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Field Survey of 2021 Typhoon Rai –Odette- in the Philippines

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Abstract

Typhoon Rai struck the Philippines on 16th December 2021, damaging and inundating many coastal areas in the Visayas region. The typhoon brought with it violent winds, storm surges and high waves, which left a trail of destruction and debris in its wake. In order to understand the various damage mechanisms, the authors conducted a field survey to measure the water level heights reached by the storm surge at several locations in the provinces of Cebu and Bohol. As part of the survey, local residents were interviewed to understand the phenomena and survey the heights reached by the storm surge. The maximum storm surge level measured were 2.54 m and 4.06 m across coastal towns in the provinces of Cebu and Bohol, respectively. Finally, some interesting characteristics of the storm surge are summarised, and the lessons learnt in terms of disaster risk management are discussed.

Keywords

Storm surge, Philippines, Typhoon Rai, Field survey

1 Introduction

Typhoon Rai (known as "Odette" in the Philippines), the last typhoon in the Western Pacific basin in 2021, entered the Philippine Area of Responsibility (PAR) on the 14th December at 23:00 Philippine Standard Time (PST; UTC+08:00) with a minimum central pressure of 985 hPa and maximum sustained winds of 100 km/h (NDRRMC 2022). This triggered the issuance of Tropical Cyclone Warning Signal (TCWS) No. 1 to Samar and Surigao provinces. Rai became a typhoon on the 15th December 2021 08:00 PST and gained strength as it moved westward towards the Philippines. TCWS No. 4, the maximum warning level in the Philippines was declared the next day for Leyte, Bohol, and Surigao provinces as the storm reached its minimum central pressure of 915 hPa (JMA 2021).

The typhoon made the first of its nine landfalls at Siargao Island in Surigao del Norte on 16th December 2021 13:30 PST and brought strong winds and rainfall to the Visayas region. Southern Leyte, Bohol, Cebu, Negros Occidental, and Negros Oriental were severely affected as the eye of the typhoon traversed through these provinces (see Figure 1). In Southern Leyte, a storm surge of 3.66 m was reported in the coastal towns of Saint Bernard, Libagon, and San Juan. Reports of storm surges were also received in at least ten coastal towns in Bohol (ECOWEB 2021).

A storm surge occurs due to the dual effect of the low pressure at the centre of a typhoon and high winds pushing the water mass, increasing the level of water around the coastline. Notable past events include Cyclone Sidr in 2007 in Bangladesh (Tasnim et al. 2015), Cyclone Nargis in 2008 in Myanmar (Tasnim et al. 2014), Haiyan (Yolanda) in the Philippines in 2013 (Mikami et al. 2016, Esteban et al. 2015, Leelawat et al., 2013), hurricane Sandy in New York (Mikami et al. 2015) or typhoon Jebi in Japan in 2018 (Takabatake et al. 2019). There is also the fear that climate change will increase the intensity of these events, further increasing the threat that they pose to coastal communities (see for example Knutson et al. 2010, Hoshino et al. 2016, Nakamura et al. 2020).

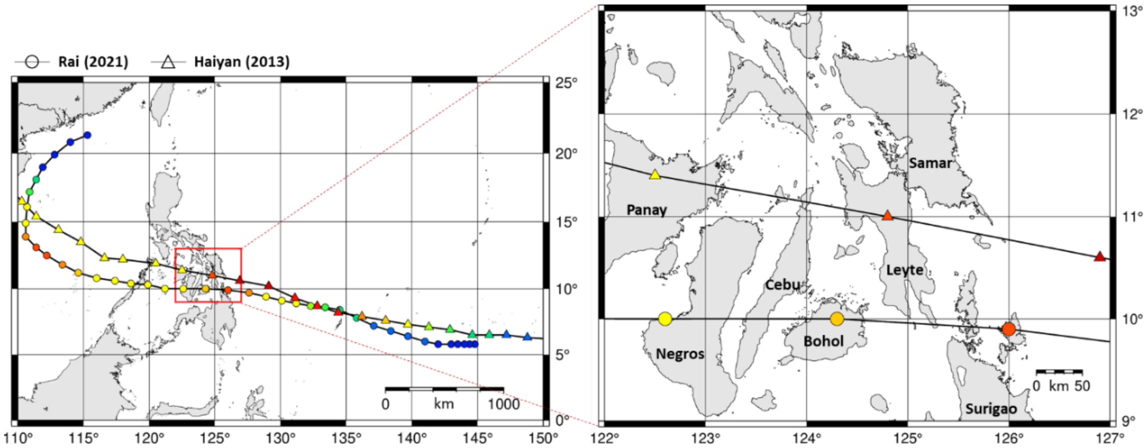

Figure 1. Typhoons Rai and Haiyan Best Track Data from the Japan Meteorological Data (JMA).

The damage by Typhoon Rai was documented by the National Disaster Risk Reduction and Management Council (NDRRMC) of the Philippines. Despite the country having made initiatives to reduce potential damage (Ong et al. 2016) after the onslaught of Typhoon Haiyan (which also hit the Visayas region 8 years prior to Typhoon Rai, as shown in Figure 1), such as updating the structural design code (Valdez et al. 2022), the Visayas region was still heavily affected. The government declared a State of Calamity across 493 cities and municipalities (NDRRMC 2022). A total of 444 cities and municipalities had power outages and 156 suffered water supply interruptions, which also disrupted potable water supply. In some instances these power supply disruptions lasted for a long time. For example, more than half of the 500 typhoon-hit villages in Southern Leyte were still without power by February 2022 - nearly two months after the typhoon (Meniano 2022). Two towns in Bohol remained without power four months after the typhoon (Saavedra 2022).

