which is approximately the altitude reached by the maximum tsunami penetration (inundation line) in the study area in Viña del Mar (in the case of Valparaíso, this value reaches 8,9 m). It is interesting that RC fares worse than MA despite being nearly at half the distance from its shelter than the latter. This indicates that other elements might be in play for an adequate response, for instance RC's evacuation trajectories include a segment parallel to the coastline (i.e. not moving away from the tsunami attack).

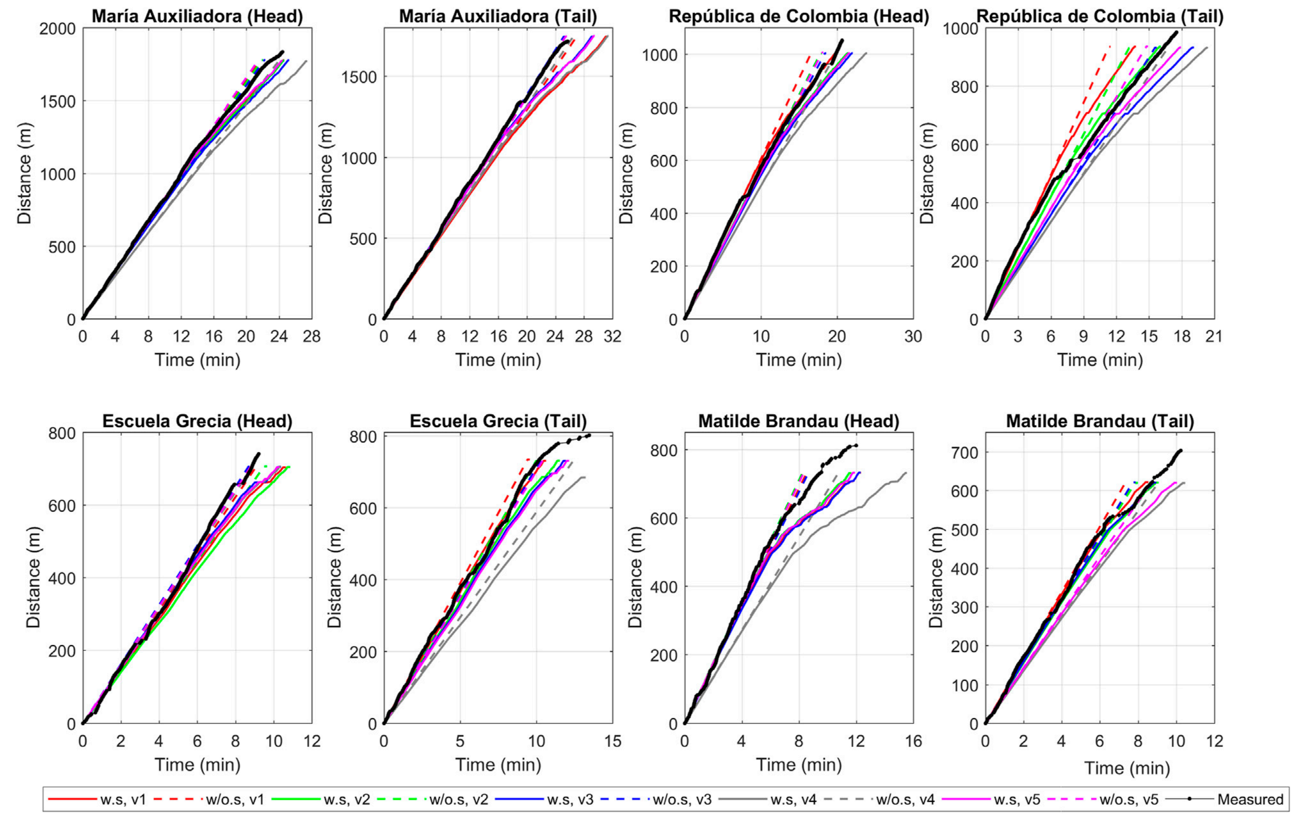

FIGURE 4 | Comparison between the surveyed and modelled evacuation speeds of the four examined schools.

