VULNERABILITY OF SCHOOLS IN PUERTO RICO TO TSUNAMIS[1]

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ABSTRACT: The archipelago of Puerto Rico is a region of high danger to tsunamis (ATC, 2019). Recognizing that the school population in Puerto Rico is around 600,000 people (including students and teachers, according to 2016 data), and that schools are essential facilities to safeguard against extreme events, the objective of the research has been to evaluate if the Puerto Rican schools are vulnerable to tsunamis. In the first instance, a comprehensive database of schools in Puerto Rico that could be affected by tsunami events was developed and critical municipalities were identified. The municipalities of San Juan and Cataño were selected as case studies in which a more detailed evaluation was carried out. This evaluation included the analysis of the evacuation time required to move from each schoolyard to a safe place as the main vulnerability factor. The shortest route and several alternative routes were evaluated for each school. The analysis included as a complementary factor the status of the critical school evacuation route in each of the two municipalities. In addition, a survey form was developed and administered to collect data on school evacuation preparedness. The study found that the most vulnerable schools in each study municipality present excessive evacuation times and unsafe and inadequate evacuation routes for the evacuation process. Several additional study areas have been identified to improve the vulnerability assessment of schools. Therefore, a second phase of the research is being developed to obtain better estimates of evacuation times, including all stages of the evacuation process (evacuation timeline), analyzing the factors that affect pedestrian dynamics and simulation of each of these phases and integrating data from evacuation drills. The results of these investigations are expected to contribute to the rehabilitation processes of coastal schools by providing refined tools to decide if vertical evacuation is required.

Keywords: tsunamis, tsunamis effects, school vulnerability, school safety, community resilience

VULNERABILIDAD DE ESCUELAS DE PUERTO RICO A EVENTOS DE TSUNAMI

RESUMEN: El archipiélago de Puerto Rico es una región de alto peligro a tsunamis (ATC, 2019). Reconociendo que la población escolar en Puerto Rico es de alrededor de 600,000 personas (incluyendo estudiantes y maestros, según datos de 2016), y que las escuelas son instalaciones esenciales para salvaguardar frente a eventos extremos, el objetivo de la investigación ha sido evaluar si las escuelas de Puerto Rico son vulnerables a los tsunamis. En primera instancia, se desarrolló una base de datos integral de las escuelas de Puerto Rico que podrían verse afectadas por eventos de tsunamis y se identificaron los municipios críticos. Se procedió a seleccionar los municipios de San Juan y Cataño como casos de estudio en los que se realizó una evaluación más detallada. Esta evaluación incluyó el análisis del tiempo de evacuación requerido para moverse desde cada patio escolar hasta llegar a un lugar seguro como principal factor de vulnerabilidad. Se evaluó la ruta más corta y varias rutas alternativas para cada escuela. El análisis incluyó como factor complementario el estado de la ruta de evacuación de la escuela crítica en cada uno de los dos municipios. Además, se desarrolló y administró un formulario de encuesta destinado a recopilar datos sobre la preparación para la evacuación de las escuelas. El estudio encontró que las escuelas más vulnerables en cada municipio de estudio presentan tiempos de evacuación excesivos y rutas de evacuación inseguras e inadecuadas para el proceso de evacuación. Varias áreas de estudio adicionales han sido identificadas para mejorar la evaluación de la vulnerabilidad de las escuelas. Por tanto, se está desarrollando una segunda fase de la investigación para obtener mejores

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estimaciones de los tiempos de evacuación, incluyendo todas las etapas del proceso de evacuación (línea de tiempo de evacuación), analizando los factores que afectan a la dinámica peatonal y la simulación de cada una de estas fases e integrando datos de simulacros de evacuación. Se espera que los resultados de estas investigaciones contribuyan a los procesos de rehabilitación de las escuelas costeras brindando herramientas refinadas para decidir si se requiere evacuación vertical.

Palabras clave: tsunamis, efectos de tsunamis, vulnerabilidad de escuelas, seguridad de escuelas, resiliencia comunitaria

INTRODUCTION

Any construction in Puerto Rico (PR) could experience very strong shakings due to earthquakes (NIBS, 2010). This high seismic hazard is due to PR being located on a microplate sandwiched between the edge of the North American Tectonic Plate and the extreme northwest of the Caribbean Tectonic Plate. The interaction between these two plates has generated several significant faults in the region, (Figure 1, showing only the offshore faults). Some of these faults have the potential to generate local tsunamis, including the Puerto Rico trench (NOAA, 2010) or a repeat of the 1918 tsunami in the Mona Canyon (Reid and Taber, 1919).

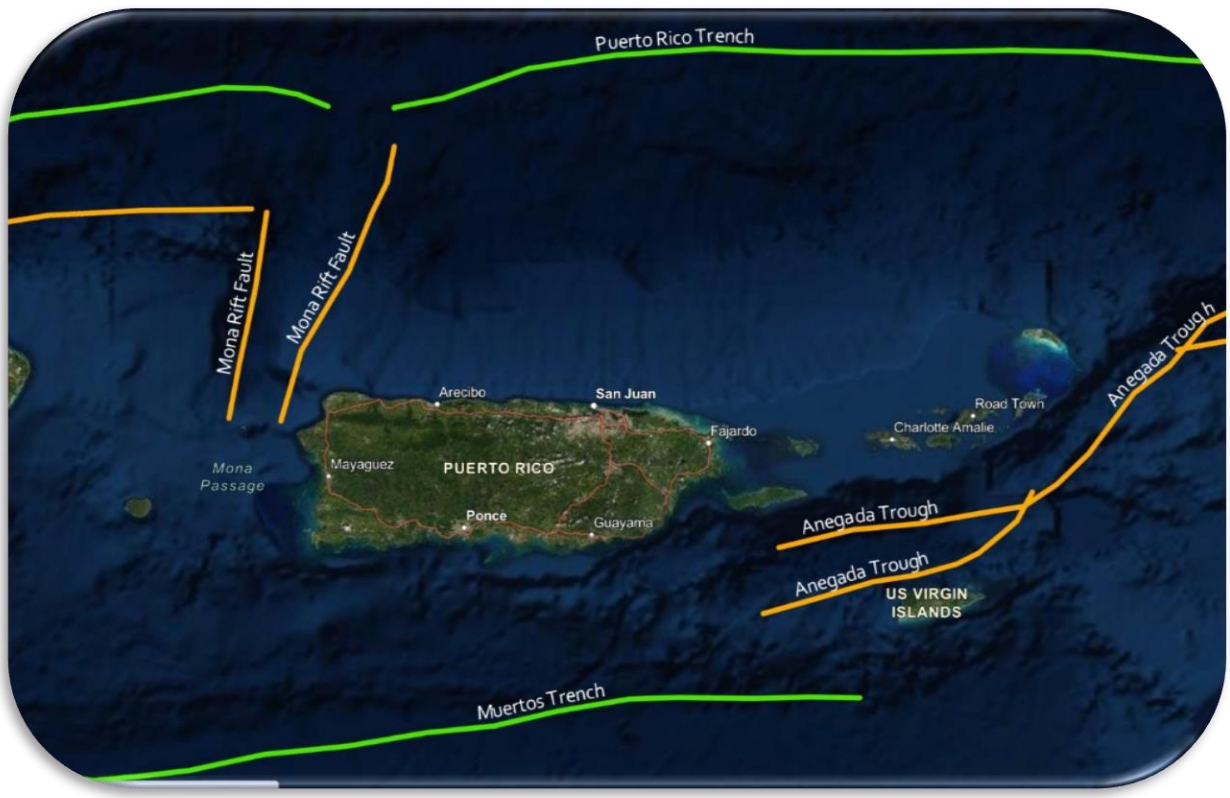

Figure 1: Puerto Rico Offshore Seismic Faults (QuakeFeed App, Artisan Global LLC., n.d.).

On January 7, 2020, a 6.4 magnitude earthquake affected PR, with high intensities in the southern west area, as presented in Figure 2, causing damages and collapse on diverse types of buildings and facilities in several municipalities. Figure 3 presents examples of the collapse of houses mounted on stilts located in Guánica, while Figure 4 presents the collapse of Agripina Seda School in Guánica.

