Storm Surge and Evacuation in Urban Areas during the Peak of a Storm

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1 **Abstract**

2 The present paper examines the impact of floodwater caused by the storm surge brought
3 about by Typhoon Haiyan in 2013, focusing on downtown Tacloban in Leyte Island, the
4 Philippines. A reliable numerical model for predicting such flooding was developed by
5 calibrating the results of field investigations, including footage from a video clip taken
6 during the storm surge. The simulation reveals that flow velocities along the streets in
7 downtown Tacloban reached up to 7m/s due to flow contraction along the high-density
8 blocks of houses, and how water levels reached their peak in just 10 minutes. According
9 to the depth-velocity product criteria, often used for evaluating the vulnerability of
10 people and buildings to floodwaters, only 8% of the length of streets in downtown
11 Tacloban were within the safe limits that allow pedestrian evacuation. Based on these
12 findings, the present research concludes that pedestrian evacuation in the middle of a
13 storm surge generated by a strong typhoon is a *high-risk behaviour*. Thus, clearly and
14 objectively, evacuation during this time should not be encouraged, even when seawater
15 intrudes the houses of local residents. In this respect, it would appear imperative that
16 prior to the arrival of the typhoon all residents should evacuate areas at risk of being
17 flooded. Though the flood height was significant in the downtown area, the damage to
18 these houses was limited. If it was not possible for some reason to evacuate prior to the
19 arrival of the typhoon, those in solid houses should first consider vertical evacuation
20 and the possibility that they could survive in their place, rather than courageously
21 evacuating in an unpredictable water flow.

22 **Keywords:** *Typhoon Haiyan (Yolanda), Philippines, Tacloban, Storm Surge, Flooding,*

23 *Pedestrian Evacuation, Inundation, Numerical Simulation, Manning's n value,*
24 *Depth-velocity product*

25

26 **1. Introduction**

27 Typhoon Haiyan (Yolanda, according to its local name) struck the Philippines on
28 November 8, 2013, causing enormous damage to Leyte, Samar and many other islands.
29 6,245 individuals were reported dead, 28,626 were injured and 1,039 are still missing
30 (NDRRMC, as of 6 March 2014). Such a large death toll was caused not only by the
31 large size of the storm surge, but also due to issues related to the level of knowledge and
32 awareness by local residents on what is a “storm surge” (Esteban et al., 2014; Esteban et
33 al., 2015). Indeed, despite the fact that two historical storm surges had previously
34 devastated Tacloban, one in 1897 killing up to 1,500 and another in 1912 killing 15,000
35 (Langmay et al., 2015), local awareness about such events was non-existent (Esteban et
36 al., 2014). The total economic loss associated with infrastructure and agriculture was
37 estimated to be around 34,366 million pesos (776 million USD), possibly the most
38 expensive natural disaster in the history of the country (TIME, 2013).

39

40 Haiyan was one of the strongest typhoons known to have ever made landfall, not only in
41 the Philippines but the entire world (Schiermeier, 2013, Lin et al., 2014). The forward
42 speed of the typhoon, reaching around 41 km/hr at landfall, was also unusual amongst
43 other events of comparable intensity during the past 6 decades in the Western North
44 Pacific (Takagi et al., 2015a). Haiyan can be characterized as both the fastest moving

45 and strongest typhoon measured in the Philippines. The return period for a Haiyan-class
46 typhoon to make landfall was estimated to be 200 years (Takagi and Esteban, 2015). As
47 a result of its strong intensity, the typhoon caused a massive storm surge in many islands
48 in the Philippines. The storm surge inundated most of the coastline of Leyte Gulf,
49 causing particularly large damage to Tacloban City, the biggest city in Leyte Island. A
50 maximum inundation height of up to 6-7m was observed in this city, where the largest
51 number of casualties took place (Shibayama et al., 2014; Mas et al., 2014; Takagi et al.,
52 2015a). It is important to note the local amplification of the water surface elevation due
53 to seiche effects inside Leyte Gulf (Mori et al., 2014).