As shown by **Figure 7** and **Figure 8**, the steep topography in the last sections of the evacuation routes (see **Figure 2**) has disparate impacts across the examined schools (although noticeably limited). If the influence of the terrain slope on evacuation speeds is considered in the model, largest changes are as follows. G school (head route, EOT = 16 min) increases its average percentage of affected pupils from 50 to 60%, approximately. MB school (tail route, EOT = 11 min) grows from roughly 2–5%. MA school (tail route, EOT = 9 min) augments from around 5–8%. Lastly, RC school (tail route, EOT = 8 min) increases from 20 to 27%, approximately.

DISCUSSION

Experiences collected from the 2011 Great East Japan Earthquake and Tsunami show the critical importance of proper tsunami evacuation protocols and training, especially for schools and their vulnerable pupils. This example is particularly significant for Chile, as the lag times between the earthquake and the arrival of the tsunami during that event (roughly 30–60 min, see for instance Hayashi et al. (2011)) were significantly larger than those commonly recorded in the South American country. In this respect, the 'Kamaishi Miracle' and the Okawa elementary school (Ishinomaki City) provide contrasting examples. In the former, about 3,000 elementary and junior high school pupils successfully evacuated following the disaster prevention education previously given (including frequent drills) and taking last-minute decisions based on their own judgment (Katada and Kanai, 2016). In the latter, 74 of 78 pupils, and 10 out of 11 teachers, died in the tsunami, despite being the school located right next to a high hill that could had served as shelter. As Hiroyuki (2016) points out, the Okawa school did not have a proper updated plan to deal with this threat, even though the Board of Education of Ishinomaki City had asked schools to prepare one. Moreover, the lack of preparedness led to indecision and stagnation by the school's authorities (Lloyd Parry, 2017). As a result, children and teachers waited for more than 50 min in the playground until the tsunami arrived.

Sixteen primary and secondary schools in Valparaíso and 43 in Viña del Mar are in tsunami-exposed areas. As requested by the Chilean Board of Education, all of them have established emergency response protocols for tsunamis and undergo periodic evacuation training as part of regional-level evacuation exercises enacted by ONEMI. Our analysis (combining fieldwork data and computer-based modelling) for four case studies shows that, despite these frequently practiced drill procedures, safe evacuation might not be fully achievable for a significant number of these schools' pupils in case of a large near-field tsunami, if short EOTs cannot be achieved. In this respect, the 2019 drill-surveyed average pedestrian evacuation speeds for the case studies (from 0.92 to 1.49 m/s) are in line, for