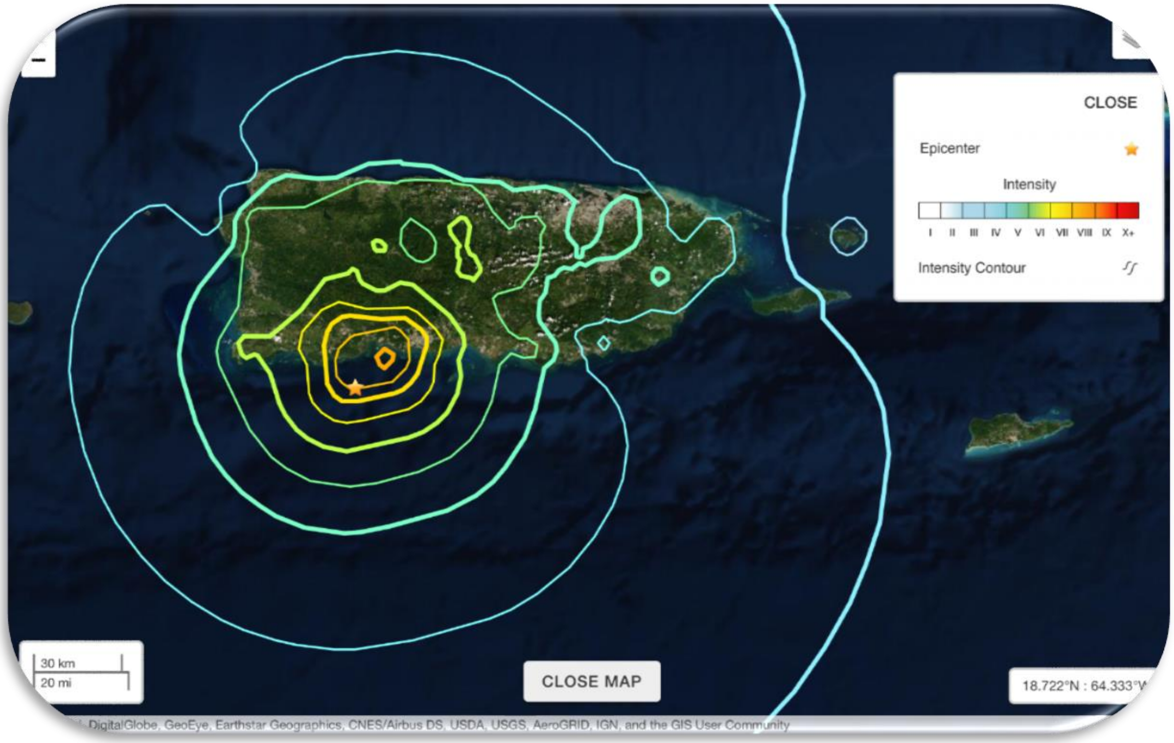

Figure 2: Intensity contours due to January 7, 2020 M6.4 Earthquake (USGS, 2020a and 2020b)

Figure 3 : Examples of Collapse and Damages to Houses in Guánica due to January 7, 2020 Earthquake (Pacheco-Crosetti, 2020).

Figure 4 : Collapse of Agripina Seda School in Guánica due to January 7, 2020 Earthquake (Pacheco-Crosetti, 2020).

After the earthquake of January 7, 2020, the damages on soils and structures have been extensively studied, documented and disseminated in papers, reports, and conferences (i.e., Bernal et al, 2020; Chen et al, 2022; Knoper et al, 2020; Miranda et al, 2020; Pacheco-Crosetti, 2020). Topics such as the impact of the informal construction, the lack of seismic steel detailing, the quality of materials, and the presence of intrusive elements in structural elements have been addressed. Considering the catastrophic collapse of the school in Guánica (Figure 4), significant damage to many other schools, and that many of the schools do not meet actual code requirements (Noticel, 2020), the identification of the vulnerabilities and the rehabilitating of schools has emerged as a societal priority. Nevertheless, the proposed improvements are considered not enough (CBEE, 2021), since they are focusing only on the presence of short columns instead of a comprehensive assessment of school rehabilitation needs.

Despite the fact that several topics associated to seismic design have been addressed as critical as a consequence of the 2020 events, the consideration of the possible impact of tsunamis has not emerged as a significant topic in general, and in schools' rehabilitation in particular. According to the report FEMA P-646 - Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (ATC, 2019a), Puerto Rico is a region with a high hazard of experiencing tsunami impacts, as presented in Figure 5. Indeed, the effects of tsunamis can be very destructive (Figure 6, and as described in FEMA P-646 report).

Table 2-1 Qualitative Tsunami Hazard Assessment for U.S. Locations, (Dunbar and Weaver, 2015)

Region	Hazard Based on Historical Record and Earthquake Probabilities	Number of Reported Deaths
Alaska	High to Very High	222
Alaska Arctic Coast	Very Low	None
American Samoa	High	34
Guam and Northern Mariana Islands	High	1
Hawaii	High to Very High	293
Puerto Rico and U.S. Virgin Islands	High	164
U.S. Atlantic Coast	Very Low to Low	None
U.S. Gulf Coast	Very Low	None
U.S. West Coast	High to Very High	25*

* Excludes any deaths caused by the 1700 Cascadia tsunami on the U.S. West Coast.

Figure 5: Qualitative Hazard to Tsunamis in the US (ATC, 2019a).

Figure 6: Tsunami inundating Yamada, Japan, in 2011 (NOAA, 2019).

The most recent devastating tsunami in Puerto Rico occurred on October 11, 1918, due to the 7.3 magnitude San Fermin earthquake, in the Mona Passage. The earthquake resulted in 116 casualties and more than four million dollars in property loss, according to the US Congress Report (1919). The earthquake generated a tsunami. The waves travelled quickly, taking between just five to six minutes after the shaking to arrive to Aguadilla shoreline in northwestern Puerto Rico (Reid and Taber, 1919). Near Punta Agujereada (North to Aguadilla) the elevation of the wave was calculated to be approximately 20 feet (Reid and Taber, 1919). The simulation by Mercado and McCann (1998) replicated fairly well the observations by Reid and Taber. In the town of Aguadilla, 32 people drowned and nearly 300 existing ranches on the beach were destroyed (Figure 7); in the vicinity of Punta Agujereada, 8 people drowned (Reid and Taber, 1918; PRSN, 1918 Earthquake).

Figure 7: Effects of the 1918 Tsunami on Aguadilla Shoreline, La Ñamera Sector (Biblioteca Nacional de Puerto Rico, 1918).

The Puerto Rico Seismic Network (PRSN) has led the development of a comprehensive analysis of the possible impact of tsunamis on the coasts of Puerto Rico. Together with the local and state emergency management agencies it also has prepared evacuation zones maps for all the 46 municipalities of Puerto Rico at risk from tsunamis inundation and made them available in pdf format and digital format on their web page, as depicted in Figure 8 by the yellow areas.

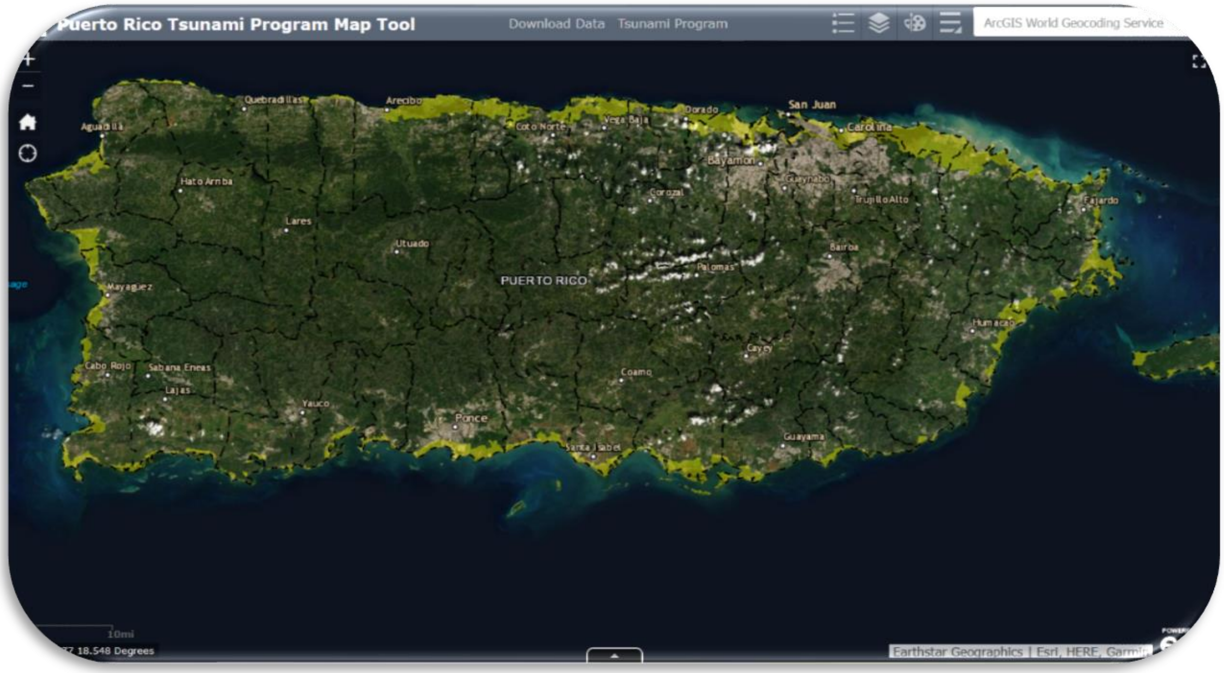

Figure 8: Puerto Rico Tsunami Program Map Tool, Evacuation Maps (PRSN, n.d. a, b and c).

According to Disdier-Flores and Cruz-Soto (2019), for the year 2016 there were more than 2,200 public and private schools in Puerto Rico, with a students and teacher population of around 600,000. Considering that schools should be treated as essential facilities, their exposed population, and that many are also used as shelters and voting centers (with a different and potentially larger exposed population), and the given tsunami hazard in PR, the objective of this research project was to evaluate the vulnerability of coastal schools of PR to this type of event. The main purpose has been to provide useful information that could contribute to the decision-making process of school's rehabilitation, both in assigning priorities (assessing more vulnerable schools) and in determining rehabilitation requirements (i.e., need of vertical evacuation due to excessive horizontal evacuation time, and/or evacuation routes improvements due to their poor condition). Reliable data that support planning contribute to safer and more resilient communities.

METHODOLOGY

This section presents a summary of the stages of the study that can be summarized as: (a) data gathering, (b) school's tsunami hazard identification, (c) case studies selection for detailed evaluation, (d) vulnerability analysis selection, selection and development of tools, (e) vulnerability assessment of case studies, (f) vulnerability assessment of other critical cases, and (g) analysis of results. After that, the summary and conclusions, and the recommendations for further studies are presented.