54

55 High inundation heights were observed even outside Leyte Gulf along the east coast of
56 Eastern Samar, which faces the Pacific Ocean and the deep Philippine Trench (Tajima et
57 al., 2014). Maximum hindcast significant wave heights during the storm reached up to
58 19 m off Eastern Samar, though they decreased to less than 5 m in Leyte Gulf near
59 Tacloban (Bricker et al., 2014).

60

61 Understanding the nature and degree of exposure of coastal areas to flooding is
62 important for reducing its effect on people and property. Such assessments may be
63 developed through field observations, modeling studies, or some combination of the two
64 (Brown et al., 2007). Flood mitigation agencies need to designate floodplains and high
65 hazard zones to identify the risks of flood damage or loss of life. For adequate mapping
66 of flood hazards it is important to examine where dangerous zones are located within a

67 particular area (Jonkman et al., 2008). For the case of Tacloban city, an early warning
68 system was in place prior to the arrival of Haiyan, which made use of hazard maps and
69 flood drills. These hazard maps were created as part of the READY project, a joint
70 effort in risk mapping among government and donor agencies (Langmay et al., 2015).
71 However, these maps greatly underestimated the extent of the inundation (Langmay et
72 al., 2015).

73
74 An early evacuation, based on a reliable and accurate warning system, is crucial to
75 survive typhoons and their subsequent storm surges. Local authorities might either
76 advice people to leave or sometimes even conduct forced evacuations, and it appears
77 that a combination of the two was used by the various barangays (smallest
78 administrative divisions in the Philippines) in Leyte and Samar (Esteban et al., 2015).
79 However, despite such evacuation orders and typhoon and storm surge warnings by
80 local authorities and media before the arrival of Typhoon Haiyan, many people did not
81 evacuate. A number of reasons were given by local residents to explain why they stayed
82 in their residences, such as uncertainties in the expected typhoon level, attempting to
83 secure their houses and properties, or problems with poorly maintained evacuation
84 centres (Esteban et al., 2015, Leelawat et al., 2014).

85
86 If residents fail to evacuate prior to the arrival of the typhoon, they may find themselves
87 in a very difficult situation. At that stage it would be hard for them to rationally
88 determine whether they should evacuate or stay home, particularly when extremely

89 strong gusts and heavy rain affects the area during the pass of the typhoon. The primary
90 objective of this research is thus to rationally review if it was actually advisable and
91 possible to evacuate during the passage of super typhoon Haiyan. To do so, the authors
92 first conducted a series of field surveys to reveal the extent of inundation in downtown
93 Tacloban. The observed inundations were compared with the water levels computed by
94 a storm surge simulation to validate the model's accuracy. Once the reliability of the
95 numerical model was established, it was possible to examine whether pedestrian
96 evacuation during the passage of strong typhoon would be safe, focusing on Tacloban
97 and typhoon Haiyan as a case study.

98

99 **2. Field Survey**

100 **2.1 Methodology**

101 The authors conducted field surveys at three different times after the disaster: (1)
102 December 4-13, 2013, (2) May 1-6, 2014, and (3) October 16-21, 2014. The primary
103 purpose of these surveys was to identify the extent of the inundation due to the storm
104 surge along the coastline of Leyte Island. The last two surveys involved a topographical
105 survey of Tacloban, conducted at the same time as the flood investigations (see Fig.1).
106 The storm surge inundation height was established by checking physical evidence and
107 interviewing local residents at each site. Laser range finders and GPS receivers were
108 used to establish the inundation height at each location (with reference to the local sea
109 level) to within a few centimetres accuracy, which was adjusted to take into account the
110 tidal levels at the time of the survey and during the passage of the typhoon. Laser range

111 finders were also used for surveying the ground elevation of different parts of
112 Tacloban's downtown, essentially densely populated residential areas built on top of
113 both flat and hilly terrains.

