SIMULATION OF 2004 TSUNAMI INUNDATION IN GALLE CITY IN SRI LANKA AND REVISIT THE PRESENT EVACUATION MEASURES

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Tsunami inundation was successfully reproduced for the Galle City, Sri Lanka using Delft3D-Flow model and Delft Dashboard Tsunami Tool. Previously identified tsunami hazard maps agreed with the simulation results. Existing tsunami early warning system and preparedness for evacuation are in a favourable condition. Based on the outcome of numerical simulation and field investigations, suitable horizontal evacuation measures were proposed, and vertical evacuation points were suggested primarily considering the identified hazardous zones with lack of proposed buildings and evacuation routes in previous studies.

Keywords: Delft3D, inundation, early warning, vertical/horizontal evacuations, safe areas

INTRODUCTION

Tsunamis are long-period gravity waves generated by a variety of underwater disturbances such as earthquakes, landslides, volcanic eruptions, or sudden movement of the ocean surface due to nuclear explosions or meteorite impact in the ocean. Tsunami waves are characterised by wave periods of between 5 minutes to 1hour. In the deep ocean, a group of tsunami waves have small wave heights, huge wavelengths, and very low steepness. Hence, tsunami waves propagate in very deep water at high speeds with little dissipation of energy. However, while approaching the shoreline with a tremendous amount of remained energy, heights of tsunami waves are amplified dramatically due to shoaling, refraction, and resonance effects. Sudden energy dissipation of amplified tsunami waves and successive inundation and coastal flooding could cause extensive damages for lives and properties in coastal areas (Reeve et al., 2012; Sorensen, 1997). Coastal areas of the rim counties of Indian Ocean, including Sri Lanka, are vulnerable for tsunami attacks due to the frequent higher magnitude earthquakes in Sumatra-Andaman subduction zone (Josiah et al., 2020). In the Great Chronicle of Sri Lanka, there is evidence on a tsunami (i.e. ocean engulfment of land) during the reign of King Kawanthissa (205-161 BC) (Laknath and Sasaki, 2011). Further, according to Mörner et al. (2008), there is historical evidence on seismic related activities in coastal areas of Sri Lanka (i.e. "terrible earthquake" in 1615 in western coast) and recorded paleoseismic event at Kalamatiya in southern coast during AD 200–400.

Out of 60 tsunami events occurred in the Indian Ocean during the last 250 years, Sri Lankan coastline was affected from 1762, 1847, 1881, 1882, 1883 and 1946 tsunami events, including the tsunami from the eruption of the Krakatau volcano in 1883 (Levy and Gopalakrishnan, 2005). On 26th December 2004, Sri Lanka experienced a tsunami as the worst natural disaster ever recorded in Sri Lankan history. Galle City, the capital of Southern Sri Lanka, is one of the most damaged coastal cities by 2004 tsunami. Having faced the powerful waves of the 2004 tsunami, the whole Galle town area was swept, resulting in a significant loss of life and damages to properties. Subsequently, a widening in research areas was triggered, including the mechanism of tsunami generation, propagation, and inundation processes, linking the field of tsunami science and coastal engineering. Based on the identified possibility of occurring the same event, tsunami inundation studies were conducted for Galle City. Furthermore, evacuation routes were suggested, and hazard maps were prepared in 2008 and 2012, respectively. Disaster Management Center (DMC) in Sri Lanka has also proposed evacuation points along with significant improvements in dissemination of advisories and warnings. Several studies have been published in the context of structural vulnerability of the buildings in the inundation area, mitigation measures, dissemination of warnings etc. However, none of these studies assesses the present conditions of the aforementioned tsunami early warning and evacuation measures proposed by DMC based on inundation maps in the Galle City in the scientific literature. Hence, understanding the possible vulnerable areas for future tsunami events to prepare and implement disaster mitigation and management plans while evaluating the applicability of the current practices are essential. Accordingly, the present study was carried out (i) to reassess the tsunami inundation areas in Galle City from 2004 tsunami and (ii) to propose suitable evacuation plans based on identified hazardous areas and the availability of present evacuation measures.