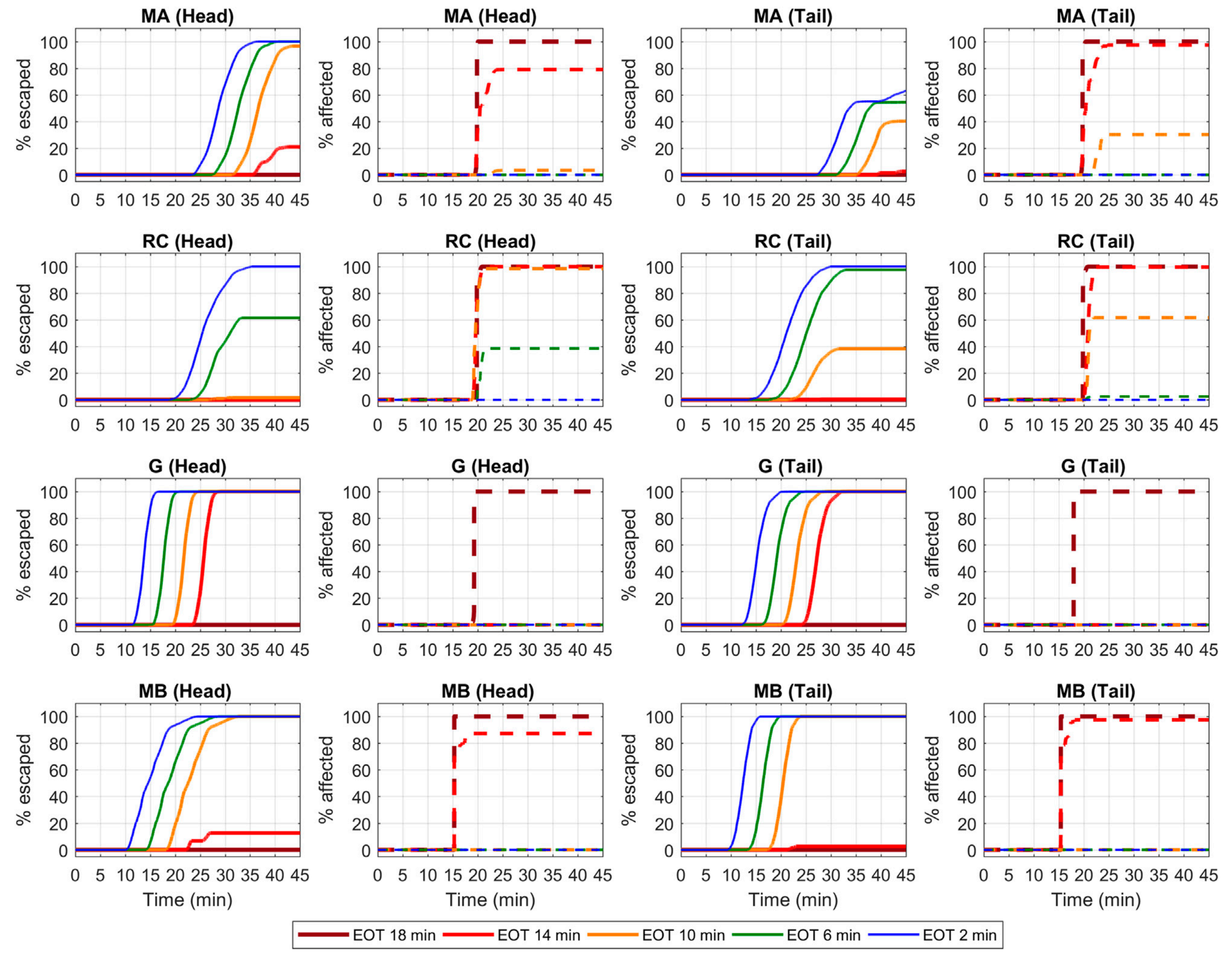

FIGURE 5 | Evacuation curves of the four examined schools (EOT = 2, 6, 10, 14, and 18 min.

instance, with the results reported by Buchmüller and Weidmann (2006) and by (Yosritzal Putra et al., 2020), suggesting a normal performance. Moreover, the data also shows that the pupils behaved according to practiced protocols, rapidly leaving their school buildings, and following the shortest paths to the designated shelters. However, they did not always arrive at them, as shown by the routes of the Grecia and the República de Colombia schools in **Figure 1C** and **Figure 1E**, respectively.

Despite these overall appropriate evacuation behaviours, long distances to safe locations (up to roughly 1,840 m) combine with steep terrain slopes (see **Figure 2**) that could diminish evacuation speeds, and with short tsunami-arrival times, to make full evacuation unlikely in the case of a catastrophic tsunami event. This dangerous situation could occur if the schools' evacuation onset times (which include previous indoor evacuation) exceed threshold values between 3 and 14 min. These short windows impose severe restrictions for an evacuation. On the other hand, our results show that the terrain slope, frequently included on tsunami evacuation modelling (Sahal et al., 2013; Schmidtlein and Wood, 2015; Solís and Gazmuri, 2017) might have a limited impact on pedestrian speeds and therefore on the number of affected evacuees in our case studies. A reason for this could be that, while Tobler's classic hiking function (Tobler, 1993) predicts significant speed reduction as slope increases, pedestrians (especially young ones, like the K-12 pupils included in this research) might be able to sustain evacuation speed along steep slopes, if these segments do not extend excessively. In our case studies, route sections with terrain slope above 3° do not last for more than 600 m, approximately (see **Figure 2**). In this respect, we note that (Yosritzal Putra et al., 2020) found out that during short walking distances (190–515 m) in a tsunami evacuation drill in Padang, Indonesia, children walked at faster speeds compared to adults in a long-distance.