In the Central Visayas region, Typhoon Rai affected nearly 4.4 million individuals of whom 1.3 million were located in the province of Bohol and around 2.5 million in the province of Cebu (NDRRMC 2022). In the same region, the typhoon caused a total of 220 total reported deaths and 546 injuries. The typhoon damaged more than 1.1 million houses in the Central Visayas, nearly a quarter of which were totally destroyed. In Cebu province alone around 708,000 homes were damaged, while around 300,000 houses were damaged in Bohol. Damage to agriculture in Cebu and Bohol was estimated at around P2 and P1.3 billion (38 million and 25 million USD), respectively. Typhoon Rai also affected nearly 100,000 fisherfolk in Bohol and over 40,000 in Cebu. In terms of infrastructure damage, Cebu was the worst hit in Central Visayas, with around P3.5 billion in damages (67 m USD), of which about P2.3 billion (44 m USD) was reported in the municipality of Alegria. This was due to the damage and collapse of a seawall caused by the impact of strong waves. Bohol reported an estimated P726 million in infrastructure damage (13 m USD). Transportation services were also severely affected. Eight (8) airports and 139 seaports were reported to have suspended operations. In addition, the Department of Tourism recorded P2.5 billion in losses to the Cebu tourism industry (48 m USD), while a loss of P433 million (8 m USD) was reported in Bohol province (Philippine Daily Inquirer 2022).

In the present work the authors set out to survey the storm surge heights in a variety of coastal areas in Cebu and Bohol, focusing on some of the areas reported to have been damaged the worst. The main purpose of the survey was to ascertain which areas had suffered inundation due to storm surge, clarify damage patterns, and determine inundation and run-up heights. Additionally, the authors conducted drone surveys to map some of the affected areas and bathymetry surveys to characterise the depth of the seafloor. All data collected is either included as attachments to this paper or will be freely distributed upon request.

2 Methodology

A field survey was conducted approximately two months after the typhoon, between the 18th and 28th of February 2022. This was the earliest possible opportunity to enter the country for authors that were not residents of the Philippines, amid restrictions due to the covid-19 pandemic. The activities conducted were part of a large collaboration between a number of institutions in Japan (led by Waseda University) and the Philippines (including the University of the Philippines Cebu and Manila Observatory), along with other partners from different institutions (please refer to the list of authors). The survey concentrated around the islands of Cebu and Bohol, and smaller islands located offshore from these two provinces. The survey started from Cebu City and covered large sections of the southwest and southeast coast of Cebu island. Then, islands offshore of Bohol that were particularly badly hit by the typhoon were surveyed, including those within the jurisdiction of Tubigon town and the large island of President Carlos P. Garcia (former Pitogo Island).

2.1 Survey of inundation heights

Given that over two months had passed since the typhoon made landfall, the authors had to rely on interviews with local people encountered at the various survey sites in order to obtain an idea of the phenomena (as opposed to other surveys conducted closer to the time of landfall, which could use visual clues indicating the likely level of the storm surge). The heights of the levels reached by the storm surge (as indicated by interviewees at the various locations) were surveyed by using a laser ranging instrument, a prism and staffs. The precise location of each survey point was then recorded using GPS, following established surveying techniques for these types of exercises (Esteban et al. 2018). All inundation heights were established using the sea water level as a reference point, and were corrected to the tidal height of nearby substations (which are tied to the Cebu tidal station datum (listed in Table 1) at the time of the storm surge's arrival by using WXTide[1], an open source global tidal prediction software (Flater 2007). The substations used in WxTide32 were selected based on their proximity to the survey points to determine the tidal level during the watermark measurement and at the estimated passage of the typhoon. Using the typhoon track (JMA 2021) and a government report (NDRRMC 2022), the authors assumed that the typhoon arrived at President Carlos P. Garcia islands around 16th December 2022 18:30 PST, at Tubigon around 20:45 PST, and at southern Cebu around 22:00 PST (see Figure 2). The tidal range in the area is in the order of ~1.3 to 1.5 m (on 19th of February 2022 the tidal range was 1.3 m).

[1] The Cebu tidal station was established in the year 1935 (the second oldest in the Philippines, after the one in Manila, which was established in 1901). The tidal station undergoes annual relevelling, and the level given is with respect to *zero tide staff* (the staff from which the levels are read has its bottom placed at a certain level, according to measurements of the tide). For the Cebu tidal station the MLWL =1.044 m, MLW =1.234 m, MSL=1.768, MTL= 1.752, MHW = 2.286 m MHHW =2.545. Overall, through time the readings at this tidal station have been consistent, and are only affected by local sea level rise (no significant ground subsidence or tectonic activity have affected them). Private communication with the Physical Oceanography Division of the National Mapping and Resource Information Authority (NAMRIA) of the Philippines.

2.2 Bathymetry surveys

At some locations, bathymetric surveys were conducted using a Garmin GPSMAP 585 echosounder (care was taken to keep the speed of the boat below 8 knots/hr, given the operational limitations of such instruments).

2.3 Aerial drone survey

The aerial drone surveys were conducted using a Phantom 4 Pro+ unmanned aerial vehicle (UAV) (Da-Jiang Innovations Science and Technology Co. Ltd.). The overlap rate of the vertical pictures in the UAV forward moving direction ranged from 70% to 90%, and these were then stitched together to produce larger maps of the areas of interest.

3 Results

The measured storm surge inundation and run-up heights are summarized in Table 1 and Figure 2. A total of 22 points were surveyed (including several points where no reading could be taken. The maximum storm surge inundation height (4.24 m) was recorded at Tubigon port, in Bohol (See Figure 2). The total level was determined with reference to Cebu tidal station datum.