Data Gathering

The first stage consisted in obtaining the following data for public and private schools of Puerto Rico: (1) geolocation, (2) population, (3) usage as an emergency shelter, (4) usage as a voting center. Also obtained was the tsunami evacuation zone for the 46 at risk coastal municipalities.

The following sources were consulting: (a) the *Homeland Infrastructure Foundation-Level Data -HIFLD* (U.S. Department of Homeland Security, 2020), (b) *Profiles of USA Public Schools* (Public School Review, n.d.), (c) "Busca tu Escuela - 2018-2019" ("Departamento de Educación de Puerto Rico", 2019a), (d) "Plan Operacional para Emergencias e Incidentes Catastróficos 2018-2019" ("Departamento de Educación de Puerto Rico", 2019b), (e) "Centros de Votación" ("Comisión Estatal de Elecciones de Puerto Rico", 2020), (f) "Anuario Estadístico del Sistema Educativo" ("Instituto de Estadísticas de Puerto Rico", n.d.), (g) *Puerto Rico Tsunami Evacuation Maps and Puerto Rico Tsunami Program Map Tool* (Puerto Rico Seismic Network, n.d. b, c and d).

School's Tsunami Hazard Identification

The geolocation of schools obtained from the Homeland Infrastructure Foundation-Level Data -HIFLD for public schools (U.S. Department of Homeland Security, 2020) and the tsunami evacuation zone obtained from the Puerto Rico Tsunami Program Map Tool (Puerto Rico Seismic Network, n.d. b, c and d) were inserted as GIS layers in ArcGIS Online (Esri, n.d. a and b), as presented in Figure 9. With the two sets of data, every one of the 46 coastal municipalities at risk were evaluated to identify the schools in the tsunami evacuation zone (see Figure 10 for an example of San Juan municipality). **Note: for the purpose of this study, the tsunami evacuation zone was considered as equivalent to the tsunami hazard zone**.

After identifying each school in the tsunami evacuation zones, the information regarding the school population, and its usage as an emergency shelter and a voting center was obtained, from the references presented in the previous section. Table 1 presents the results for each coastal municipality, indicating the number of schools that are located in the tsunami evacuation zone and their total population (students, teachers and administrative and support staff) as well as the number of those schools that are also used as shelters and voting centers. The table highlights the municipalities with schools in the tsunami hazard zone (THZ) and distinguish between those municipalities with lower number of schools in the THZ (one to three) and those with a higher number of schools in the THZ (four or more), as a visual aid to identify municipalities that have more schools vulnerable to tsunamis.

It is important to point out that the first cycle of this research (August 2020-July 2021) focused only on public schools, since the geolocation of private schools was not available in any of the sources consulted. This article presents the findings of this first cycle. A second cycle of the research is currently under development (August 2021-present), and its objectives are briefly summarized in the Further Studies Section (at the end of the article). During this second cycle, the private schools placed in the tsunami evacuation zones were identified, locating each school manually (due to the lack of information in their geolocation). It was decided to also present these results in Table 1, to provide the reader with a more comprehensive view of tsunami hazards in the schools of Puerto Rico. But the remaining of the sections focus primarily on public schools.

Figure 9: ArcGIS Data Processing with Public Schools Locations and Tsunami Evacuation Zones.

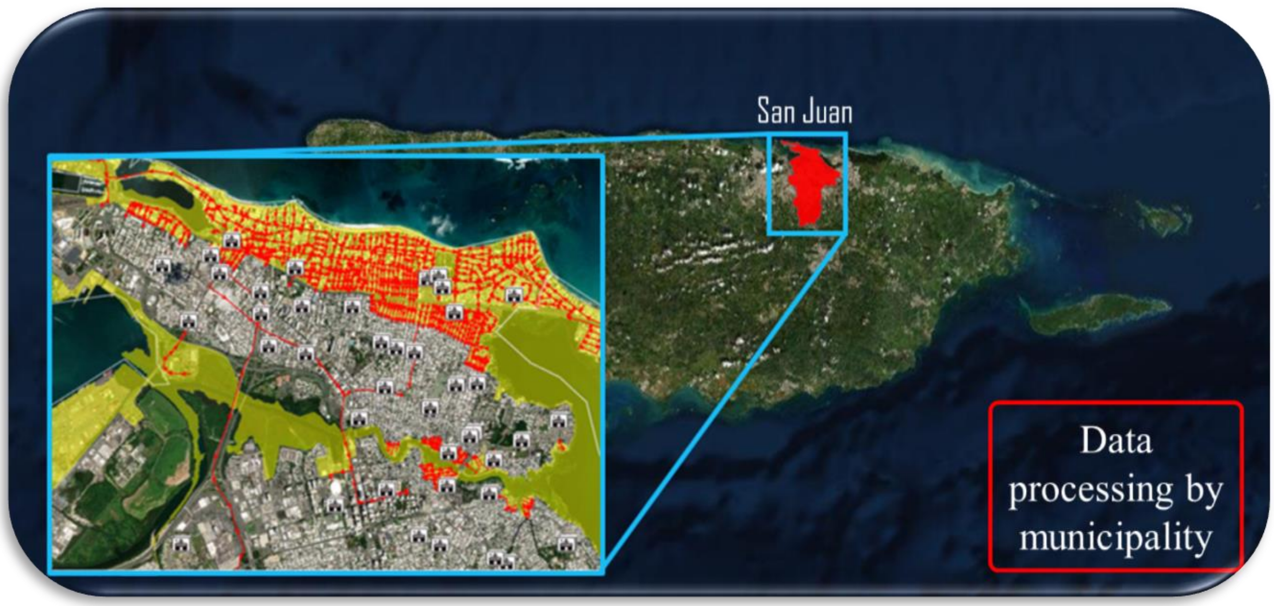

Figure 10: Example of Identification of Schools in the Tsunami Evacuation Zone in San Juan Municipality.

From the processed data it was determined that there are 74 public schools in the tsunami evacuation zone, located in 25 coastal municipalities (21 of the coastal municipalities do not have public schools in the hazard zone), and with a school population that may be affected by tsunami events of about 20,900; 34 of these schools are also used as voting centers, and nine are used as shelters.

It was also determined that there are 35 private schools in the tsunami evacuation zone, distributed among 12 coastal municipalities (34 of the coastal municipalities do not have private schools in the hazard zone), and with a school population that may be affected by tsunami events of about 6,600. Four of these schools are also used as voting centers, and none is used as shelter.

There is a total of 109 schools (public and private) in the tsunami evacuation zone. They located in 25 coastal municipalities, with a school population that may be affected by tsunami events of about 27,500; 38 of these schools are also used as voting centers, and nine are used as shelters.

Table 1: Summary of Schools in Tsunami Evacuation Zones.

Municipality	Public Schools				Private Schools				Public + Private Schools			
	Schools in Tsunami Hazard Zone	Voting Centers	Shelters	Population	Schools in Tsunami Hazard Zone	Voting Centers	Shelters	Population	Schools in Tsunami Hazard Zone	Voting Centers	Shelters	Population
Aguada	3	1	0	1,457	2	0	0	Unknown	5	1	0	1,457
Aguadilla	3	1	0	519	1	0	0	150	4	1	0	669
Añasco	1	0	0	0	0	0	0	0	1	0	0	0
Arecibo	1	0	0	97	3	0	0	110	4	0	0	207
Arroyo	0	0	0	0	0	0	0	0	0	0	0	0
Barceloneta	0	0	0	0	0	0	0	0	0	0	0	0
Bayamón	0	0	0	0	0	0	0	0	0	0	0	0
Cabo Rojo	3	1	0	931	0	0	0	0	3	1	0	931
Camuy	1	1	0	0	0	0	0	0	1	1	0	0
Canóvanas	0	0	0	0	0	0	0	0	0	0	0	0
Carolina	2	0	0	0	3	0	0	646	5	0	0	646
Cataño	4	2	0	1,465	1	0	0	0	5	2	0	1,465
Ceiba	0	0	0	0	0	0	0	0	0	0	0	0
Culebra	1	1	1	190	0	0	0	0	1	1	1	190
Dorado	1	0	1	937	1	1	0	668	2	1	1	1,605
Fajardo	0	0	0	0	0	0	0	0	0	0	0	0
Guánica	0	0	0	0	0	0	0	0	0	0	0	0
Guayama	1	0	0	115	0	0	0	0	1	0	0	115
Guayanilla	0	0	0	0	0	0	0	0	0	0	0	0
Guaynabo	0	0	0	0	0	0	0	0	0	0	0	0
Hatillo	1	0	0	0	0	0	0	0	1	0	0	0
Humacao	1	1	0	386	0	0	0	0	1	1	0	386
Isabela	0	0	0	0	0	0	0	0	0	0	0	0
Juana Díaz	2	1	0	529	0	0	0	0	2	1	0	529
Lajas	1	0	0	108	0	0	0	0	1	0	0	108
Loíza	8	4	3	2,401	2	1	0	394	10	5	3	2,795
Luquillo	3	1	0	596	0	0	0	0	3	1	0	596
Manatí	0	0	0	0	0	0	0	0	0	0	0	0
Maunabo	0	0	0	0	0	0	0	0	0	0	0	0
Mayagüez	9	5	1	3,247	0	0	0	0	9	5	1	3,247
Naguabo	0	0	0	0	0	0	0	0	0	0	0	0
Patillas	0	0	0	0	0	0	0	0	0	0	0	0
Peñuelas	1	0	0	245	0	0	0	0	1	0	0	245
Ponce	4	2	0	1,577	2	0	0	108	6	2	0	1,685
Quebradillas	0	0	0	0	0	0	0	0	0	0	0	0
Rincón	1	0	0	183	1	0	0	166	2	0	0	349
Río Grande	0	0	0	0	0	0	0	0	0	0	0	0
Salinas	4	3	0	541	0	0	0	0	4	3	0	541
San Juan	9	5	0	2,083	**7**	**1**	**0**	**2350**	16	6	0	4,433
Santa Isabel	1	1	1	486	1	0	0	Unknown	2	1	1	486
Toa Baja	8	4	2	2,802	**11**	**1**	**0**	**1987**	19	5	2	4,789
Vega Alta	0	0	0	0	0	0	0	0	0	0	0	0
Vega Baja	0	0	0	0	0	0	0	0	0	0	0	0
Vieques	0	0	0	0	0	0	0	0	0	0	0	0
Yabucoa	0	0	0	0	0	0	0	0	0	0	0	0
Yauco	0	0	0	0	0	0	0	0	0	0	0	0
Total	**74**	**34**	**9**	**20,895**	**35**	**4**	**0**	**6,579**	**109**	**38**	**9**	**27,474**