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Figure 1. (a). Study area - Galle; (b). Location of Galle in Sri Lanka; (c). Cricket Stadium just after tsunami;(d). Galle bus stand at the time of tsunami; (e). Historical evidence of tsunami in the western coast of Sri Lanka during 205 -161 BC *(Sources: Murata et al., 2011, Ruwanpura et al., 2009, https://john-tyrrell.blogspot.com)*

STUDY AREA

Galle is a coastal city and famous tourist destination in the Southern Province of Sri Lanka. It is the provincial capital and largest city of Southern Province of the country. The city extends about 8 km east to west and 7.5 km north to south directions. The hilly land area to the north of the city is a residential zone. In the west side of the city, a fort and old port are located. Galle Port and fishery ports are on the east side of the central part of the City (Figure 1). The city consists of higher educational institutes, hospitals, central bus terminal, railway station, government administrative buildings as well as many commercial buildings, which make Galle city a highly vulnerable and risk-prone area for tsunami events. Before 2004 tsunami event, Galle had experienced 1m high water levels followed by receding water from the tsunami generated by the eruption of Krakatau volcano in the Sunda Strait on 27th August 1883 (Murata et al., 2011). The water level fluctuations were not severe, and there was no inundation in Galle for the 1883 event. However, unlike Krakatau event, the Galle City was severely affected due to the higher vulnerability from the 2004 tsunami event.

The Sumatra–Andaman earthquake and Boxing Day Tsunami (Indian Ocean Tsunami) occurred on 26th December 2004 at 6:28 am (Sri Lankan time) in the Indian Ocean off northwest Sumatra where the epicentre was located. After triggering tsunami by a magnitude 9.1 earthquake beneath the Indian Ocean near Indonesia, the first wave of the tsunami arrived at Galle approximately 3 hours later at around 9.30 am. The tsunami attack was continued to the Galle City for several hours. Galle City lies beside a wide bay and natural headland. In terms of tsunami hazard, location of Galle has been identified as heavily exposed (UNDP, 2011). Hence, city was severally damaged from tsunami waves, inundation, and flooding, resulting from the diffraction of tsunami waves around the southern coast of Sri Lanka and reflection from the Indian subcontinent (Murata et al., 2011). Very reflective vertical non-porous walls of Galle Fort, poorly constructed buildings and inadequate drainages had intensified the tsunami damages to the city. Further, high tsunami waves had travelled to the city centre and landside through the Dutch Canal (*Kapu Ela*). At the coast and port areas, maximum heights of the tsunami had been recorded as 5 m above MSL. In the city area, the inundation had extended about 500 m inland. Along the natural/man-made channel, tsunami run-up had reached more than 1 km inland. This destructive event affected 8,120 people in the Galle area, causing 1,600 and 1,300 houses and building damages, respectively.

METHODOLOGY

Numerical Simulation

Numerical Tool

The December 2004 Sumatra Earthquake source parameters described by Koshimura et al. (2009) were used for generating initial sea surface displacements. In this study, the Tsunami Tool of Delft Dashboard developed by Deltares was used to reproduce initial water levels, generated by the 2004 tsunami. The hydrodynamic effect induced by the 2004 tsunami was considered for the simulation. For the detailed understanding of the hydrodynamic characteristics, tsunami propagation in the Indian Ocean, coastal amplification of the tsunami waves, and successive land area inundation were simulated using the Delft3D-Flow model. Figure 2(a) shows the numerical modelling framework adopted in this study. As shown in Figure 2 (b) three level of nested grids were established to conduct the computation. Parameters of the computational grids are explained in Table 1.