114

115 Another important factor investigated in the present study was the flow velocity at a
116 particular location in the downtown area of Tacloban. Interestingly, a video clip taken
117 from a hotel in this area (Hotel Alejandro) during the peak of the storm surge shows that
118 the flow was relatively slow, and nearby local residents could walk across the flooded
119 street to evacuate from their house to the hotel shown in Fig.2(a) (iCyclone, 2013). The
120 flow velocity and direction was roughly estimated by visual investigation through the
121 elapsed time shown imbedded in the video clip. The distance moved by pieces of
122 floating rubbish captured in the video was estimated by reference to a photo showing a
123 measuring staff, taken by the authors during their surveys (Fig.2(c)). Finally, the
124 velocity could be calculated by dividing the time it took for the debris to cross the
125 points shown in the measuring staff. Obviously, a certain degree of estimation error is
126 present in the visual measurement with a floating object. However, such errors can be
127 minimized by considering and calculating the speed of the multiple objects that
128 simultaneously flow within the video.

129

(a) Inundation height

(b) Inundation height

(c) Inundation height

(d) Topographical survey

130

Fig.1 Site investigation on May 2014 at Tacloban in Leyte Island, the Philippines

131

132

133 **Fig.2** Field investigations nearby Alejandro Hotel: (a) iCyclone's video clip taken from
 134 the hotel during the surge peak, showing family members exiting their house and
 135 evacuating to the hotel, (b) interview with the family featured in iCyclone's video to
 136 understand more details about the situation during the storm surge, and (c) a photo
 137 with a measuring staff taken from the same position where the video clip was filmed,
 138 and which was used for measuring the flow velocity during the flood

139

140 2.2 Results

141 Fig.3 shows the topography around downtown Tacloban, which was reproduced by the

142 authors using the measured elevations, together with a satellite image showing the city
143 before the typhoon. In this area many houses were built on relatively low-lying land,
144 only 1 – 3 metres above sea level. The storm surge heights, which were measured from
145 the astronomical tide at the time of typhoon landfall, are plotted in Fig.4, showing that
146 inundation took place even in the middle part of the downtown area. Though the flood
147 height was significant (in the range of 0.6 to 4.2m), the damage to these houses was not
148 as severe as in other areas of the city that had informal settlements, as shown in Fig.1
149 and Fig.2. Essentially, houses in the downtown area were typically rather strong
150 cement or concrete two-story or higher buildings, and thus floodwaters intruded through
151 the streets (rather than passing over the roofs of houses).

152

153 The flow velocity at the street in front of Alejandro Hotel was estimated to be about
154 0.6m/s. This agrees well with field survey observations, as water flow at such low speed
155 will not cause catastrophic damage to houses, though minor damage could be observed
156 in all areas that were flooded. It also explains why it was possible for local residents to
157 walk through the water flow shown in Fig.2(a).

158

159
 160 **Fig. 3** (a) Satellite image of Tacloban taken before the typhoon (©Google Earth), (a')
 161 densely populated residential area around Hotel Alejandro, and (b) Topography of
 162 Tacloban which was used in the simulation
 163

164
 165 **Fig.4** Storm surge heights (black) adjusted to the tidal level at the time of passage of the
 166 typhoon, and inundation depths above ground level (blue) measured around Tacloban

167 downtown area (unit: metres)

168

169 **3. Storm Surge Simulation**

170 **3.1 Methodology**

171 The authors performed numerical simulations to estimate the spatial distributions of the
172 storm surges using three different scales. First, the simulation was carried out for a wide
173 area which encompasses most of the Philippines, in order to assess which areas of the
174 country were affected. Then, a more detailed simulation was carried out for San Pedro
175 Bay in Leyte Gulf, an area where the storm surge engulfed and claimed thousands of
176 lives. The reliability of the numerical simulation for these two domains was already
177 confirmed by Takagi et al. (2015a), showing a storm surge larger than 3 metres along
178 the entire bay, and up to 6 metres high in its inner part. Such simulation results agree
179 well with the observations of field surveys (Takagi et al., 2015a, Lagmay et al., 2015).