Municipalities with no schools in tsunami hazard zone

Municipalities with 1 to 3 schools in a tsunami hazard zone

Municipalities with 4 to more schools in a tsunami hazard zone

Total results

Case Studies Selection

Two municipalities were selected as case studies for a more detailed analysis on schools' vulnerabilities to tsunami events. The criteria for selection were that the municipalities have a relatively large number of schools in the THZ, that the schools have multiple uses (also used as voting centers and/or shelters), and that they are close to the San Juan Metropolitan Area (SJMA), so a visual inspection of evacuation routes could be performed. Cataño and San Juan municipalities were selected. Table 2 summarizes the school tsunami hazard found in the previous stage for both municipalities.

Table 2: Summary of School Tsunami Hazard for the Selected Case Studies.

	Cataño	San Juan	Totals
Schools in THZ	4	9	13
Student Population	1367	1920	3287
Teacher Population	98	163	261
Total Population	1465	2083	3548
Voting Centers	2	5	7
Shelters	0	0	0

Vulnerability Analysis Selection, Tools Adoption and Development

The ***required time to evacuate*** from the school's internal assembly area to a safe place was adopted as the primary factor to assess school vulnerability to tsunami events. Two analyses were performed: (1) the required time to evacuate from the internal assembly area to the point of exit of the tsunami evacuation zone, and (2) the required time to evacuate from the internal assembly area to the external assembly point.

To obtain this time, the procedures proposed in the USGS publication "*The pedestrian evacuation analyst: Geographic information systems software for modeling hazard evacuation potential*" (Jones, Ng, and Wood, 2014) were adopted. They propose four walking speed values, in mph, according to the walking type: (a) 2.46 mph for slow walk, (b) 2.70 mph for moderate walk, (c) 3.40 mph for fast walk, and (d) 2.50 mph for average walk.

The analysis consisted in: (a) Identifying the internal assembly area and the external assembly point. (b) Identifying possible evacuation routes. The shortest route was identified, and between two (2) to four (4) alternate routes were also evaluated, to see the impact of possible after earthquake obstructions to the shortest route. (c) Plotting each route and computing the required evacuation time according to the travel distance to the tsunami evacuation zone exit point and to the external assembly point. The ***Route Planner for walking, running, cycling*** provided by ***Ploaroute.com*** (n.d.) was used to trace the routes and compute the times. Figure 11 presents an example of the use of this web app.

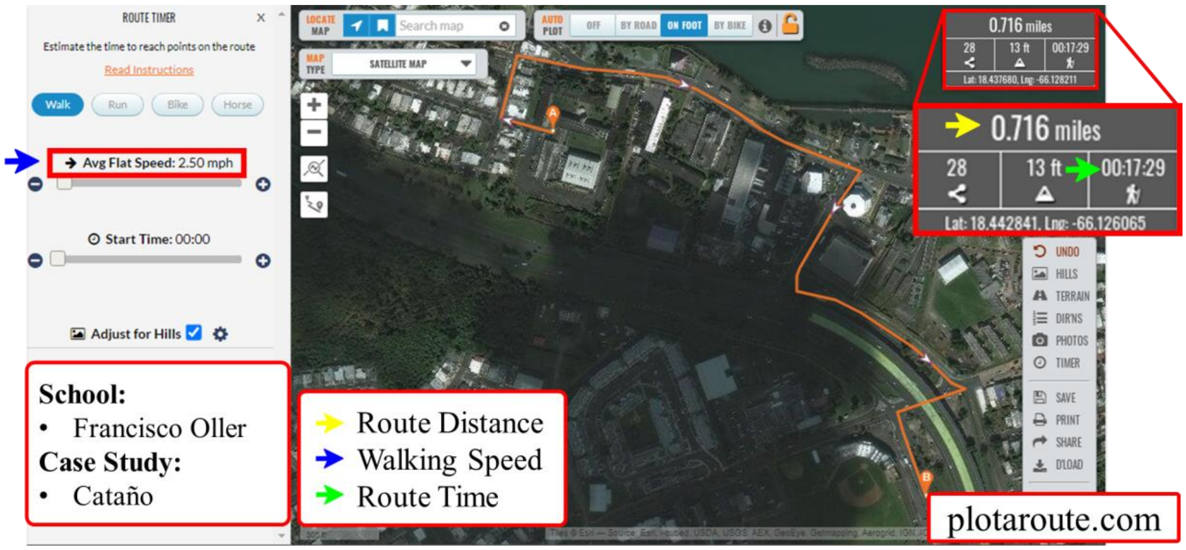

Figure 11: Example of Plotaroute Web App Usage for Francisco Oller School in Cataño.

The ***evacuation route condition*** was used as a complementary factor to assess school vulnerability to tsunami events. This analysis evaluated: (a) the percentage of the trace of the route that runs parallel to the shoreline, thus not moving away from the danger, (b) the presence of obstacles, discontinuities, or reduced effective width of the walkway, (c) the existence of evacuation signs along the route, (d) if the route passes near facilities that may represent, in the case of collapse, possible after earthquake obstacles that could force a change in evacuation route (i.e., electric lines and bridges), thus increasing the required evacuation time.

This analysis was originally envisioned to be carried out through field visits and visual inspections. But due to limitations in mobility and accessibility imposed by the COVID pandemic, a virtual tour using ***Google Earth Pro*** and its ***Street View*** capabilities was performed.

The ***school evacuation plans and evacuation drills*** were also considered as a complementary factor to assess school vulnerability to tsunami events. For that purpose, a detailed ***survey*** was developed in ***Google Forms***, that request information on: (a) municipality, (b) type of instruction (primary, secondary, high school), (c) building year of construction, (d) trainings on tsunamis received by school personnel, (e) tsunami evacuation plan, (f) drills practice, (g) evacuation time from the classrooms to internal assembly place, (h) external assembly point, (i) evacuation time from the internal assembly place to the external assembly point, (j) vertical evacuation plans, (k) vertical evacuation place, (l) evacuation time from the internal assembly place to the vertical evacuation place. The response was completely anonymous. The form was sent to all the schools of the case studies. The form can be accessed in: https://docs.google.com/forms/d/e/1FAIpQLSfoeD_VJwr3IGc2wfU0H3XBIrqrgc0qDLXfbIaX8Q0haDhGxQ/viewform

Vulnerability Assessment of Case Studies – Evacuation Time

The analysis was performed on the shortest evacuation route for each school, using the four (4) walking speeds of Jones, Ng, and Wood (2014). The results for Cataño public schools are presented first. Figure 12 summarizes the evacuation time, in minutes, from the internal assembly place to the point of exiting the tsunami hazard zone. Considering the average walking speed of 2.50 mph, the evacuation times range from 6 to 16 minutes, being Francisco Oller the school that requires the longest evacuation time.

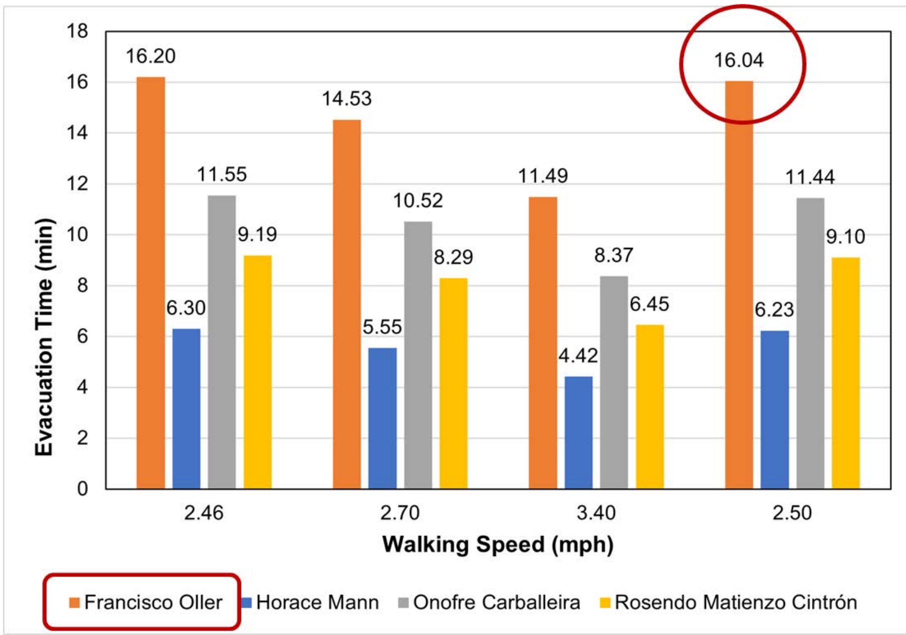

Figure 12: Evacuation time until exiting the tsunami evacuation zone for Cataño Public Schools.