Existing and frequently-practiced evacuation protocols are based on reasonable nation-level criteria: aiming at reaching an open public space with an elevation of at least 30 m, out of the floodable area, using the shortest possible route, which are enforced by municipal emergency offices following ONEMI's guidelines. Moreover, as shown by the 2019 drill report (ONEMI, 2019), the coastal municipalities of the Valparaíso

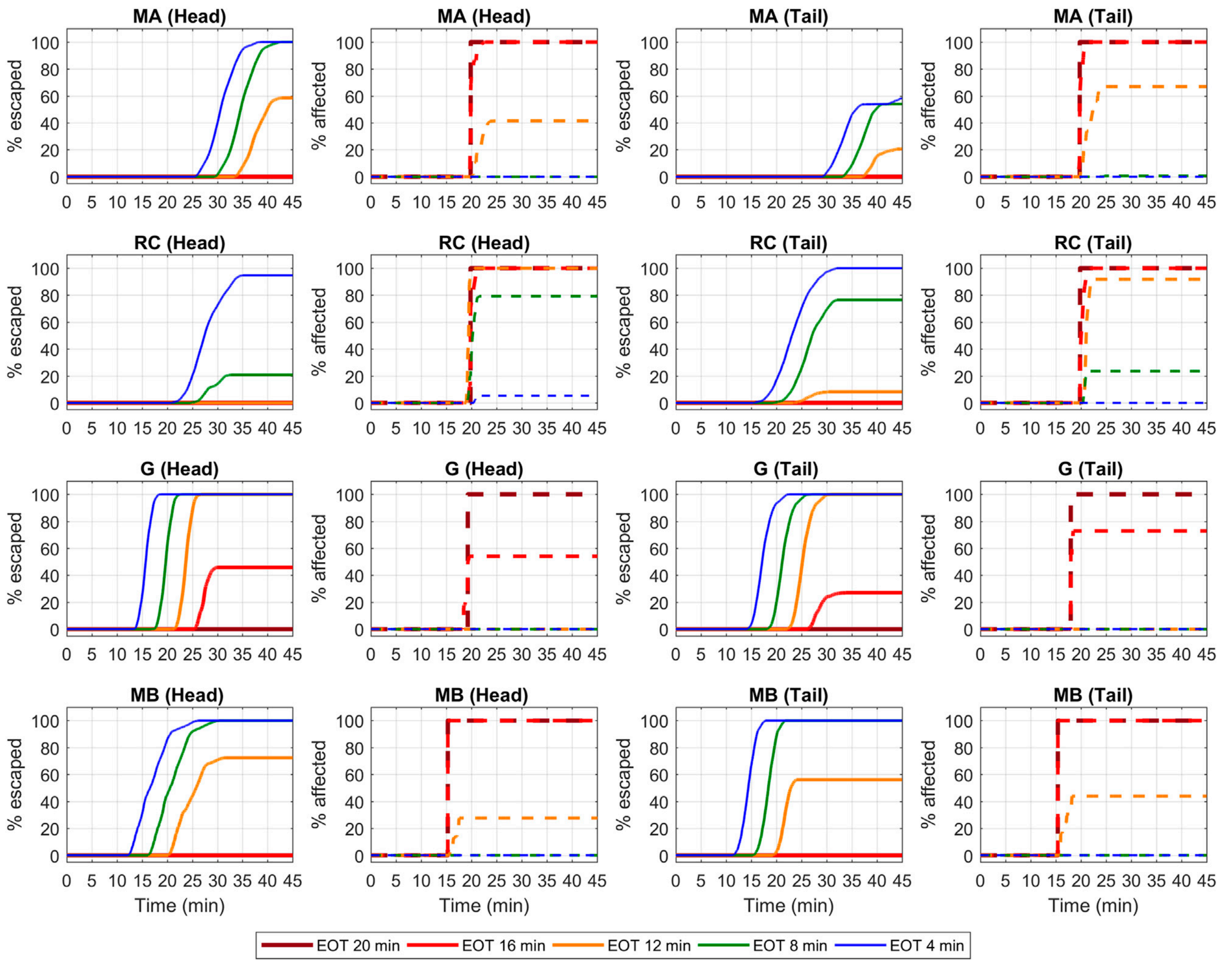

FIGURE 6 | Evacuation curves of the four examined schools (EOT = 4, 8, 12, 16, and 20 min.

region have disparate accomplishments of these guidelines (e.g., six of 21 municipal emergency plans had not been updated when the drill was held), which highlights the importance of a nation-level guidance for disaster risk reduction. However, as demonstrated by our results, this top-down approach might not be sufficient to adequately cope with a worst-case scenario in cities like Valparaíso and Viña del Mar, given the demanding on-site conditions as those underlined above. Hence, we suggest complementing existing national-level protocols with a more detailed, case-by-case and bottom-up approach, comprising at least two further lines of development. First, recent advances in tsunami hazard microzoning (Zamora et al., 2021) allow to examine the tsunami threat as the outcome of multiple stochastic earthquake scenarios, leading to a qualitative, spatially-detailed, hybrid characterization of the hazard through the combination of resulting flow depths and arrival times. This type of microzoning could allow the development of more detailed evacuation strategies for each school, aiming at finding the least hazardous routes (Zamora et al., 2021) instead of the shortest ones. Moreover, probabilistic tsunami modelling allows better grasping of non-linear effects such as refraction, which would impact on the extension and duration of the inundation.

Second, the ongoing approach to evacuation planning could also be enriched with improvements based on the judgment of the staff of the schools (collected, for instance, after a drill), or inputs provided by the community, real-world experts and academia, with the final aim of fostering active and practical decision-making during an emergency (Oka et al., 2020). As shown by Nakano et al. (2020), consensus-making between disaster experts and non-experts can lead to establishing improved and proactive preparedness activities by non-expert teachers. Moreover, evacuation models like the one included in this paper could help schools to critically examine current evacuation scenarios and related information (e.g., evacuation maps) to support enhanced responses in a disaster. In line with this, autonomous actions to deal with last-minute changes (e.g., blocked roads due to the tsunamigenic earthquake or a remarkably rapid arriving tsunami) are not currently prepared