180

181 In the present research the authors carried out detailed inundation simulations that
182 focused on Tacloban's downtown (1.7km x 1.7km square grids). The simulation used a
183 10m fine computational grid and incorporates details of the city down to the block level
184 to examine how the urban geometry can mitigate or intensify the impact of flooding.

185

186 In previous studies, many types of numerical codes have been applied to reproduce
187 coastal floods due to recent major storm surges or tsunamis (e.g. the COMCOT model
188 for the 2004 Indian Ocean tsunami (Wijetunge et al., 2008), the ADCIRC model for

189 Hurricanes Katrina and Rita (Dietrich et al., 2011), or the FVCOM model for the 2008
190 Cyclone Nargis (Tasnim et al., 2015) and for the 2011 Tohoku Earthquake Tsunami
191 (Sasaki et al., 2012)).

192

193 In this study, the authors applied the parametric typhoon model developed by Takagi et
194 al. (2012, 2014, 2015c), coupled with the fluid dynamics model Delft3D-FLOW to
195 estimate the extent of the storm surge. The typhoon model calculates both the pressure
196 and wind fields using parameters obtained from the typhoon track dataset, namely, the
197 central positions and pressures at every recording period. Delft3D-FLOW was then used
198 to simulate how a storm surge travels from the deep sea to shallow water, and eventually
199 flows over downtown Tacloban. Though this model can be applied to a 3D domain, the
200 present study used a 2D horizontal grid, and thus the code is equivalent to a non-linear
201 long wave model, commonly used for storm surge simulation.

202

203 The standard drying and flooding algorithm in Delft3D-FLOW is efficient and accurate
204 for coastal regions, tidal inlets, estuaries, and rivers. In combination with the flooding
205 scheme for advection in the momentum equation, the algorithm known as “*drying and*
206 *flooding*” in this numerical model is effective and accurate for rapidly varying flows
207 with large water level gradients due to the presence of hydraulic jumps or the
208 occurrence of bores as a result of dam breaks (Stelling et al., 1986, Stelling and
209 Duinmeijer, 2003).

210

211 The numerical settings used in the model are summarized in Table.1. Data regarding the
212 typhoon and bathymetry in the target area were obtained from the Japan Meteorological
213 Agency and The General Bathymetric Chart of the Oceans (GEBCO) datasets,
214 respectively. The simulation was run for 18 hours, which encompasses the final
215 approach of the typhoon towards Tacloban, and also its passage through the rest of
216 Leyte, Cebu and Panay islands. The bathymetry for the detailed simulation was
217 produced by digitizing a nautical chart of NAMRIA (National Mapping and Resource
218 Information Authority). The astronomical tide at Tacloban at the time of landfall was
219 calculated by using the software WXTide32, showing that the tidal level was very
220 similar to MLLW (Mean Lower Low Water, which corresponds to the chart datum),
221 with the difference to this level being only a few centimetres. Therefore, the bathymetry
222 of the chart was used directly in the simulation (i.e. without it having to be modified for
223 tide levels).

224

225 Manning's n coefficient is one of the most important parameters for the accurate
226 simulation of inundation over land. For the case of tsunami inundation simulations
227 MLIT (2012) recommends using a Manning's n value in the range of 0.04 to 0.08 for
228 the case of residential areas. Arcement and Schneider (1984) propose that the estimation
229 of n values for a flood plain should depend on soil surface, surface irregularities, size of
230 the cross section, obstructions, vegetation and sinuosity of the flood plain. Taking the
231 maximum numbers from the range of possible values of each of these factors, the
232 maximum n value calculated by their method is 0.25. It is thus clear that Manning's n

value can take a wide variety of values depending on the conditions considered. Furthermore, it appears that the n value for coastal floods in an urban area has not been researched in detail because such extreme flood events rarely occur. In light of the constraints regarding the information available, the authors chose to conduct a series of simulations with different settings of Manning's n , in order to find an appropriate value that best describes the flow velocity in front of Alejandro Hotel.