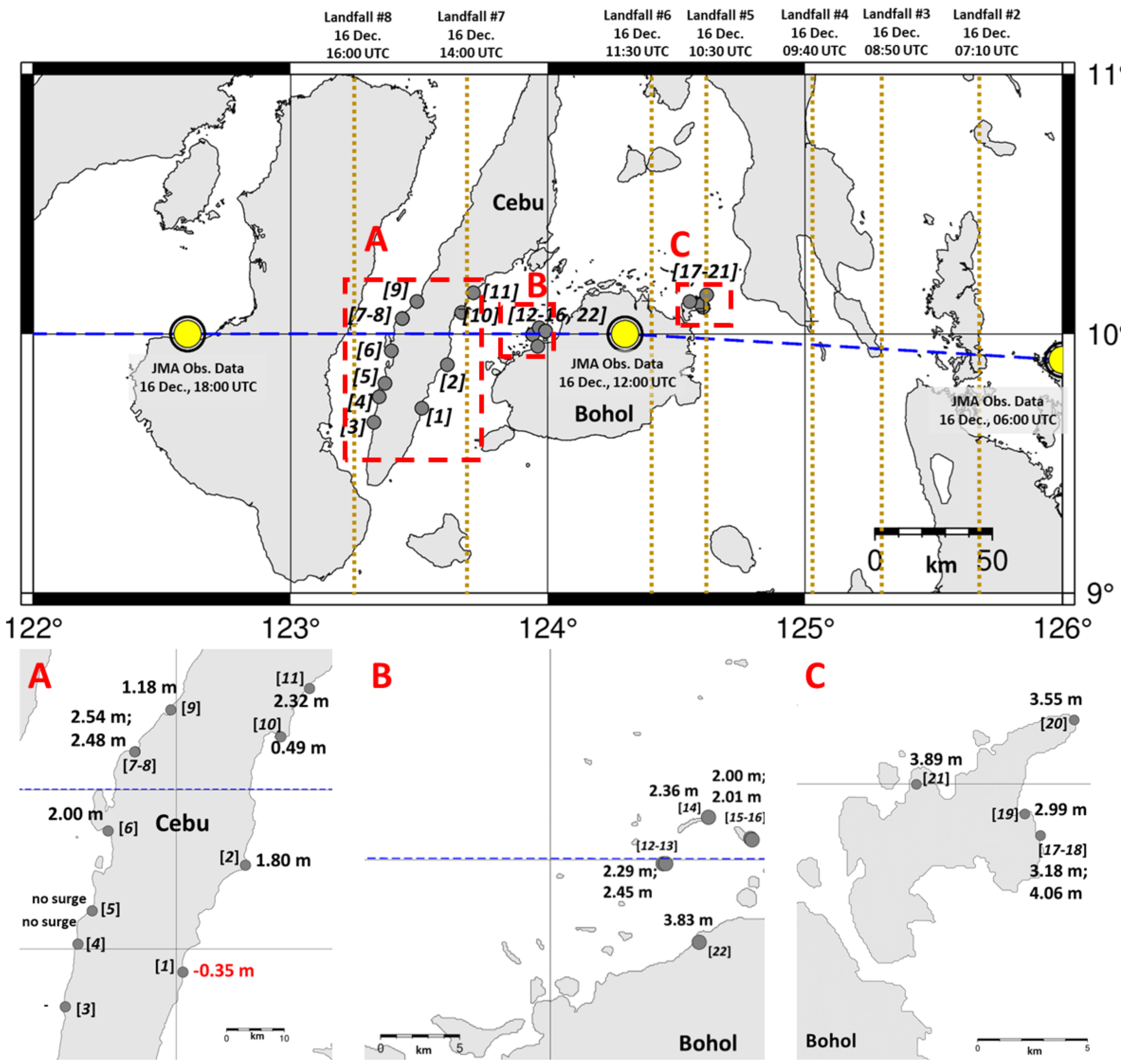

Figure 2. Path of the typhoon, location of the points surveyed (in brackets), and estimated storm surge (in meters) at each location (see Table 1).

Table 1. Storm surge inundation and run-up heights (types of heights are either inundation height (I), run-up height (R) or –likely- wave splash (W). Estimated storm surge indicates the deviation in water levels from the astronomical tide expected at the time of the passage of the storm. The substations used for all tidal levels in this table all use the datum established as the Cebu tidal station (i.e. all tidal level measurements thus refer to this Cebu datum).

No.	Place	Latitude (S)	Longitude (E)	Type	Inundation Depth (m)	Type	Date of measurem.	Time of measurem.	Measurem. above water (m) at survey point	**Nearest substation from survey point (in WxTide32)**	Tidal level measurem. (m) at nearest substation	Total level (m) from Cebu tidal station datum	**Est. Time of Typhoon Passage (UTC)**	**Tidal level during event (m) at nearest substation**	**Est. Storm Surge Height (m)**
1	Alcoy Port	9.71362	123.51044	R	-	Local residents explanation	19/02/2022	8:23am	0.82	Boljoon	-0.08	+0.9	12/16/2021 15:00pm	1.11	-0.35
2	Argao	9.88164	123.60936	I	0.4	Local residents explanation	19/02/2022	09:53am	2.7	Boljoon	0.3	+2.4	12/16/2021 14:30pm	1.2	1.8
3	Malabuyoc	9.6592	123.32436	W	-	Local residents explanation (wave splash only?)	19/02/2022	14:15pm	-	Moalboal	-	-	12/16/2021 15:45pm	1.24	-
4	Alegria	9.75768	123.34437	-	-	No storm surge	19/02/2022	-	-	Moalboal	-	-	12/16/2021 15:45pm	1.24	-
5	Badian	9.80991	123.36688	-	-	No storm surge	19/02/2022	-	-	Moalboal	-	-	12/16/2021 15:45pm	1.24	-
6	Moalboal Town Centre Port	9.93543	123.3921	I	0.47	Coast guard explanation	20/02/2022	09:10am	3.23	Moalboal	0.01	+3.22	12/16/2021 15:45pm	1.24	2
7	Dumanjug market	10.05981	123.43469	R	-	Local residents explanation	20/02/2022	10:45am	3.43	Barili Bay	0.52	+2.91	12/16/2021 15:00pm	1.41	2.54
8	Dumanjug residential area	10.05961	123.43425	R	1.57	Local residents explanation	20/02/2022	11:04am	3.27	Barili Bay	0.62	+2.65	12/16/2021 15:00pm	1.41	2.48
9	Barili	10.12552	123.49134	-	-	Local residents explanation	20/02/2022	13:16am	1.4	Barili Bay	1.19	+0.21	12/16/2021 15:00pm	1.41	1.18
10	Carcar	10.08327	123.6653	R	-	Local residents explanation	20/02/2022	14:59pm	0.94	Carcar Bay	0.95	-0.01	12/16/2021 14:00pm	1.4	0.49
11	San Fernando	10.15909	123.71073	I	0.85	Local residents explanation	21/02/2022	8:42am	3.55	Carcar Bay	0.02	+3.53	12/16/2021 15:00pm	1.25	2.32