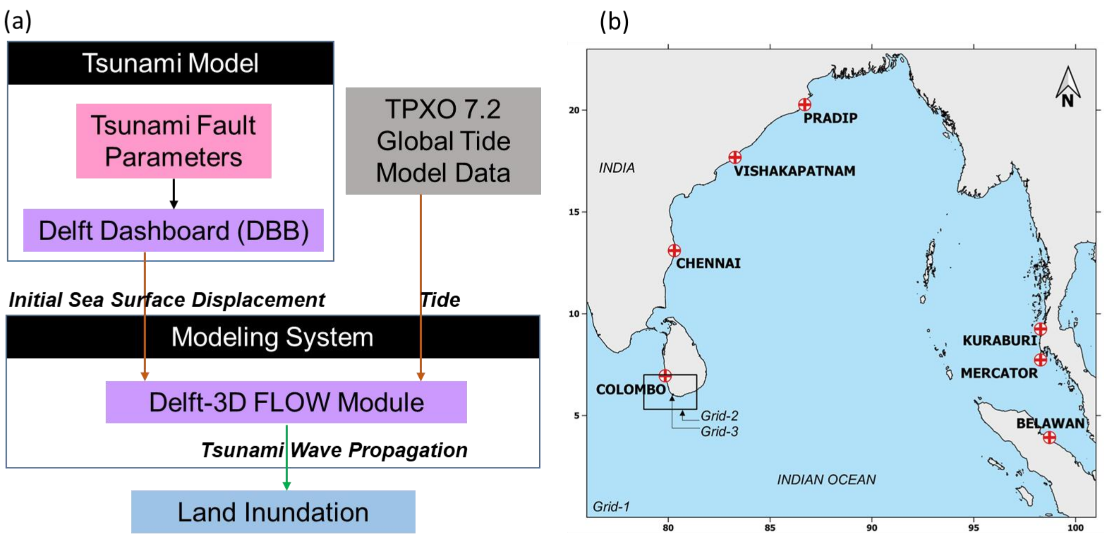

Figure 2: (a) Modeling framework (b) Computational domain with tide gauges used to calibrate the model

The bathymetry was generated using the gridded bathymetric data set provided by the GEBCO and field measured data in the nearshore in 2012. Topography data was obtained by SRTM1 land elevations and LiDAR datasets.

Table 1: Details of the computation domain

Grid No.	Domain Extent		No. of Grids	Grid Spacing (^{0}deg.)
	Longitude (^{0}deg.)	Latitude (^{0}deg.)		
1	76.000 ~ 101.000	0.000 ~ 23.000	1250 x 1150	0.02 (~2000 m)
2	78.800 ~ 81.400	5.300 ~ 7.000	1300 x 850	0.002 (~ 200 m)
3	80.200 ~ 80.250	6.000 ~ 6.050	250 x 250	0.0002 (~ 20 m)

Model Verification

Simulated wave propagation was compared with the tide gauge data recorded during tsunami around the coastal regions of the Indian Ocean (Figure 2 (b)), as described in Josiah et al. (2020). Accordingly, tsunami wave propagation in the regional model was verified. Further, the simulated tsunami water level in nearshore and land inundation depths were verified with the field survey data recorded by Wijetunge (2006) and Murata et al. (2016) respectively. As seen in Figure 3 (a & b), there is a good agreement between field measurements and simulated results of water levels and inundation depths. Thus, the model was verified successfully in regional and local domains.