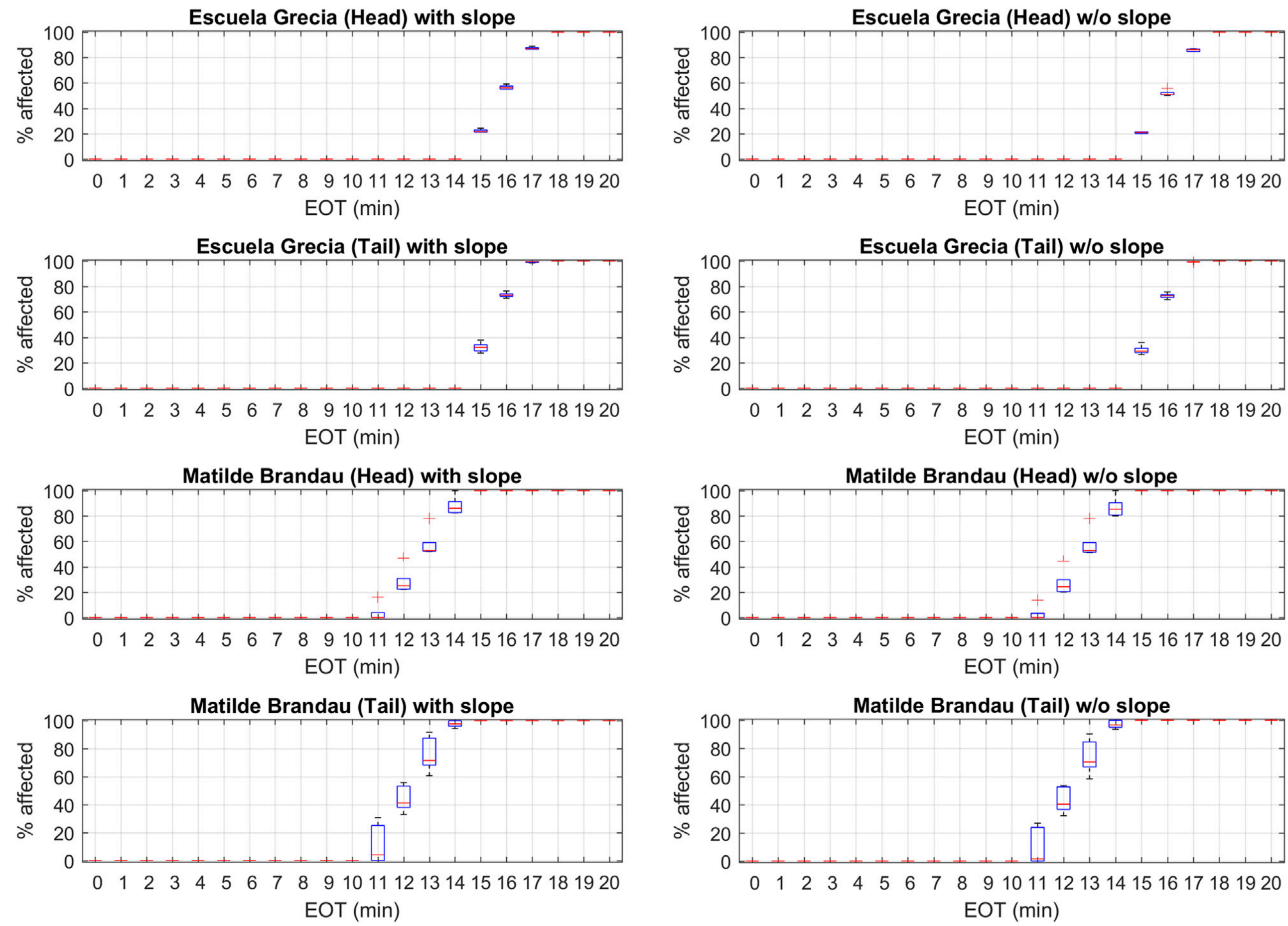

FIGURE 7 | Box plots showing the percentage of affected evacuees of the G and MB schools in Valparaíso, for evacuation speeds v1 to v5.

in the examined area. For instance, most schools in the floodable areas are close to suitable high-rise buildings that could serve as tsunami vertical-evacuation refuges, therefore significantly shortening evacuation times. Nevertheless, ONEMI recommends vertical evacuation only as a second alternative only if horizontal escape is not feasible (ONEMI, 2014b).

Following these lines of development, the evacuation potential of each school could be assessed and improved in the light of its particularities, for a range of disaster scenarios, under the guidance of local municipal emergency officers. These singularities might include geomorphological features (e.g., location, expected tsunami arrival time and flow depth, condition of the evacuation routes and/or shelter) and the characteristics of pupils and staff. However, this approach could imply significant difficulties for local emergency officers and the non-expert teachers and staff of schools, due to a lack of scientific knowledge or updated data. These difficulties could be mitigated, for instance, with recent efforts (Newton, 2012; Wood et al., 2017) to develop online user-friendly simulation platforms, where diverse types of users could build disaster scenarios and also test different evacuation responses to them. These results, in turn, could be used for both management, educational and training purposes.