12	Isla Pangpasan (I)	9.99775	123.9401	I	1.36	Local residents explanation	26/02/2022	11:00am	3.09	Tubigon	0.6	+2.49	12/16/2021 12:45pm	1.4	2.29
13	Isla Pangpasan (II)	9.9978	123.94159	I	1.22	Local residents explanation	26/02/2022	11:30am	3.19	Tubigon	0.66	+2.53	12/16/2021 12:45pm	1.4	2.45
14	Isla Ubay	10.02437	123.96627	I	0.77	Mudline on a wall	26/02/2022	13:35pm	2.82	Tubigon	0.94	+1.88	12/16/2021 12:45pm	1.4	2.36
15	Isla Batasan (I)	10.01219	123.99064	I	1.53	Local residents explanation	26/02/2022	15:19pm	2.22	Tubigon	1.18	+1.04	12/16/2021 12:45pm	1.4	2
16	Isla Batasan (II)	10.01143	123.99142	I		Damaged roof by floating debris according to local resident	26/02/2022	15:37pm	2.19	Tubigon	1.22	+0.97	12/16/2021 12:45pm	1.4	2.01
17	Barangay Kabankalan (I)	10.10375	124.6033	I		Local residents explanation	27/02/2022	09:54am	3.65	Ubay	0.52	+3.13	12/16/2021 10:30am	0.99	3.18
18	Barangay Kabankalan (II)	10.10375	124.6033	R		Line of debris on side of a hill	27/02/2022	10:00am	4.52	Ubay	0.53	+3.99	12/16/2021 10:30am	0.99	4.06
19	Barangay Santo Rosario	10.11264	124.59679	I	0.19	Local residents explanation	27/02/2022	10.27am	3.41	Ubay	0.57	+2.84	12/16/2021 10:30am	0.99	2.99
20	Barangay Tugas	10.1514	124.6173	I	0.83	Local residents explanation	27/02/2022	11:44am	3.88	Ubay	0.66	+3.22	12/16/2021 10:30am	0.99	3.55
21	Sitio Paraiso	10.12487	124.55168	I	1.34	Local residents explanation	27/02/2022	13:45pm	4.09	Ubay	0.79	+3.3	12/16/2021 10:30am	0.99	3.89
22	Tubigon Port	9.95285	123.9609	I	1.07	Local residents explanation	28/02/2022	09:12am	4.79	Tubigon	0.44	+4.35	12/16/2021 12:45pm	1.4	3.83

3.1 Cebu island

3.1.1 Southeast shoreline

3.1.1.1. Alcoy Municipality

The survey started from Cebu City and proceeded southwards to Alcoy town. The town has a small port, around which some small single story holiday cottages are located. The sea in the vicinity of the port is shallow, with a wide reef flat (intertidal area), where local people can walk and gather seafood (see Figure 3). A local resident interviewed indicated that there was no storm surge and that the flood waters they experienced descended from the mountains due to rainfall. The typhoon hit at high tide, with the water reaching the foreshore of the beach, to a level of +0.9 m (according to the resident, the waves reached the entrance of the property, which was about 10 metres from the shoreline). This corresponded to an estimated storm surge of -0.35 m (when the tide at the time of the passage of the typhoon was taken into account, see Table 1).

Figure 3. Left. Shallow bathymetry around the port pier of Alcoy. Right. Boats washed onshore by the waves.

3.1.1.2. Argao Municipality

The survey then moved to Argao town, where workers at the "Baluarte de Argao Resort" indicated that the storm surge reached the bottom staircase inside a house situated ~20 m from the water edge (see Figure 4, essentially the ground floor of the house was flooded to a level of 0.4 m, indicating a storm surge that reached a level of +2.4 m). The resort was protected by a seawall that had been constructed to a level of around 2 m above water level (different parts of the seawall were built to slightly different levels, see Figure 4). Residents evacuated at 10 pm and did not return until 2 am, when they witnessed damage to the roof due to the wind (repaired by the time of the survey), wave damage to railings on their seawall and heavy concrete flower pots having been displaced by the surge and waves. Overall, it did not appear that the storm surge itself caused any structural damage, although the waves were high, and the splash reached a level of around 2-3 m above the ground floor in front of the house. The waves carried with them a considerable amount of sand (brown in colour, as it had apparently originated from the river Argao, not the coral sand in front of the property), which had since been cleaned.

3.1.1.3. Carcar City

The area surveyed in Carcar City is known as Sitio Bantayan in Barangay Tuyom. The resident of a coastal house indicated that the storm surge was limited in height, although waves were high and there was considerable splash, causing localised damage to houses situated right next to the water (see Figure 5). The maximum storm surge was 0.49 m, measured on the fourth step of a staircase used to access the narrow beach in front of the property (residents noted that this level was higher than they would have expected at that time, but not that much more than usual high tides). The family stayed in place and did not evacuate, and structural damage was generally low in the area.

Figure 4. Left. Resident indicating the inundation height at a house located close to the shoreline. Right. The seawall in front of the house had been built to slightly different levels.

Figure 5. Left. Minor damage to houses located right next to the waterfront. Right. The storm surge only reached the middle of a small staircase used to reach the beach.

3.1.1.4. San Fernando Municipality

The area surveyed was the port of South Poblacion, where the water reached the top of the pier and inundated it to a level of 0.77 m above its floor (+3.53 m). At the time of the passage of the typhoon (Dec 16th at ~20:00) the tidal level at Carcar Bay station (nearest tidal station) should have been +1.25 m, indicating a skew tide of 2.32 m (it is worth noting that the maximum tide on that day was supposed to be +1.43 at 09:23, and the lowest tide +0.12 m at 04:03). There was considerable splash from waves and some houses near the waterfront were damaged. The pier also suffered medium damage, as shown in Figure 5.