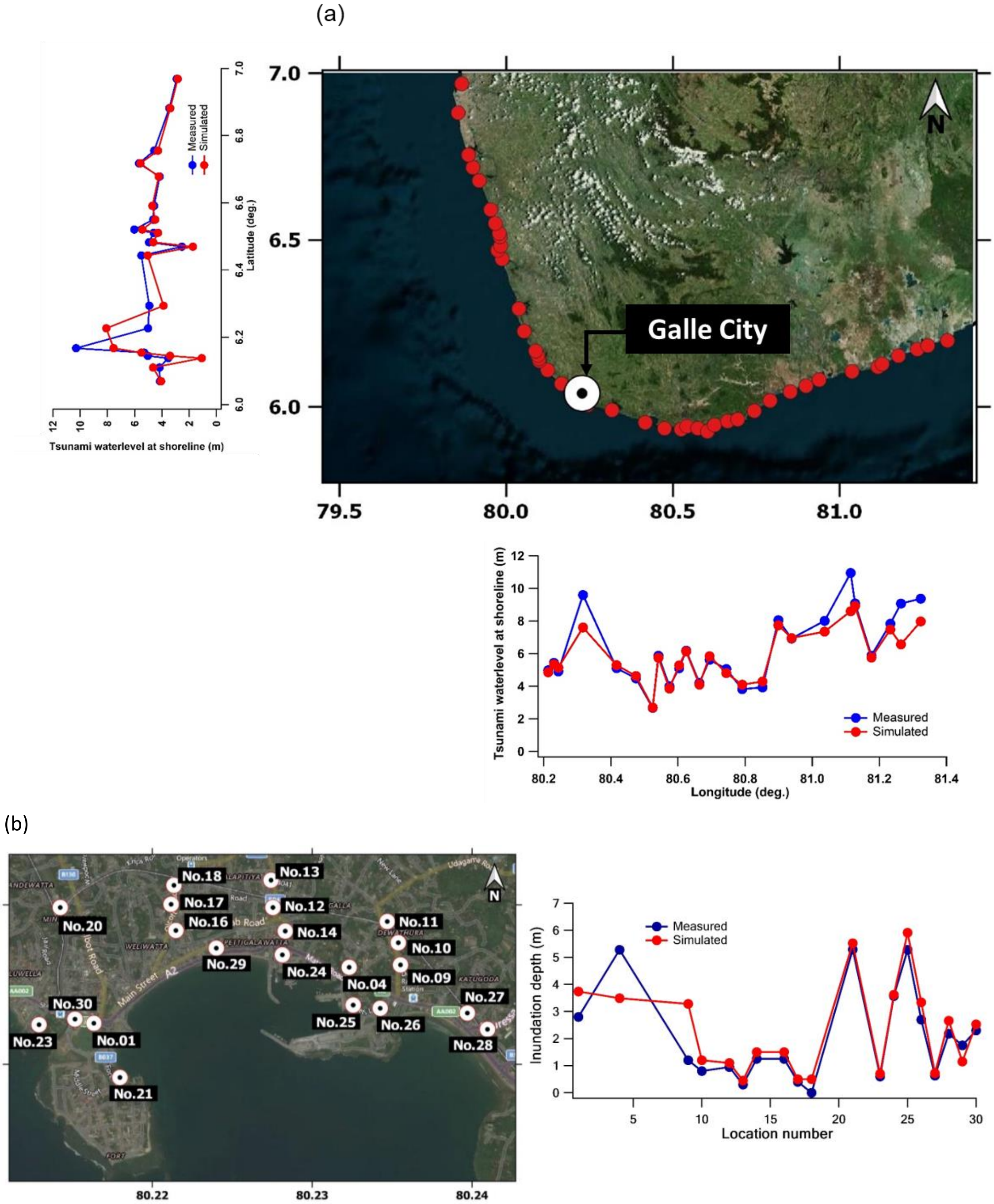

Figure 3: Model verification: (a) Comparison of simulated and measured water levels near coastline by Wijetunge (2006) (b) Comparison of field-measured inundation heights by Murata et al. (2016) with the simulation results.

Field Investigation

Further, availability and functionality of the available vertical and horizontal tsunami evacuation facilities with safe evacuation routes were investigated from the field investigations and key informant surveys. Field investigated data was used to propose additional tsunami evacuation assembly points and potential immediate vertical evacuation pathways. Based on the simulation results, hazardous areas were identified, and evacuation measures were proposed for areas where safe evacuations plans are currently unavailable.

RESULTS AND DISCUSSION

Numerical simulation of the 2004 tsunami in Galle

Through the reproduction of the 2004 tsunami event, inundation extent, depth and safe areas were identified. Simulated inundation in Galle City was compared with previously published maps such as DMC (2012), Hettiarachchi et al. (2016), and Sakthiparan (2020) to reassess the present condition. Figure 4 shows the simulated inundation map with the tsunami water levels. Outcomes of Hettiarachchi et al. (2016) and Sakthiparan (2020) have shown the similarity in inundation extent, which is relatively lower compared to DMC (2012) and the results of the present study. For the present study, high-resolution bathymetry data in nearshore (i.e. bathymetry survey data in 2012) and topography data (i.e. LiDAR) was used as input for the simulation. This would be a reason for the improvement of the inundation extent. Further, tsunami source used to predict the wave propagation for the present study (i.e. Koshimura et al.,2009) would be another reason for the difference. Nevertheless, all studies have predicted the similar extent of non-inundated areas which was safe during the disaster event in 2004. According to the simulation, tsunami level has varied between 2 m to 5 m MSL and above 5 m in some areas of the Gale City. Coastal area west to the Galle Fort area has shown highest inundation. Further, Galle Fort and Galle Port regions have shown the highest inundation where major offices are located, and business is performed. Rumassala region has not experienced any inundation as its elevation is very much higher compared to Galle city. Generally, the tsunami inundation in the city area is less than 1 km. On the west of the headland, it can be observed that tsunami waves have moved into the Kapu Ela (*Dutch Canal)* and run-up in the channel and reached more than 1km inland. These results are agreed with the outcome of Murata et al. (2011). Based on the inundated areas, safe and the vulnerable areas were identified.