Lastly, we underline that there are significant opportunities for increasing the use of tsunami evacuation drills in Chile as sources of data for scientific research, ultimately leading to better evacuation planning and emergency management policies. Currently, during every drill ONEMI coordinates hundreds of volunteers that act as examiners of the activity, having to complete an assessment checklist focused on both the evacuees' performance and the characteristics of the evacuation routes. However, more accurate data is not typically surveyed, nor are information technologies included in these analyses. In line with these, protocols for gathering and assessing information, like the one introduced in this work, complemented with other technologies like drone imagery and automatic processing of videos from traffic cameras, could be also enforced by ONEMI. This gathered data could be used, for instance, for the validation of evacuation models for enhancing future evacuation planning (see for instance Solís and Gazmuri (2017)). In line with this, while the focus of this study was on K-12 students, we suggest that our approach is also helpful to examine other emergency scenarios and populations. These include (for instance) night-time evacuation drills for the general population (as the one conducted by ONEMI in the northern coast of Chile in 2012), which aim to train and examine the inhabitants' response during other times apart from

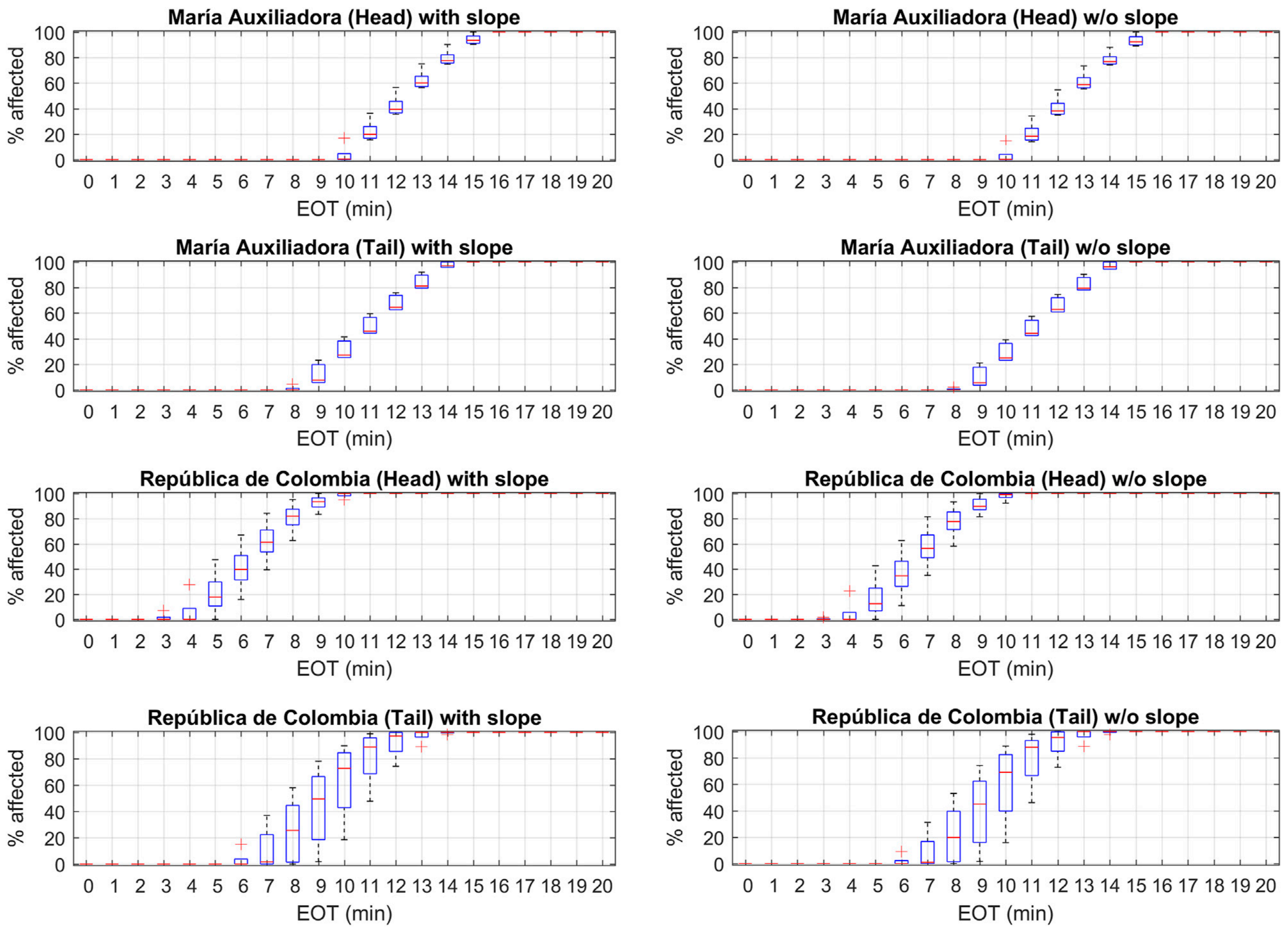

FIGURE 8 | Box plots showing the percentage of affected evacuees of the MA and RC schools in Viña del Mar, for evacuation speeds v1 to v5.

working hours. By expanding the scope of our analysis, through its integration with state-of-the-art seismic and tsunami modelling practices, and the public discussion of its findings, we would be able to deliver a critical assessment of existing tsunami risk policies at a general level in Chile and, more important, to contribute to fostering a 'ready-to-act' condition across the population.

CONCLUSION

This paper analysed the evacuation performances of four schools in Valparaíso and Viña del Mar, Chile, coupled with tsunami flood modelling. Our findings allow us to deliver several conclusions that could contribute to tsunami evacuation planning and further research.

- We engaged with four primary and secondary schools in Valparaíso and Viña del Mar and developed a methodology to survey their evacuation performances during a tsunami evacuation drill held on September 5, 2019.