Between the port and the resort of Pulchra, situated north along the coastline, an almost continuous ridge of boulders had been displaced by the typhoon and placed on top of the reef flat. A bathymetry survey was conducted in this area, together with an aerial survey using a drone. A separate diving survey on the state of the coral reef in the area in January 2022, which was not part of the activities documented here (but which was conducted by one of the authors of this study separately), found that almost all corals in the area had died. Particularly, all branching corals were destroyed, and only massive coral colonies were left (although even many of those were overturned by the waves).

3.1.2 Southwestern shoreline

3.1.2.1. Malabuyoc and Alegria municipalities

The southernmost point reached by the survey was Malabuyoc town, where the team surveyed the area of the coastline close to the “People’s Palace” (the town hall). In this area the coastal road runs very close to the waterline, and there is usually only one house between it and the water. Many houses have been built on land reclaimed from the sea using stones or concrete piles, resulting in them being situated right to the edge of the water or on top of it.

At one house residents claimed there had been another dwelling behind theirs, which was completely destroyed by the waves. It was claimed that this was caused by a storm surge that reached waist level outside the house (to a level of 0.87 m above the floor), with the floor of the house being raised to a level of +1.44 m (see Figure 6). However, it appears unlikely that there was really a storm surge at this location, given that this was not reported in any of the other towns from that point northwards up to Moalboal, and thus residents were probably just confusing the level of the splash by the waves with an actual storm surge (there was often such confusion during the interviews, with the survey team asking numerous questions to attempt to fully differentiate the phenomena from the descriptions by interviewees).

It should also be noted that the distance between Cebu and the island of Negros to the west (both islands are separated by the Tañon Strait) is quite short, and that there are thus limitations to the size of the waves that can develop due to the short fetch in the area. This, together with the protecting coral reef, explains why houses could normally be built right up to the shoreline without suffering damage, although in this event the powerful wind-generated waves caused much damage. In several sections of the coastline between Malabuyoc and Alegria the road had suffered significant scour and collapsed into the sea, with construction work taking place to rebuild it. In one stretch from Alegria to Badian the section under construction was over 3 km, with maybe half of that being caused by the complete collapse of the road into the sea (see Figure 6).

In Alegria, residents of a house located close to the sea (at a distance of less than 10 m) did not report that a storm surge had affected the area. The flooding they suffered came from rainwater descending from the mountains, with the mangroves and wide reef flat in front of the house offering some protection from the waves (hence they did not suffer any structural damage).

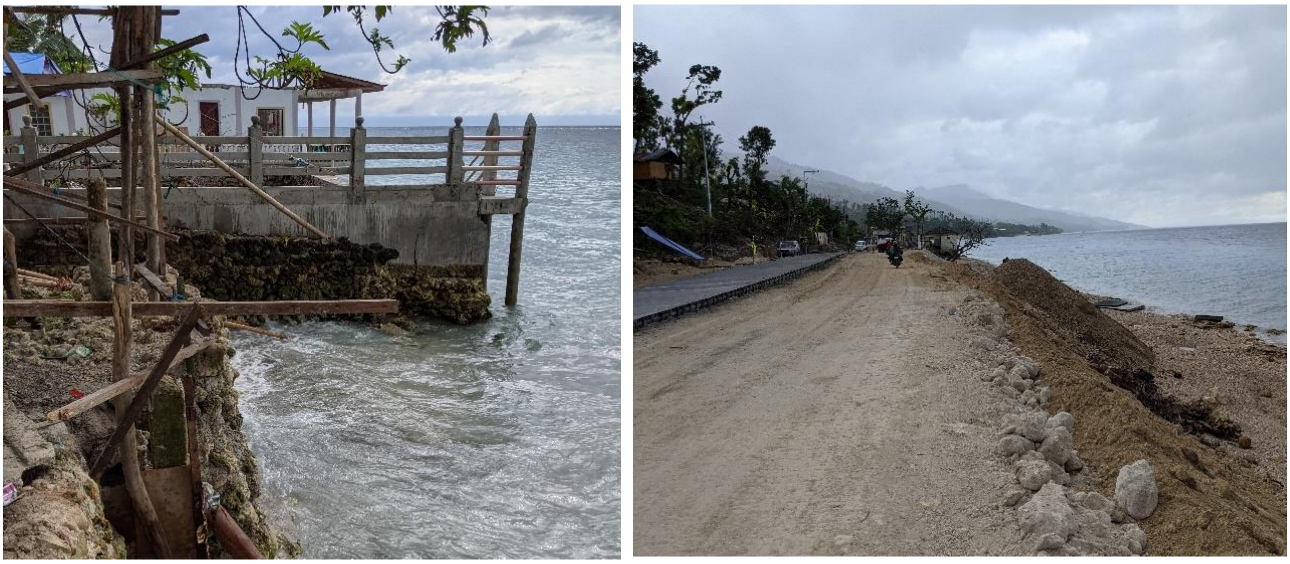

Figure 6. Left. In Malabuyoc houses were built on top of the beach, in many cases by reclaiming land. Right. The road between Malabuyoc and Alegria suffered severe scour damage and in some places was completely removed, with recovery activities underway at the time of the survey.

3.1.2.2. Badian Municipality

In Badian the coastline in front of Barangay Matutinao was surveyed, which had a seawall that survived the event, although some damage to its top return wall was observed. It was interesting to observe that in this area a boulder ridge had been created by the typhoon, at a distance of ~110 m from the seawall (see Figure 7). According to a local diver these boulders had been taken from the coral slope, from a depth of around 8-9 m. The corals in the area had been almost completely wiped out by the typhoon, which hit at high tide. However, no storm surge was reported in the area, with the observed damage to houses taking place as a result of the high waves and powerful winds.

Figure 7. Boulder ridge created by the typhoon offshore Badian (from aerial drone surveys by the authors).