Figure 13 summarizes the evacuation time, in minutes, from the internal assembly place to the external assembly point. Considering the average walking speed of 2.50 mph, the evacuation times range from 7 to 17 minutes, being Francisco Oller the school that requires the longest evacuation time. The external assembly point is close to the point where the THZ is left, so the increase in evacuation time from the previous analysis to this one is about one minute.

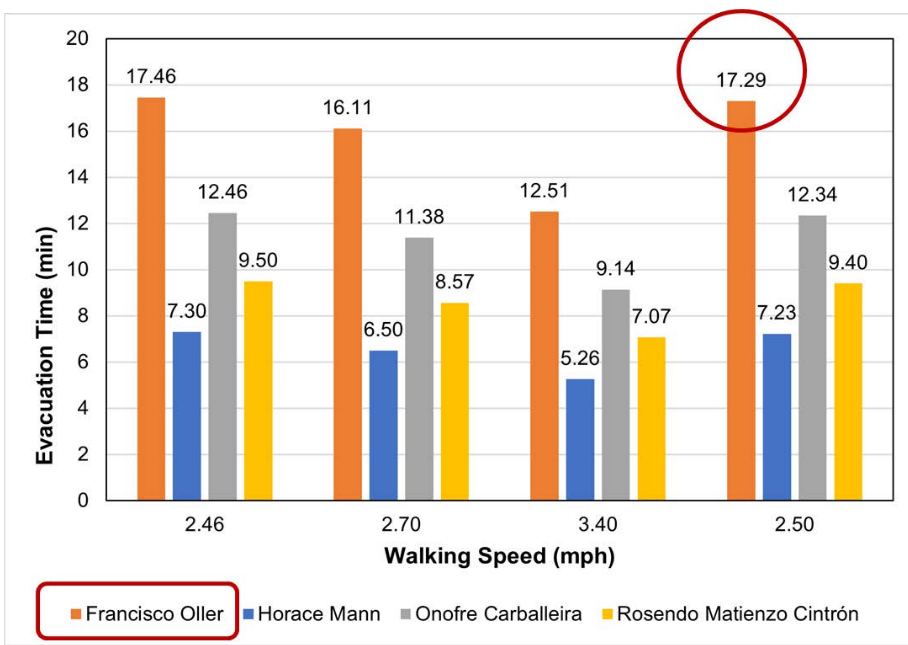

Figure 13: Evacuation time until reaching the external assembly point for Cataño Public Schools.

Second, the results for San Juan public schools are presented. Figure 14 summarizes the evacuation time, in minutes, from the internal assembly place to the point of exiting the tsunami hazard zone. Considering the average walking speed of 2.50 mph, the evacuation times range from 1 to 26 minutes, being Luis Llorens Torres the school that requires the longest evacuation time.

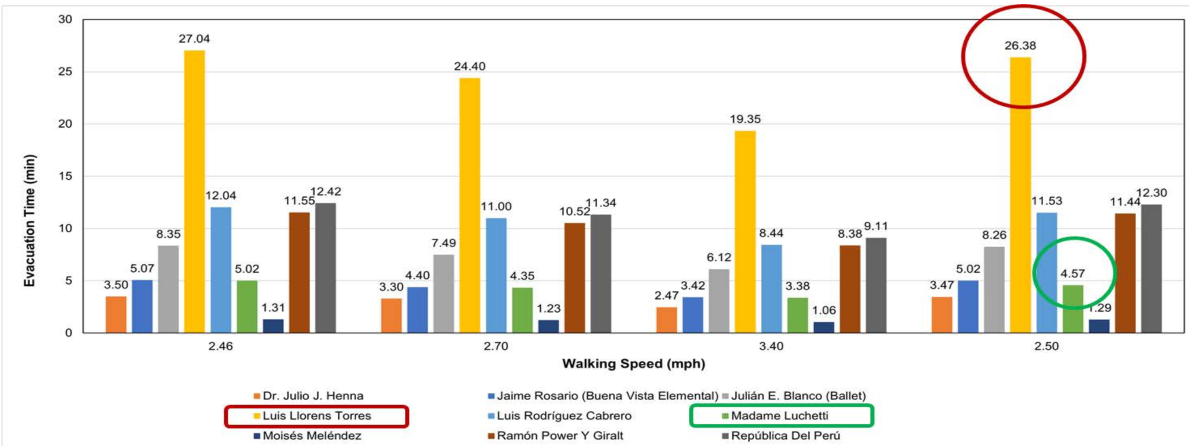

Figure 14: Evacuation time until exiting the tsunami evacuation zone for San Juan Public Schools.

Figure 15 summarizes the evacuation time, in minutes, from the internal assembly place to the external assembly point. Considering the average walking speed of 2.50 mph, the evacuation times range from 9 to 49 minutes, being Madame Luchetti the school that requires the longest evacuation time. The external assembly point is not close to the point where the THZ is left for most of the schools, so the increase in evacuation time from the previous analysis to this one ranges from 7 minutes to 45 minutes.

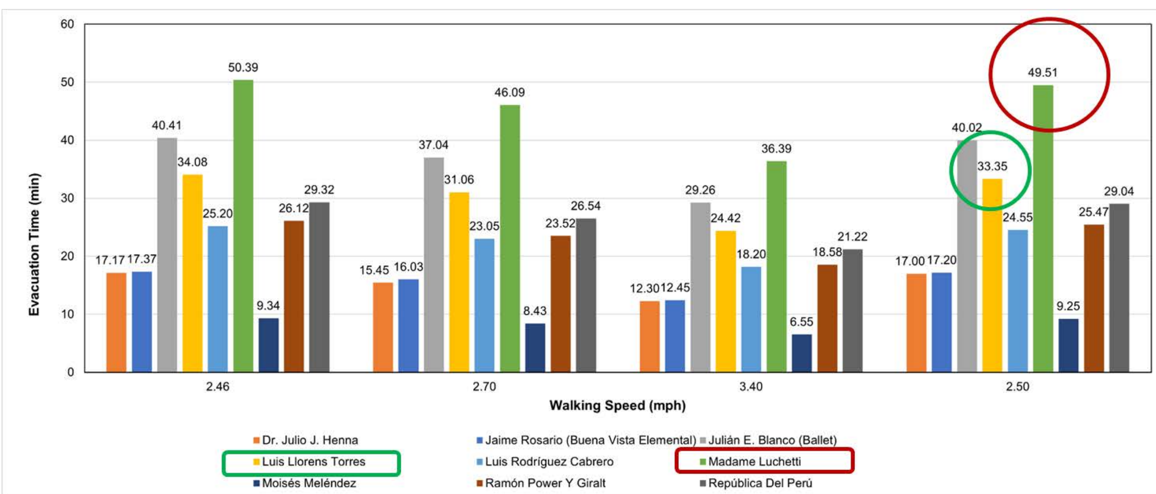

Figure 15: Evacuation time until reaching the external assembly point for San Juan Public Schools.

Finally, Table 3 presents, for both municipalities, a comparison between the evacuation time required until reaching the external assembly point following the shortest route, and the time required following alternate routes, using the time format (hh:mm:ss). Two to four alternative routes were evaluated for each school. There was always an increase in the evacuation time required by the alternate routes, increase that ranged between 1 minute to 33 minutes.

Table 3: Comparison of Required Evacuation Time until Reaching the External Assembly Point between the Shortest Route and Alternate Routes.

Municipality	School	Minimum Evacuation Route	Alternate Evacuation Routes				Difference between times			
			1	2	3	4	1	2	3	4
Cataño	Francisco Oller	00:17:29	00:19:35	00:35:22			00:02:06	00:17:53		
	Horace Mann	00:07:23	00:09:03	00:08:17			00:01:40	00:00:54		
	Onofre Carballeira	00:12:34	00:15:33	00:35:59			00:02:59	00:23:25		
	Rosendo Matienzo Cintrón	00:09:40	00:10:13	00:11:01	00:41:33		00:00:33	00:01:21	00:31:53	
San Juan	Dr. Julio J. Henna	00:17:00	00:18:23	00:18:33	00:49:57		00:01:23	00:01:33	00:32:57	
	Jaime Rosario	00:17:02	00:17:43	00:23:31	00:42:28		00:00:41	00:06:29	00:25:26	
	Julián E. Blanco	00:40:02	00:40:36	00:42:45			00:00:34	00:02:43		
	Luis Llorens Torres	00:33:35	00:37:58	00:37:00	01:06:34		00:04:23	00:03:25	00:32:59	
	Luis Rodríguez Cabrero	00:24:55	00:29:41	00:27:14	00:57:24		00:04:46	00:02:19	00:32:29	
	Madame Luchetti	00:49:51	00:55:46	00:56:21	01:14:12		00:05:55	00:06:30	00:24:21	
	Moisés Meléndez	00:09:25	00:10:25	00:11:03	00:29:02	00:33:12	00:01:00	00:01:38	00:19:37	00:23:47
	Ramón Power Y Giralt	00:25:47	00:30:31	00:26:53			00:04:44	00:01:06		
	República Del Perú	00:29:04	00:31:38	00:30:05			00:02:34	00:01:01		