- We demonstrated that our previously developed agent-based model could accurately grasp the drill performance of the evacuees. Therefore, we used it to assess this performance coupled with a worst-case historic tsunami scenario (based on historical data from the 1730 event), using the four schools as case studies.
- Our results for these four case studies show that following nation-level evacuation strategies (frequently trained on drills) might lead to significant human losses across these schools (up to 100% of their pupils) if rapid Evacuation Onset Times (EOT) cannot be enacted.
- Currently, these evacuation strategies are not based on precise tsunami flood modelling, nor do they grasp the characteristics of each school (relative to pupils, staff, and geomorphological conditions).
- User-friendly tools need to be developed to allow each school community to build and assess disaster scenarios, leading to better disaster education and improved responses in an earthquake and tsunami emergency.
- Tsunami evacuation drills in Chile offer significant research opportunities, which have not (hitherto) been fully addressed by current emergency management authorities. Updated protocols for gathering and assessing information during drills, supported by information technologies, could

lead to enhanced and validated models for better evacuation planning.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

The study was conceived and developed by all authors, who also directed the field survey AG carried out the tsunami and evacuation modelling JL prepared the first version of the manuscript with reviews by PAC and AG All authors contributed to editing the final version of the article.

FUNDING

JL, PAC, and AG were funded by the Research Center for Integrated Disaster Risk Management (CIGIDEN), ANID/FONDAP/15110017. JL was also funded by the research grant ANID/FONDECYT/11170024. PAC and AG were also funded by ANID, Chile through its grant FONDEF ID19I10048. PAC was also funded by the Centro Científico Tecnológico de Valparaíso, ANID PIA/APOYO AFB180002.

ACKNOWLEDGMENTS

This research was supported by the supercomputing infrastructure of the NLHPC (ECM-02). We also would like to thank Margarita Martínez from ONEMI for her valuable insights into evacuation drills planning in Chile.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.