3.1.2.3. Moalboal Municipality

At the port at the centre of Moalboal town a member of the coastal guard, who was the last person to evacuate the area at 22:30 on the day that the typhoon hit, after instructing all remaining fisherman to leave (some had not evacuated with the rest of the population in order to secure their boats), indicated that the storm surge reached the top of the pier (to a level of +3.23 m). The waves overtopped the pier and then inundated the houses behind (although the water that flooded the pier itself was mostly due to the overtopping waves). The pier itself suffered medium damage, with some of the concrete revetments slabs breaking and revealing the rubble fill (see Figure 8). Prior to the storm there were 280 registered boats in the area, but only 30% remained (and of those many had still not been fully repaired). At the edge of the reef flat there were was a boulder line/ridge, which was already there before the coastal guard started working at Moalboal (likely transported there by an earlier typhoon event). It is unclear why this event did not transport or remove any boulders in the area (possibly due to the direction of the waves and local geography).

3.1.2.4. Dumanjug Municipality

At the Municipality of Dumanjug north of Moalboal the coastal area surveyed was in front of the open-air market, which was protected by a series of seawalls built at different times using a variety of designs. Two points were surveyed. At the first point two fishermen indicated the storm surge reached the top of the seawall, to a level of +2.91 m, but did not overtop it (see Figure 9). At a second survey point, about 100 m further down the coastline, residents indicated the inundation level at their house, to a level of 1.57 m above ground floor (again, to level of +2.91 m). The house was situated 30 m from the water, and suffered partial damage (it was built using concrete columns and a wooden/steel roof, with the roof being partially damaged by the waves). At this point the seawall suffered substantial damage, with much of the material behind it being removed by the waves (see Figure A8).


Figure 8. Left. Damage to port pier at Moalboal. Right. The storm surge level reached the top parapet on the side of the port pier.


Figure 9. Left. The storm surge reached the top of the seawall in front of Dumanjug market. Right. The storm surge overtopped some of the older seawalls, with scour taking place behind them due to the waves.

3.1.2.5. Barili Municipality

An elderly resident of a house situated right on the coastline (half a dozen metres from the water edge) was interviewed. He did not evacuate during the event. While the house in front of his (belonging to his son, built on concrete piles) was washed away, other wooden constructions within sight survived the incident, indicating that the storm surge was minimal at this point. However, waves were high and splash reached the second floor of houses. Little rain was reported, although the wind was strong during the passage of the typhoon. The overtopping waves flowed through the narrow concrete paths between the houses, and then flooded the centre of the area (situated at a lower level that the newly reclaimed houses on its edge).

3.2 Bohol island

In Bohol, the survey covered some of the smaller islands to the north, which were badly hit by the typhoon.

3.2.1 Tubigon Municipality

The town is located in the northern part of Bohol, and has a ferry port with numerous daily connections to Cebu Island. A barge was carried by the surge and slammed into houses next to the port (See Figure 10), although many of them were subsequently rebuilt. At a house next to this barge, the inundation level reached 1.07 m above the floor, although there was substantial run-up that reached the main church of the town (situated around 430 m from the shoreline).

Offshore of the town there are a number of small coral islands located on the southern end of the Danajon Bank, one of only six double-barrier reefs around the world. In these impoverished islands most residents gain their livelihoods from the sea. Due to the 2013 Bohol Earthquake, the islands experienced land subsidence of about one meter, and as a result get flooded even during regular high tides (Jamero et al. 2019).

Figure 10. Left. Barge slammed into houses close to Tubigon port. Right. Inundation level in the shop seen on the left side of the figure.

3.2.1.1. Isla Pangapasan

The storm surge submerged the low-lying Pangapasan island to a depth of 1.36 m (as measured in front of the barangay hall, see Figure 11). Many of the wooden buildings in the islands, and others that were sturdier but situated next to the sea, were destroyed by the waves. An elevated pathway that runs around the edge of the island, which offered some protection to houses situated inside of it (as opposed to those between it and the beach, which suffered more damage). One of the barangay councillors was interviewed, who reported that his house –a stilted construction located next to the shoreline- was washed away at 22:00. This happened due to the waves lifting his house and then transporting it away (although he had evacuated to his mother's house within the island).

The residents of a wooden house situated next to one of the piers in the island (which was completely destroyed by the waves, see Figure 11) indicated that the water reached a level of 1.22 m from the floor of the house). They initially evacuated to the school, which was destroyed and this forced them to relocate to the 2nd floor of another house.

Figure 11. Left. A resident indicates the level of the water in front of the barangay hall. Right. At the right side of the photo is one of the houses surveyed in front of what is left of the pier (structure on the right side)

3.2.1.2. Isla Ubay

This small island was one of the worst affected by the *2013 Bohol Earthquake*, currently suffering the most severe inundation during high tides, and is arguably the most impoverished settlement within those the Danajon bank. Many of the houses built around the circumference of the island were damaged or completely destroyed by the waves. A new barangay hall had been built next to the basketball court in the two years prior to the survey, and was covered by a steel roof which survived the winds with little damage. The barangay hall was built to a level higher than the buildings around it, although the storm surge flooded to a level of 0.77 m above the floor (as indicated by a mudline on the walls, see Figure 12). Most islanders evacuated to the 2nd floor of the barangay hall, although when the roof collapsed they had to descend to the ground floor (where they stood with water up to their waists).

Waves around the island were high, with splash reaching the 2nd floor of some houses. Only 4 of the 20 boats in the island survived the typhoon, although some others appeared to have been repaired at the time of the survey. Rainwater collection systems, on which the islands depend for much of their freshwater, were damaged, and only two remained (see Figure 12). One person was reported to have died in the island, when their house was washed away (three people were in the house at the time, two managed to survive).

Figure 12. Left. Mudline in the barangay hall. Right. Basketball court adjacent to the barangay hall (building on the left side) and the remaining rainwater collection systems (blue cylinders on the right side).