Vulnerability Assessment of Case Studies – Route Condition

In each municipality of the case studies, the school that requires the longest time until exiting the tsunami evacuation zone was selected to perform a virtual tour exploring the conditions of the walkway and the alignment. The analysis was conducted on the shortest evacuation route. The principal findings can be summarized as follows:

Francisco Oller School in Cataño – Shortest evacuation route:

- The route has a distance of 0.656 miles to leave the tsunami hazard zone and 0.716 miles to get to the external assembly point, "Estadio Peruchin Cepeda". There were two signs indicating the evacuation route along this route.
- It takes 16 minutes and 4 seconds to exit the tsunami hazard zone, and 17 minutes and 29 seconds to reach the external assembly site, considering an average walking speed of 2.50 mph.
- Travels approximately 0.300 miles parallel to the shoreline, representing a 46% of the 0.656 miles required to leave the tsunami hazard area. The layout of the route does not allow to move quickly away from the coast.
- Segments of the sidewalks presented unfitted conditions (Figure 16):
    - Has discontinuities of the walkway, and segments with reduced total width (in one segment, 28 in were measured; far less than the 36 in effective width required by ADA).
    - Has abundant presence of obstacles, such as urban furniture and cars that produce a reduction of the effective width.
    - There were damages to the walking surface, such as deterioration and cracks.
- Passes near power lines, and under a bridge located on the PR-165, that represent possible obstructions to the passage of pedestrians in case they collapse from the movement of the earthquake prior to the tsunami (Figure 17). This situation my force a change in the evacuation route.
- There could be conflicts with vehicular traffic, since the route moves along principal arteries of the zone.

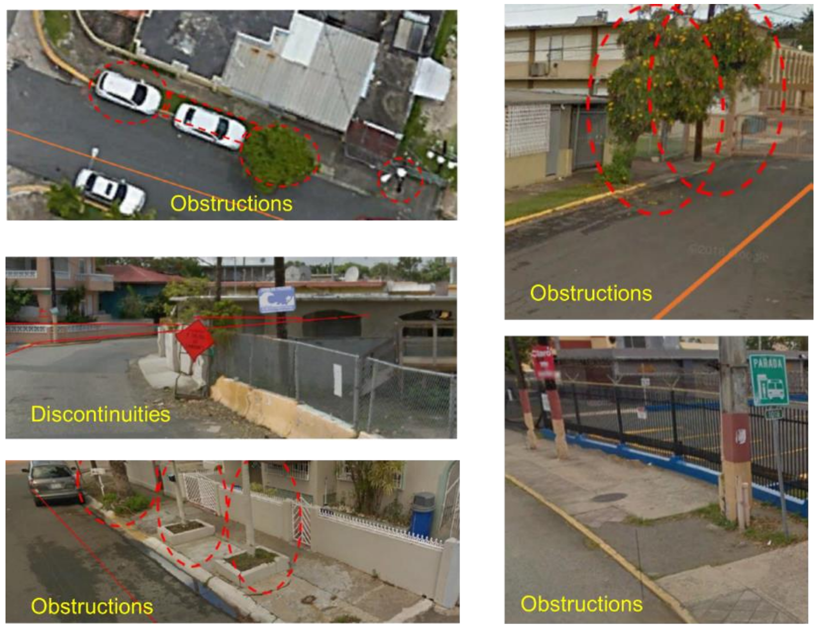

Figure 16: Obstruction, Reduced Effective Width, and Discontinuities on the Sidewalk for Francisco Oller Evacuation Route.

Figure 17: Obstruction on the Sidewalk and Potential After Earthquake Hazards for Francisco Oller Evacuation Route.

Luis Llorens Torres School in San Juan:

- The route has a distance of 1.074 miles to leave the tsunami hazard zone and 1.317 miles to get to the external assembly point, “Plaza Barceló”. This route only has a sign indicating that it is the tsunami evacuation route.
- It takes 26 minutes and 38 seconds to get out of the hazard zone, and 33 minutes and 35 seconds to get to the external assembly point for a walking speed of 2.50 mph.
- Travels 0.486 miles parallel to the shoreline, representing 45% of the 1,074 miles required to exit the tsunami hazard zone. The layout of the route does not allow to move quickly away from the coast.
- Segments of the sidewalks presented unfitted conditions (Figure 18):
    - Has discontinuities of the walkway, and segments with reduced total width (in one segment, 12 in were measured; far less than the 36 in effective width required by ADA).
    - Has profuse presence of obstacles, such as urban furniture and cars,that produce a reduction of the effective width.
    - There were damages to the walking surface, such as deterioration and cracks.
- Passes near power lines, and under a bridge located on the Pellín Rodríguez Street, that represent possible obstructions to the passage of pedestrians in case they collapse from the movement of the earthquake prior to the tsunami (Figure 19). This situation may force a change in the evacuation route.
- There could be conflicts with vehicular traffic, since the route moves along principal arteries of the zone.

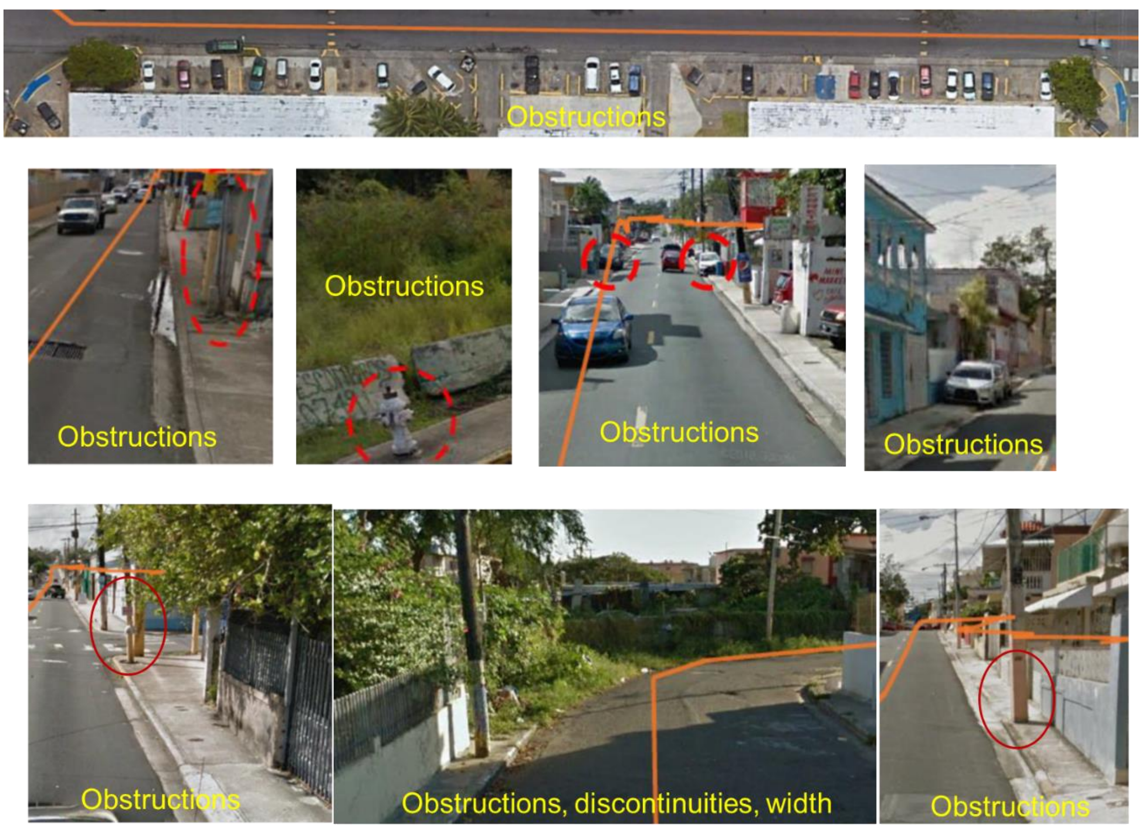

Figure 18: Obstruction, Reduced Effective Width, and Discontinuities on the Sidewalk for Luis Llorens Torres Evacuation Route.

Figure 19: Obstruction on the Sidewalk and Potential After Earthquake Hazards for Luis Llorens Torres Evacuation Route.

Vulnerability Assessment of Case Studies – School Survey

Two schools responded to the survey (a primary school in Cataño and a high school in San Juan. The information obtained is summarized as follows:

- Both schools were built before 1987 (therefore, considered pre code in terms of seismic details).
- Both schools have tsunami evacuation plans, and know their external assembly point (Parque Perucho Cepeda for the school in Cataño, and Plaza Barcelo Santurce for the school in San Juan).
- One school reported that during the drills the emergency siren to evacuate in case of tsunami events was not audible from the school.
- Both schools have conducted evacuations drills once a year or once every two years.
- Both schools reported evacuation times for the drills:
    - Cataño school: three minutes to evacuate from the classroom to the school internal assembly place, and eight minutes to evacuate from the school internal assembly place to the external assembly point.
    - San Juan school: one hour to evacuate from the classroom to the school internal assembly place, and one (hour to evacuate from the school internal assembly place to the external assembly point.
- One school reported that they have vertical evacuation plans, using the same school building as a shelter. Both schools reported vertical evacuation times.

Vulnerability Assessment of other Critical Cases - Evacuation Time

Two additional cases were analyzed, one in Loiza and one in Toa Baja, since the evacuation conditions of these municipalities were considered critical, and the computations confirm that assumption.

For the Medianía Alta public school in Loiza, considering the average walking speed of 2.50 mph, the evacuation time required to move from the internal assembly place until leaving the tsunami evacuation zone is one hour and 29 minutes (89 minutes), as presented in **Figure 20**.