Table 1. Numerical model and settings

Typhoon Path	JMA Typhoon Best Track http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html
Typhoon Model	Pressure: empirical estimation by Myers Formula, Wind: Gradient winds considering Super-gradient Wind effect
Fluid Dynamics Model	Delft3D Flow Ver. 3.42
Domain	Cartesian (UTM51N), grid @3000m (Philippines), @100m (San Pedro Bay), and @10m (Tacloban)
Bathymetry	GEBCO_08 Grid (Philippines) NAMRIA Chart (San Pedro Bay and Tacloban)
Terrain Data	ASTER GDEM 30m Resolution (San Pedro Bay) Measured by the authors (Tacloban)

Fig.5 Three-scale computational domains: (A) Country scale, (B) Bay scale (both after Takagi et al., 2015a), and (C) City scale, focusing on Tacloban (present research). Color contours present the maximum storm surge heights during the passage of the typhoon

3.2 Results

Inundation simulations were conducted for a variety of values of Manning’s n coefficient in the range between 0.02 and 0.32. An $n=0.04$ was found to provide the results that best fit the flow velocities in front of Alejandro Hotel (Fig.6). This value falls within the 0.04 to 0.08 range recommended by MLIT (2012). However, Takagi and Bricker (2014) and Bricker et al. (2015) point out that the recommended values by MLIT would underestimate the mitigating effect of buildings when not taking into

255 account urban geometries (such as streets and residential blocks). The present study
256 confirms that the simulation, based on the recommended values by MLIT (2012), could
257 yield a good estimation when urban geometries are appropriately incorporated into the
258 model.

259

260 Figure 7 presents a time series of the simulated flow velocity with $n=0.04$, comparing it
261 to the estimated velocity calculated through the observation of the iCyclone video.
262 Though the simulated peak velocities agree well with the observed velocity, there is a
263 slight difference in the arrival time of the floodwater. According to the video the
264 strongest flow occurred before 8:00AM, as indicated in Fig.2, whereas the flood in the
265 simulation starts after 8:00AM. This 30-minute difference could have been caused by a
266 discrepancy between the typhoon's location recorded by the JMA Typhoon Best Track
267 Data and the actual typhoon course. Basically, the JMA Typhoon Best Track Data is
268 given at 3 hour intervals and therefore the position of the simulated typhoon between
269 these data points might be slightly inaccurate. Nevertheless, the flow would otherwise
270 appear to be well simulated, and for example, during the period of peak flow water
271 moves along the street in the southwest direction, which corresponds exactly with the
272 actual direction shown in the video.

273

274 Figure 8 shows how the simulated and observed storm surge heights at the various
275 locations shown in Fig. 4 are in good agreement at many points, such as Alejandro
276 Hotel. In fact, the coefficient of determination R^2 , which is a number that indicates how

277 well data fits a statistical model, was calculated as 0.574. This implies that the
278 calibration of Manning's n value, by using the observed flow velocity at even just one
279 point, can be expected to improve the accuracy of the simulation of storm surge heights.

280

281 However, the authors do acknowledge that there are still many uncertainties that present
282 in the numerical results. The best estimated Manning's n could also vary according to
283 the local topography, which can create various levels of resistance to the flow due to
284 differences in bottom friction, friction on the walls and parked cars. Despite this, the n
285 value in the present study was set to be uniform throughout the entire land domain.

286 Mignot et al. (2006) attempted to improve the reliability of an urban flood modeling
287 with two different n values of 0.025 and 0.050, according to different road widths.

288 Changes in Manning's n in this manner could be one possible option to further improve
289 the estimation of velocities and inundation depths. It should also be noted that the flow
290 condition at some particular locations in the downtown area can be considered to be
291 supercritical. The energy loss during such a regime cannot be correctly evaluated
292 because the formulation in terms of friction used in the present model merely assumes
293 subcritical flow (though Manning's n can be still applied to a rapid flow, such as that
294 induced by a tsunami's overflow, by using an appropriate value, see Bricker et al., 2015).