3.2.1.3. Isla Batasan

This narrow-elongated island is protected around its circumference by mangroves that were planted over a decade ago, though many of them suffered due to the typhoon. There is only one path in the island that traverses it from one edge to the other, with houses located at each side of the road (see Figure 13). Measurements were taken at two locations. The church was flooded to a level of 1.53 m above the floor (see Figure 13). Another house located at a short distance away from the southernmost edge of the island was flooded up to the roof level, with locals indicating the debris damage it sustained. Interviews with the locals also indicated that, to the best of their knowledge, no families had permanently relocated to the mainland due to the typhoon. Indeed, many houses had been rebuilt to some degree, and the settlement appeared to be on a recovery path.

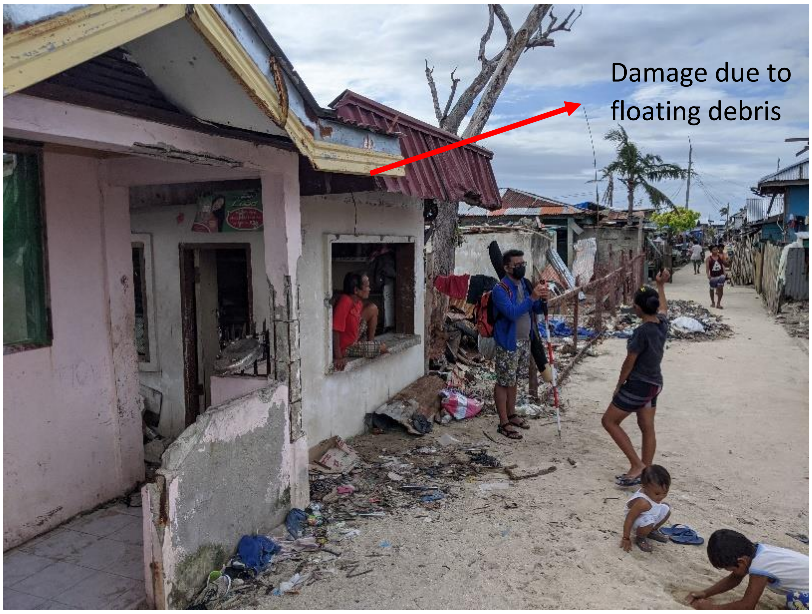

Figure 13. Left. Flooding level in front of the church of Isla Batasan. Right. Damage on edge of a roof due to floating debris.

3.2.2 President Carlos P. Garcia Island

President Carlos P. Garcia, formerly known as Pitogo, is an island on the northeastern part of Bohol, which is separated from the mainland by the Basiao Channel and can easily be reached by means of a motorized outrigger boat or barge. Nestled on the eastern end of the Danajon Double Barrier Reef Bank (FISH, 2020), the island constitutes a 4th class municipality whose residents rely mainly on farming and fishing for their income. The municipality has a population of over 25,000 inhabitants, and a total area of 6,528 hectares distributed into 23 barangays. (Christie et al., 2006). Three measurements were taken there.

3.2.2.1. Barangay Kabankalan

This barangay faces the open ocean, and would have been subjected to the full force of the typhoon. In the area surveyed there was a basketball court, with residents of a house adjacent to it having been interviewed by the authors. The house was completely destroyed by the typhoon, leaving a thick pile of coral stones and gravel on top of it (the thickness of this layer was estimated at ~0.5 m, based on the interviews and the level of the rebuilt frame of the door, see Figure 14). Residents left this layer of rubble and, by the time of the surveys, they had rebuilt their house on top of it (the house also doubled as a small shop). While they had evacuated at 18:00 before the storm surge manifested itself, they indicated that they later found some of their belongings inside the basketball court (fully protected by concrete walls which survived the event), which indicated that it is likely that the storm surge was up to a level of +3.13 m. A resident of a nearby house indicated the run-up level on the side of an adjacent hill –they had also evacuated, but found many of their possessions along the typical debris line that forms on the side of hills after storm surges-, which corroborated the water levels estimated by the other household.

Figure 14. Rebuilt coastal house (at centre of the picture), adjacent to the basketball court.

3.2.2.2. Barangay Santo Rosario

The residents of a small concrete house where four other families evacuated (a total of 22 individuals, although the house was only dozens of metres from the shoreline) indicated that, at a barangay meeting the morning before the typhoon struck, residents had agreed to evacuate by 16:00 (by 14:00 the winds were already strong, and many of the houses in this area lost their roofs). The storm surge did not reach the house, although waters rose to a level of 0.19 m above the floor at a pillar next to the basketball court (at a distance of ~30 m from the coastline, see Figure 15, left).

Figure 15. Left. Inundation level in front of the basketball court of barangay Santo Rosario. Right. New (far side of picture) and old (close side of picture) seawall at barangay Tugas.

3.2.2.3. Barangay Tugas

In this area there was a seawall constructed around the edge of the settlement, with the newer concrete one surviving intact (though there was severe scour behind it), while the older one collapsed (see Figure 15, right). Houses located between the seawall and the road were completely destroyed by the waves, with a few having been rebuilt by the time of the survey (although by their own means, as they received no help from authorities or NGOs). Residents of one of the houses indicated that by 16:00 the winds were strong, and by 19:00 waves started to splash over the seawall, with the waters eventually reaching a level of 0.83 m above the floor (time at which they evacuated).

3.2.2.4. Sitio Paraiso

A family living in a house around half a dozen metres from the edge of the water indicated that most of them evacuated at 16:00, although three individuals stayed behind to check their boats. At 18:00, the water level had already started to increase, drawing the boats towards the house. They tried to control them but eventually gave up by 18:30. The typhoon was at its strongest between 19:00 and 21:00, and by 19:30 many nearby houses were destroyed, with water splash due to waves reaching the top of the roof. Around 19:30 they thus decided to evacuate, with water level to their waists. Nevertheless, they later decided to return at around 20:00, protected by motorbike helmets and wearing snorkelling gear. Water level was up to neck level (1.34 m or so above the floor level), with the father of the family almost dying when trying to leave the house once again.