Table 4 presents the total evacuation distance and summarizes the different evacuation times for this school. It is important to note that the evacuation route is along PR-187 Highway, the principal artery of the area. This may imply an increase in the pedestrian evacuation time due to interactions with vehicular traffic.

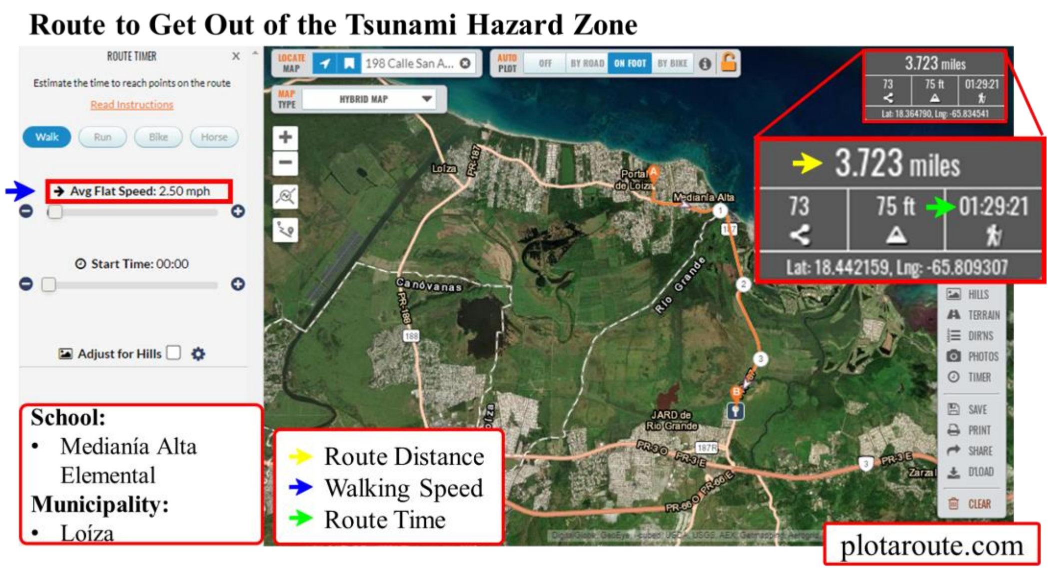

Figure 20: Plotaroute Web App Usage for Medianía Alta Public School in Loiza.

Table 4: Evacuation Times Summary for Medianía Alta Public School in Loiza.

Walking Speed USGS (mph)	Evacuation Time - PlotARoute (hr:min:sec)	
	Route to Get to the Assembly Place	Route to Get Out of the Tsunami Hazard Zone
2.46	2:00:44	01:30:48
2.70	1:50:00	01:22:44
3.40	1:27:21	01:05:42
2.50	1:58:48	01:29:21
Distance (miles)	4.950	3.723

For the Academia Espíritu Santo private school in Toa Baja, considering the average walking speed of 2.50 mph, the evacuation time required to move from the internal assembly place until leaving the tsunami evacuation zone is almost 51 minutes, as presented in **Error! Not a valid bookmark self-reference.**. Table 5 presents the total evacuation distance and summarizes the different evacuation time for this school. It is important to note that the evacuation route is along the PR-165 and PR-866 Highways, two of the principal arteries of the area, situation that may imply increase in the pedestrian evacuation time due to interactions with vehicular traffic.

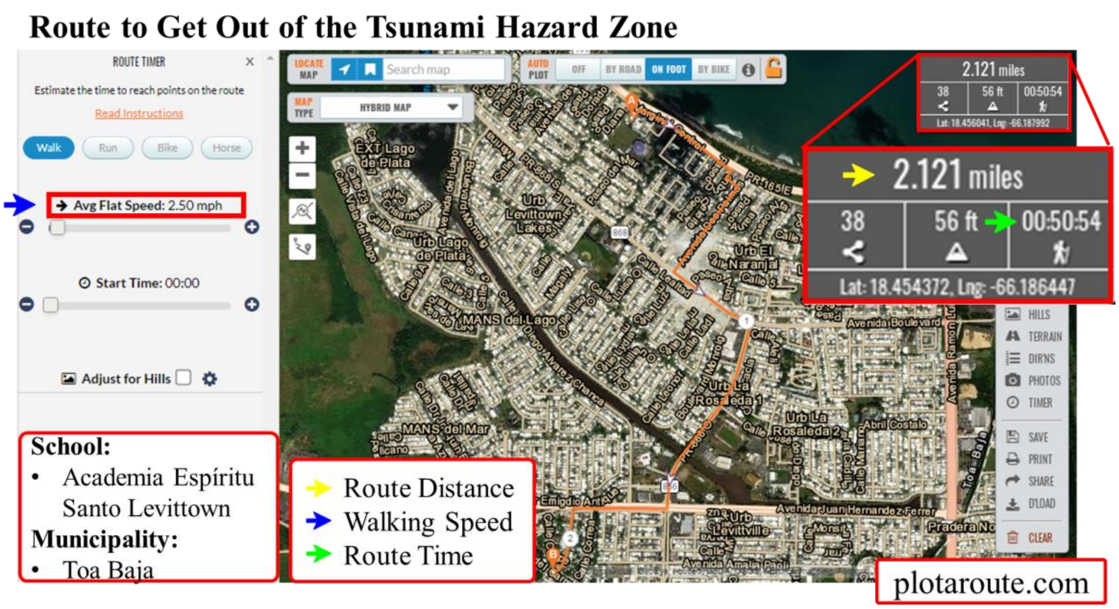

Figure 21: Plotaroute Web App Usage for Academia Espíritu Santo Private School in Toa Baja.

Table 5: Evacuation Times Summary for Academia Espíritu Santo Private School in Toa Baja.

Walking Speed USGS (mph)	Evacuation Time - PlotARoute (hr:min:sec)	
	Route to Get to the Assembly Place	Route to Get Out of the Tsunami Hazard Zone
2.46	01:04:34	00:51:37
2.70	00:58:49	00:47:02
3.40	00:46:43	00:37:21
2.50	01:03:45	00:50:54
Distance (miles)	2.656	2.121

Results Analysis

From the ***tsunami hazard identification stage***, one can consider the total number of schools in the THZ, the population of the schools, and their usage as shelters and voting centers as the parameters to differentiate between municipalities. Using this information one can identify that there are seven municipalities that may be considered critical for tsunami related rehabilitation of public schools, as presented in **Error! Reference source not found.**. The schools in these municipalities represent almost 70% of these parameters, considering the total number of public schools in the THZ. Of those seven municipalities, four are considered the most critical due to the number of schools in the THZ: Loiza, Mayagüez, San Juan and Toa Baja.

Table 6: Critical Municipalities Considering the Number of Public Schools in the THZ.

	Public Schools			
Municipality	**Schools in Tsunami Hazard Zone**	**Voting Center**	**Shelter**	**Population**
Cataño	4	2	0	1,465
Loíza	8	4	3	2,401
Mayagüez	9	5	1	3,247
Ponce	4	2	0	1,577
Salinas	4	3	0	541
San Juan	9	5	0	2,083
Toa Baja	8	4	2	2,802
Total	**46**	**25**	**6**	**14,116**
	62%	74%	67%	68%

If public and private schools are considered in the analysis, the critical municipalities increase to eleven, as presented in Table 7. These municipalities represent almost 80% of the previously mentioned parameters, considering the total number of public and private schools in the THZ. Of those eleven municipalities, the same four continue to be considered the most critical due to the number of schools in the THZ: Loiza, Mayagüez, San Juan and Toa Baja.

Table 7: Critical Municipalities Considering the Number of Public and Private Schools in the THZ.

	Public + Private Schools			
Municipality	**Schools in Tsunami Hazard Zone**	**Voting Center**	**Shelter**	**Population**
Aguada	5	1	0	1,479
Aguadilla	4	1	0	669
Arecibo	4	0	0	207
Carolina	5	0	0	646
Cataño	5	2	0	1,465
Loíza	10	5	3	2,795
Mayagüez	9	5	1	3,247
Ponce	6	2	0	1,685

Salinas	4	3	0	541
San Juan	16	6	0	4,433
Toa Baja	19	5	2	4,789
Total	**87**	**30**	**6**	**21,956**
	80%	79%	67%	80%

The ***evacuation time analysis*** results show one clear critical public school for each municipality: (a) School Francisco Oller in Cataño, with an evacuation time until exiting the THZ of 16.04 minutes considering an average walking speed of 2.50 mph. (b) School Luis Llorens Torres in San Juan, with an evacuation time until exiting the THZ of 26.38 minutes considering an average walking speed of 2.50 mph. Both evacuation times could result excessive in case of a local (near source generated) tsunami, that can arrive within 20 minutes (Christa von Hillebrandt, pers. communication, 2022), such as the case of the PR 1918 earthquake and tsunami, where tsunami inundation occurred within five and six minutes after the earthquake. Thus, vertical evacuation should be considered as an alternative evacuation strategy

For the public schools in Cataño, the difference in evacuation time until leaving the THN and until reaching the external assembly point do not differ significantly (about one minute for all the schools), but for the schools in San Juan the difference was substantial (ranging from seven minutes to 45 minutes for the different schools), due to the location of the external assembly point with respect to the schools' locations, and to the boundaries of the tsunami evacuation zones. For these cases, evaluating alternative assembly points could be advisable.