295 Therefore, it is important to recognize that the numerical settings used in this study do
296 not necessarily provide the best options for other cases or areas.

297

298

Fig.6 Flow velocity varies with Manning's n value

Fig.7 Comparison between simulated and observed velocities, together with simulated flow direction (direction can be identified by the azimuth in **Fig.4**)

304

305 **Fig.8** Comparison of storm surge between measured and simulated heights at 15

306 locations in Tacloban downtown

307

308 **4. Discussion**

309

310 This section will discuss the characteristics of the floodwater in general and the flow
 311 velocity along the streets in particular, which has a great influence on the chance that
 312 evacuees caught in the flood can survive. According to an experimental study using a
 313 large sized water flume (Suga et al., 1995), a 60 year old male did not experience any
 314 fear when he walked against a water flow as high as his crotch with speeds up to 0.8m/s.
 315 In contrast, he felt intense fear and could not walk without supporting ropes when the
 316 flow reached a height of 1m or a velocity of 1m/s. Nishihata et al. (2005) estimated that
 317 the maximum inundation depth at which people can safely evacuate is around 0.7m.

318 Likewise, in areas with high flow velocity people may not be able to evacuate because
319 of friction instability (sliding), no matter how shallow the inundation depth. Therefore,
320 the authors feel safe to presume that the family featured in iCyclone's video could cross
321 the flooded street because the flow in front of Alejandro Hotel was relatively slow, with
322 a velocity 0.6m/s or lower, as Fig.7 indicates. Figure 9 shows the maximum flow
323 velocities calculated during the passage of the typhoon. According to this it appears that
324 the flow velocity at the hotel was relatively calm compared to other parts of the city,
325 which enabled them to evacuate. In contrast, flow appears to have been particularly
326 intense along certain streets, possibly due to flow contraction, with flow velocities of up
327 to 7m/s in places.

328

329 It is worth noting that friction instability appears to occur earlier than moment
330 instability (toppling) for the combination of shallow depth and high velocities (Jonkman
331 et al., 2008). Also, individuals who are males, middle-aged, heavy, tall, in good physical
332 condition, and lightly clad are able to, on average, remain standing in higher
333 depth-velocity products (Abt et al., 1989). Some authors have proposed a critical
334 depth-velocity product to indicate a person's instability in flood waters, which would be
335 a combination of the depth and the velocity of the flood (Jonkman et al., 2008). Wright
336 et al. (2010) summarises that the depth-velocity product of $1.0\text{m}^2/\text{s}$ as the safe limit for
337 pedestrians. Figure 10 presents the histogram of the maximum depth-velocity product
338 derived by summing up the values at all the computational grids along the streets
339 surrounded by building blocks, i.e. excluding the roads that directly face the sea. This

340 figure shows that only 8% of the total street areas in the downtown section of Tacloban
341 could have been classified as being within the safe limit for pedestrian evacuation
342 during the peak of the storm surge.

343

344 The depth-flow velocity product is also considered as a critical parameter leading to the
345 damage or the collapse of buildings. Pistrika et al. (2010) proposes residential building
346 damage categories that can be determined by the depth-velocity product (dv), as
347 follows:

348

349 1) $dv < 3\text{m}^2/\text{s}$: “inundation damage”

350 2) $3\text{m}^2/\text{s} \leq dv < 7\text{m}^2/\text{s}$: “partial damage”

351 3) $dv \geq 7\text{m}^2/\text{s}$: “total destruction”

352

353 According to this criteria residential houses can withstand much stronger floodwaters
354 than people. Although the simulated depth-velocity product in Fig.10 reached up to
355 $10\text{m}^2/\text{s}$, it can be noted that water does not flow normal to the houses but typically along
356 the roads, which would further alleviate the impact of the flood. In fact, in the course of
357 the surveys conducted by the authors there was little evidence that any residential
358 houses nearby the locations surveyed in Fig.4 suffered any significant physical damage,
359 as shown also by Fig.1 and Fig.2.