4 Discussion

Typhoon Rai passed through Bohol and Cebu at around high tide and, based on the track and wind direction, water could have first been pushed from the north to President Carlos P. Garcia Island, Tubigon, and western Cebu, before receding back. The measured surges at Bohol were generally higher than at Cebu, possibly due to the stronger wind speed and shallower bathymetry surrounding the former. This is clearly evident at the islands surveyed near Tubigon, situated on top of a double reef system –and hence in very shallow waters, and which were already submerged during high tides following the land subsidence due to the 2013 Bohol Earthquake (Jamero et al. 2017, 2018). Eastern Cebu may have first experienced the water receding, before it was pushed again towards the land as the wind field changed. At Alcoy town, located below the typhoon track, a negative storm surge was measured due to wind set-down, as the wind direction throughout the typhoon was away from the shore. This can be expected in the northern hemisphere to happen to the left side of the path followed by a typhoon, given the pattern of rotating winds due to these storms and the effects of the Coriolis force.

Despite the comparative lack of resources, in recent times the Philippines has been making efforts to increase its preparedness and awareness against natural disasters. Basically, the Philippine disaster management structure has evolved through learning from earlier events such as that of Typhoon Ketsana in 2009 or Typhoon Haiyan in 2013 (Ong et al. 2016). The year 2010 saw the passage of the Philippine Disaster Risk Reduction and Management Act of 2010, which created the National Disaster Risk Reduction and Management Council (NDRRMC), which replaced the National Disaster Coordinating Council (NDCC). At the provincial and municipal levels, there is a corresponding office with an assigned disaster manager, who is referred to as the “DRRM Officer”, and a counterpart DRRM Council where different stakeholders are to create policies on DRR. The barangay levels (smallest administrative units in the Philippines, equivalent to a neighbourhood or district government) have to incorporate DRR into their development plans and create their committees on DRRM. In this manner, the law aims for a bottom-up approach in all phases of disaster risk reduction: prevention and mitigation, preparedness, response, and recovery and rehabilitation. If a disaster takes place at a barangay, the community should respond to it. When two or more barangays are affected, the emphasis shifts from the communities to the municipality or the city; when there are two or more towns affected, everyone takes action, but the province takes the lead; when two or more provinces, disaster management goes up to the region; and with two or more regions affected, the national level is in charge (Agsaoay-Sano 2011). In the case of Typhoon Rai, since it affected two or more regions, preparedness to respond was from the community up to the national level.

It is clearly important for local authorities to establish effective layer 2 countermeasures (including hazard maps and evacuation protocols). There is also the necessity to ensure intergenerational transmission of disaster information. A storm surge hazard map is created by simulating several typhoon scenarios, where the pressure distribution of the typhoon and its moving speed are often modelled in a relatively simple way (e.g., using Myers (1961) equation to reproduce the pressure distribution). However, the actual storm surge at a given point is very sensitive to local bathymetric and topographical conditions, and the exact wind patterns during the passage of the tropical cyclone. As a consequence, the actual storm surge height could be higher than the simulated one. In addition, storm surge hazard maps seldom include the effects of overtopping waves. Previous storm surge events (Esteban et al. 2015, Tasnim et al. 2014, Takagi et al. 2014), have highlighted that casualty rates depend on the level of people’s awareness and preparedness. The residents of an area should not “forget” past events, as this can prevent the construction of housing in high-risk areas. This failure to preserve intergenerational transfer of information can be seen in the case of the 2013 Typhoon Haiyan in Tacloban. Two historical storm surges had previously devastated Tacloban, one in 1897 killing up to 1500 and another in 1912 killing 15,000 (Lagmay et al. 2015), although these events had been largely forgotten. The creation of a disaster prevention day on the 1st of September, as is done in Japan, can also help promote awareness and establish a generational transmission of information (Suppasri et al. 2015).

As a consequence of the strong winds brought about by Typhoon Rai largescale wind damage could be observed, particularly on the roofs of houses. Prior to Typhoon Haiyan in 2013 the National Structural Code of the Philippines (NSCP) stated that the roofs of schools and hospitals should be designed to withstand 250 km/hr winds in Wind Zone 1 Areas such as Leyte and Eastern Samar. After the event, the design requirement for wind speed was increased and a new section was added to the code for evaluating flood loads, which are important for Building-Back-Better (Valdez et al. 2022). However, the damage observed following Typhoon Rai suggest that there can be further improvements in the overall procedure of designing resilient structures.

Gathering data on hazard, exposure, vulnerability, and coping capacity data from across the country, as well as information on building structure and vulnerability, weather forecasting and mapping using a GIS core system, could aid in disaster prevention and mitigation. Meanwhile, users (such as local entities and NGOs) can access information in real-time to get a more comprehensive understanding of specific local events, and mapping possible areas and population exposed to severe wind, or flooding in any given municipality.

5. Conclusion

Following recent typhoon events, particularly Typhoon Haiyan in 2013 and Typhoon Goni in 2020, the Philippines appears to have been steadily improving its disaster preparedness and emergency response capabilities. Nevertheless, the powerful winds and storm surge generated by Typhoon Rai in December 2021 brought widespread devastation to many communities in Central Visayas. The authors surveyed the water level heights due to the storm surge generated by this typhoon, which reached maximum values of 2.54 m, 3.83 m and 4.06 m along the islands of Cebu, Bohol and President Carlos P. Garcia Islands, respectively.

The widespread water and wind damage to buildings and other infrastructure indicate that much remains to be done in terms of disaster risk management, and that the resilience of coastal communities should improve so that rebuilding can be more effective after such events. Although some degree of damage should always be expected, it is imperative that casualties are minimised and that key infrastructure remains in operation to facilitate relief progress and reconstruction following such weather events. This is crucial given that the Intergovernmental Panel on Climate Change 6th Assessment Report (IPCC 6AR) highlights the concern that climate change could increase the intensity of tropical cyclones in the future. In that sense, geospatial information is crucial to any planning effort, monitoring, impact assessment and economic planning.

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