The critical school in San Juan has a significantly higher evacuation time until leaving the THZ than Cataño, but the average evacuation time is similar (9.4 minutes in San Juan vs 10.7 minutes in Cataño). The critical school in San Juan has a significantly higher evacuation time until reaching the external assembly point than Cataño, and also the average time is significantly higher (27.3 minutes in San Juan vs 11.6 minutes in Cataño).

If alternate routes have to be used (i.e., in the event of blockages due to the collapse of electrical infrastructure), the total evacuation time could be increased from about one minute to up to 32 minutes. This could lead to extremely excessive evacuation times.

Regarding the ***routes conditions analysis*** performed by virtual inspection tours, both routes presented similar situations. There is a significant length of the evacuation path that runs parallel to the shoreline (45% or more), thus the evacuation process does not move away quickly from the danger. Also, the conditions of the walkways are deficient in several segments due to the presence of obstacles, reduced effective width, discontinuities, and damages. Both shortest routes presented few tsunami evacuation route signs (Cataño two, and San Juan one).

The ***evacuation time analysis of other critical cases*** showed that Loiza and Toa Baja have significant more critical schools than Cataño and San Juan. The Medianía Alta public school in Loiza required 89 minutes to move from the internal assembly place until leaving the THZ (considering the average walking speed of 2.50 mph); this is 3.4 times the time required for the critical school in San Juan, and 5.5 times the time required for the critical school in Cataño. Academia Espíritu Santo private school in Toa Baja required almost 51 minutes to move from the internal assembly place until leaving the THZ (considering the average walking speed of 2.50 mph); this is almost 2 times the time required for the critical school in San Juan, and more than 3 times the time required for the critical school in Cataño.

The ***school survey*** was answered by only two schools, and the most relevant observations on their responses are:

- Both schools were built before 1987, situation that suggest special evaluation is required when assessing their seismic rehabilitation.
- Both schools have a tsunami evacuation plans and had correctly identified the external assembly point.
- The response that the tsunami evacuation siren was not audible in one school may suggest that the alarm system could require either maintenance, repair, or improvements.
- The discrepancies between the evacuation times from the classroom to the internal assembly place between both schools, and between having both horizontal and vertical evacuations may suggest that some questions were not adequately interpreted, and strongly suggest that the questionnaire should be reevaluated, and/or other strategies to collect and verify this critical data should be devised.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The study has assessed for all the 46 Puerto Rico coastal municipalities at risk from tsunamis: (a) the public and private schools in tsunami hazard (evacuation) zones, (b) their usage as voting centers, (c) their usage as shelters, and (d) the student and faculty population potentially affected. Critical municipalities in terms of quantity of schools, school population, and multiple usages of the school building have also been determined. These critical municipalities could serve as a basis in the planning process to prioritize school rehabilitation studies.

The study has assessed for all the four public schools that are in the THZ in Cataño, and all the nine public schools that are in the THZ in San Juan the time required to evacuate from the school internal assembly place until the point of exiting the tsunami hazard zone, and from the school internal assembly place until reaching the external assembly point. For each analysis, the four different walking speeds suggested by Jones et al (2014) were used. For each school, the shortest evacuation route and between two to four alternate routes were evaluated. The times to evacuate two additional schools, one in Loiza and one in Toa Baja, were also evaluated.

Schools with the longest times to leave the tsunami hazard zone are considered critical and more vulnerable to a tsunami event. These evacuation times may be used as one of the planning and decision-making criteria to prioritize rehabilitation funds, and also to evaluate the need for vertical evacuation. The total evacuation time until reaching external assembly point may mislead the assessment of critical schools, since reaching the external assembly point may imply a long walk outside the tsunami evacuation zones. Thus, it is recommended to use the evacuation time until exiting the tsunami evacuation zone for planning and decision-making analysis.

Critical schools in San Juan are more vulnerable than critical schools in Cataño. Although there are other municipalities with more vulnerable conditions, such as the cases presented for Loiza and Toa Baja.

Even though the results of the survey forms provided some useful information, such as that the schools have tsunami evacuation plans, validation of the external assembly points, showed that both schools were pre-code (1987), and participation in evacuation drills, two responses are considered not significant. Also, the reported evacuation times from drills, a critical information for this research, showed inconsistencies. It is recommended to perform one to one interview processes, to foster participation, clarify any doubt, validate the responses, and establish cooperative relationships with school administration.

The characteristics of the shortest evacuation route evaluated using Google Earth Pro for the two most critical schools showed that they may not be suitable for transit during the evacuation process due to the presence of obstacles, insufficient walkway width, pathway discontinuities, presence of potential after earthquake hazards, and routes layout parallel to the shoreline. An improvement of pedestrian facilities used as evacuation routes could be advisable. Also, the improvement of evacuation routes identification should be evaluated, since few signs were found in the shortest evacuation routes.

The use of vehicular roads as evacuation facilities (and its implications) should be considered. This alternative would require the evaluation of vehicular traffic and its possible interaction with pedestrian movement, since many of the evacuation routes move along primary arteries of the zone, with large traffic volumes.

Google Earth Pro in conjunction with ArcGIS and PlotARoute resulted useful tools to perform the evacuation time analysis and the evaluation of the conditions of the characteristics of the schools' evacuation routes.

Regarding the limitations of the study, one can point out that: (a) The school data available was from 2016 (population may have varied; some schools may be closed due to the restructuration plans of the PR Department of Education in the last few years); (b) The geolocation used for public schools was from Homeland Infrastructure Foundation-Level Data (HIFLD), U.S. Department of Homeland Security. (2020); further analysis revealed that in some municipalities (not the case studies) few schools are misplaced in the dataset; the total number of schools identified in tsunami hazard zone may have a small variation.

The most significant barrier/problem encountered was the availability and reliability of school data: data were dispersed, data sources were not obvious, some data were not up to date or was not available (i.e., population). This strongly suggest that GIS based, broad and inclusive, centralized, accessible, and validated information is essential to support data-based decision processes, allow what-if analysis, and fosters research on community safety and resilience.

The computed evacuation times, following the guidelines of the USGS publication "*The pedestrian evacuation analyst: Geographic information systems software for modeling hazard evacuation potential*" (Jones, Ng, and Wood, 2014) are considered good initial evaluation values, that provide a ***lower bound estimate*** of the total evacuation time required, since:

- Other studies showed different (and lower) average evacuation speeds, and propose speeds that vary with age (i.e., UNESCO 2020).
- The computed time consider only one stage of the evacuation process, not the complete evacuation procedure timeline triggered immediately after the earthquake event occurred, i.e., the reaction time and the time required to move from the classroom to the school patio/internal assembly site.
- Different scenarios that consider the effect of change in route due to possible obstacles to the path due to structural failures during earthquake (i.e., electric power lines and bridges) could drastically increase evacuation time.
- The particular conditions of the evacuation route, the volume of pedestrians and its interaction with other generators of high volume of pedestrian traffic, the interaction of pedestrian movement with vehicular traffic (i.e., at intersections), geometric, environmental and human factors, and other characteristics are not explicitly factored in.

These observations lead to the recommendation than further study is necessary to refine the estimate of the total time required to evacuate schools in the event of tsunamis.

The reader can obtain more details of the first cycle of the research accessing the following link, where the full 388 pp report and a poster can be found: http://prcrepository.org:8080/xmlui/handle/20.500.12475/1166

FURTHER STUDY

The findings of the first year of the research lead to define a second, longer, ongoing research process. The research team is composed by a PhD student, an undergraduate student, three PUPR faculty members, and three researchers from Volpe National Transportation Systems Center, as a cooperative agreement between the center and PUPR.

- The focus of the ongoing research is:
- To expand the analysis performed in the first cycle. Private schools hazard analysis has already been developed and presented in this publication.
- Establish an evacuation timeline that considers all the stages of the evacuation process, including the initial time required to drop, cover, and hold when the earthquake is felt, the reaction time afterwards, the movement from the classroom to the school patio, the preparation time in the patio to move to the exterior, and the movement from the school patio to the external assembly point.
- Study all the factors that affect people reaction, pedestrian dynamics, and evacuation processes (i.e., human, environmental, geometric, social, among others).
- Study pedestrian dynamics simulation models, and simulation software.
- Obtain evacuation drills information to calibrate and validate simulation models.

The main objective is to develop a methodology that allows a better estimate of the evacuation time required for schools (and other facilities) in events of tsunamis, thus providing a tool that allows to better decide when vertical evacuation is required, contributing to the development of more safe and resilient communities.

Other factors that could be added in further studies are the evacuation time required by people with disabilities, the effect of flood depths in the area where the schools are located, the training of people on the evacuation routes, and the training they have to act based on the intensity they felt from the earthquake, without waiting for the tsunami alarm to go off (which could take several minutes).

We consider that a comprehensive (holistic) approach to schools' rehabilitation is highly recommended. An approach that: (a) Focus on the safety and the resilience of the community. (b) Is not limited to evaluate one hazard condition, but considers multihazard situations (earthquakes, tsunamis, hurricanes, floods, landslides, liquefaction). (c) Is not limited to the building itself, but considers the evacuation process, the evacuation routes, and people preparedness. We expect that the first cycle and this new stage of the research effectively contribute to have reliable data that contributes to this holistic approach and the safety and resilience of schools.

Finally, is important to mention that, if required, the vertical evacuation and shelters structures should be designed according to the latest recommendations (ATC 2019a and ASCE 2017 procedures). ASCE/SEI 7-16 (ASCE 2017) does not have tsunami design parameters already established for Puerto Rico. This is an area of recommended further study and development that requires serious attention from the research and professional community.

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