360

361 The rise time of the storm surge was estimated to be less than half an hour (Takagi et al.,

362 2015b), which correlates well with interviews with survivors (Esteban et al., 2015).
363 Fig.11 also shows how water depth and velocity would have risen quickly at the street
364 indicated by St. 1 in Figure 9, with the depth-velocity product exceeding the safety limit
365 of $1.0\text{m}^2/\text{s}$ in just 10 minutes. Therefore, the case of the family featured in the iCyclone
366 video, who successfully evacuated across their street to Hotel Alejandro, can be
367 perceived as a case of good luck, brought about by the fact that the flood around the
368 area was much less violent than in other areas in downtown Tacloban.

369

370 Although this would appear rather intuitive, in fact comparatively little research has
371 focused on ascertaining such dangers and explaining why anecdotal evidence of
372 evacuation by pedestrians during the Haiyan's storm surge was possible. The present
373 research establishes that success in such cases was often a matter of luck and timing, as
374 in most cases flood inundation depths and velocities would have been too high to allow
375 any evacuation. In this sense, the results also explain why witnesses often reported how
376 it was impossible to swim in the flood waters due to the high turbulence, and how many
377 caught in them died (Esteban et al., 2015).

378

379

380

Fig.9 Maximum flow velocity simulated along the streets of Tacloban downtown

381

382

Fig.10 Histogram of the maximum depth-velocity product in Tacloban downtown

383

Fig.11 Variations in water depth and velocity at St.1 (the location shown in **Fig.4** and **Fig.9**)

5. Conclusion

In the present work the authors reported on field investigations carried out in downtown Tacloban to reveal the impact of floodwater caused by the storm surge due to Typhoon Haiyan in 2013. Inundation levels were confirmed by visual inspection and interviews with local residents. The results of a numerical model, calibrated by the flow patterns captured in a video clip by iCyclone, agree well with the observed inundation heights.

Local residents of coastal areas have to consider evacuating from their houses when facing a strong typhoon that can cause extensive flooding. Particularly, it is inevitable that they will be wanting to evacuate once floodwaters directly enter their houses, though at such point it is often hard for them to rationally determine whether they should evacuate or stay in order to survive. By using the model it was then possible to

400 understand the hazard posed by storm surge flooding, and the risks involved in
401 pedestrian evacuation during the passage of a strong typhoon. Based on such analysis it
402 can be concluded that pedestrian evacuation during a storm surge can be considered as
403 *high-risk behaviour*, at least for the case of downtown Tacloban during the peak of
404 storm.

405

406 Also, it was clear that many residential houses in downtown Tacloban withstood the
407 flood without suffering any significant physical damage, despite high flow velocity
408 along the streets, which reached up to 7m/s in places. From these findings, it would
409 appear that pedestrian evacuation during the peak of typhoons could be more hazardous
410 than staying in houses, provided that the house was of sufficient height to allow vertical
411 evacuation to its upper floors.

412

413 However, the present research only deals with the case of Tacloban City and Typhoon
414 Haiyan in 2013, and is clearly not sufficient to generalize such conclusions to all cases.
415 Therefore, more detailed investigations for other stretches of the coastline and typhoons
416 would be needed before a definitive conclusion can be reached. As a preliminary
417 conclusion, and although this would appear somehow obvious in the context of storm
418 surge risk management, evacuation should be encouraged prior to the arrival of a
419 typhoon, particularly for those living in low-level and low-strength housing. Even if it
420 was not possible for some reason to evacuate prior to the arrival of the typhoon,
421 evacuation should not be encouraged when people find that seawater intrudes into their

422 properties. Though the flood height was significant in the downtown area, the damage
423 to these houses was limited. Particularly, those in such solid houses should first consider
424 vertical evacuation and the possibility that they could survive in their place, rather than
425 courageously evacuating in an unpredictable water flow.

426

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