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Storm surge and evacuation in urban areas during the peak of a storm

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ABSTRACT

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

1. Introduction

Typhoon Haiyan (Yolanda, according to its local name) struck the Philippines on November 8, 2013, causing enormous damage to Leyte, Samar and many other islands. 6245 individuals were reported dead, 28,626 were injured and 1039 are still missing (NDRRMC, as of 6 March 2014). Such a large death toll was caused not only by the large size of the storm surge, but also due to issues related to the level of knowledge and awareness by local residents on what is a "storm surge" (Esteban et al., 2014, 2015). Indeed, despite the fact that 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), local awareness about such events was non-existent (Esteban et al., 2014). The total economic loss associated with infrastructure and agriculture was estimated to be around 34,366 million pesos (776 million USD), possibly the most expensive natural disaster in the history of the country (TIME, 2013).

Haiyan was one of the strongest typhoons known to have ever made landfall, not only in the Philippines but the entire world (Lin et al., 2014; Schiermeier, 2013). The forward speed of the typhoon, reaching around 41 km/h at landfall, was also unusual among other events of comparable intensity during the past 6 decades in the Western North Pacific (Takagi et al., 2015a). Haiyan can be characterized as both the fastest moving and strongest typhoon measured in the Philippines. The return period for a Haiyan-class typhoon to make landfall was estimated to be 200 years (Takagi and Esteban, 2015). As a result of its strong intensity, the typhoon caused a massive storm surge in many islands in the Philippines. The storm surge inundated most of the coastline of Leyte Gulf, causing particularly large damage to Tacloban City, the biggest city in Leyte Island. A maximum inundation height of up to 6–7 m was observed in this city, where the largest number of casualties took place (Mas et al., 2014; Shibayama et al., 2014; Takagi et al., 2015a;

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Nakamura et al., 2015). It is important to note the local amplification of the water surface elevation due to seiche effects inside Leyte Gulf (Mori et al., 2014).

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

Understanding the nature and degree of exposure of coastal areas to flooding is important for reducing its effect on people and property. Such assessments may be developed through filed observations, modeling studies, or some combination of the two (Brown et al., 2007). Flood mitigation agencies need to designate floodplains and high hazard zones to identify the risks of flood damage or loss of life. For adequate mapping of flood hazards it is important to examine where dangerous zones are located within a particular area (Jonkman and Penning-Rowsell, 2008). For the case of Tacloban city, an early warning system was in place prior to the arrival of Haiyan, which made use of hazard maps and flood drills. These hazard maps were created as part of the READY project, a joint effort in risk mapping among government and donor agencies (Lagmay et al., 2015). However, these maps greatly underestimated the extent of the inundation (Lagmay et al., 2015).

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

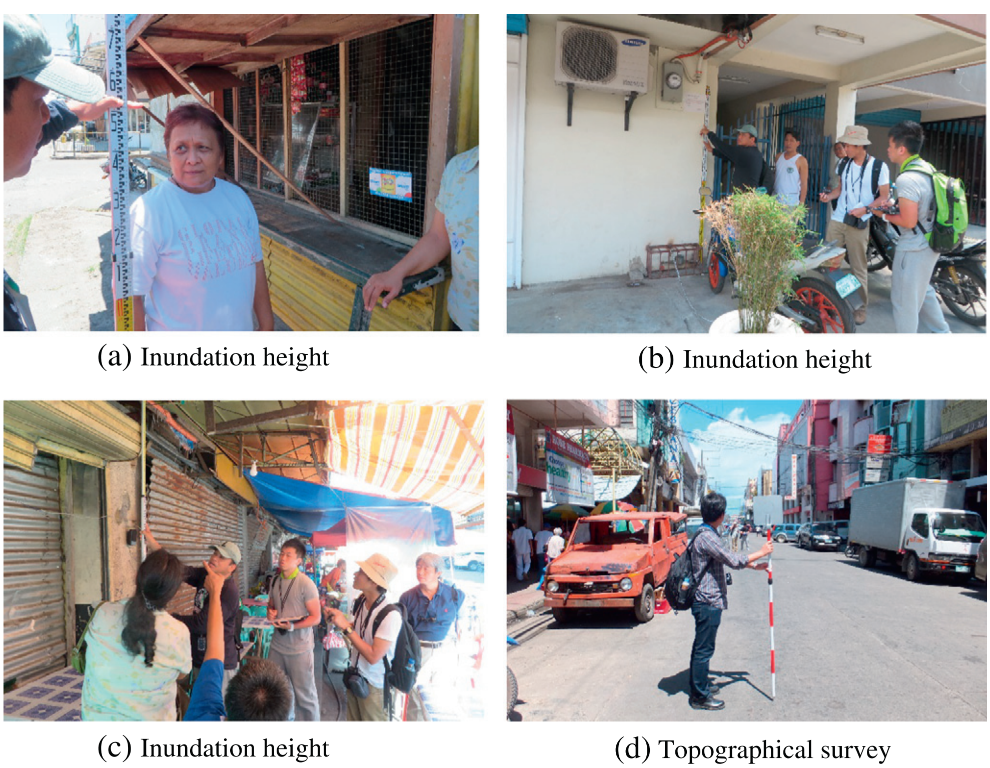
If residents fail to evacuate prior to the arrival of the typhoon, they may find themselves in a very difficult situation. At that stage it would be hard for them to rationally determine whether they should evacuate or stay home, particularly when extremely strong gusts and heavy rain affects the area during the pass of the typhoon. The primary objective of this research is thus to rationally review if it was actually advisable and possible to evacuate during the passage of super typhoon Haiyan. To do so, the authors first conducted a series of field surveys to reveal the extent of inundation in downtown Tacloban. The observed inundations were compared with the water levels computed by a storm surge simulation to validate the model's accuracy. Once the reliability of the numerical model was established, it was possible to examine whether pedestrian evacuation during the passage of strong typhoon would be safe, focusing on Tacloban and typhoon Haiyan as a case study.

2. Field survey

2.1. Methodology

The authors conducted field surveys at three different times after the disaster: (1) December 4–13, 2013, (2) May 1–6, 2014, and (3) October 16–21, 2014. The primary purpose of these surveys was to identify the extent of the inundation due to the storm surge along the coastline of Leyte Island. The last two surveys involved a topographical survey of Tacloban, conducted at the same time as the flood investigations (see Fig. 1). The storm surge inundation height was established by checking physical evidence and interviewing local residents at each site. Laser range finders and GPS receivers were used to establish the inundation height at each location (with reference to the local sea level) to within a few centimeters accuracy, which was adjusted to take into account the tidal levels at the time of the survey and during the passage of the typhoon. Laser range finders were also used for surveying the ground elevation of different parts of Tacloban's downtown, essentially densely populated residential areas built on top of both flat and hilly terrains.

Another important factor investigated in the present study was the flow velocity at a particular location in the downtown area of Tacloban.



(a) Inundation height (b) Inundation height

(c) Inundation height (d) Topographical survey

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