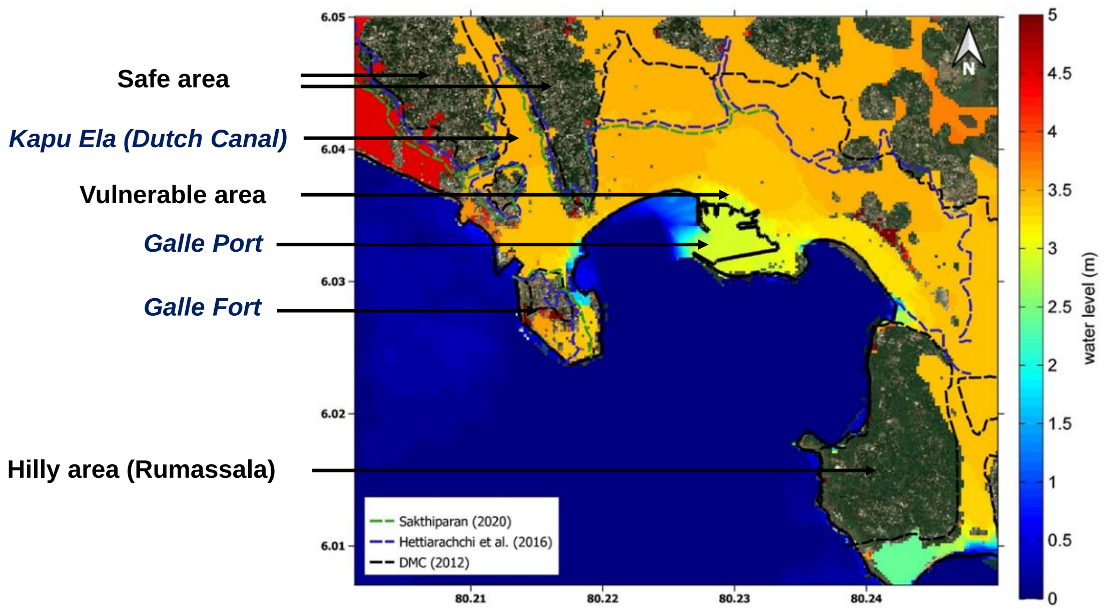

Figure 4: Simulated inundation together with inundation boundaries of previous studies (DMC 2012; Hettiarachchi et al. 2016 and Sakthiparan, 2020)

The present condition of tsunami preparedness mechanism

Acts, policies and guidelines

Even before the year 2004, selected districts including Galle were provided with Disaster Preparedness and Response Plans. The plans were to be executed under District Disaster Management Committees. Early warning and evacuations were two key responsibilities that had been assigned to two subcommittees. The Disaster Management Act was drafted in the year 2000; however, it did not actively get adopted by the time Sri Lanka face Tsunami disaster. Since 2004 event revealed the major loopholes in the context of community awareness regarding disaster preparedness and early warning the Sri Lanka Disaster Management Act, No. 13 of 2005 was introduced. National Council for Disaster Management (NCDM) and DMC were found under the act (Sri Lanka Institute of Policy Studies, 2013).

Disaster Management (DM) roadmaps (the year 2005, 2006 and 2008), National DM policy 2012, National DM plan for 2013-2017, National emergency operation plan 2016-2020, and for the present conditions, National DM plan (2018-2022) were prepared under selected DM committees. DMC was provided with the responsibility of executing evacuation orders island-wide through District Disaster Management Coordinating Units (DDMUs). Throughout the period of 2004-2020, DDMU-Galle has provided technical support in proposing warning dissemination priority routes, developed hazard maps for Galle city and proposed tsunami evacuation points while conducting evacuation drills (SLIPS, 2013).

Early warning

Sri Lanka received Tsunami warnings from Pacific Tsunami Warning Center (PTWC) and Japan Meteorological Agency (JMA), the interim advisors for the Indian Ocean nations until 2012. Later on, Australia, India and Indonesia stepped forward as regional tsunami service providers (RTSP). Sri Lanka has been receiving tsunami warning from PTWC, JMA as well as RTSP of which the alerts were identified to be quicker (within 5-6 minutes of the earthquake) than the former two (about 11 minutes from the earthquake) (Wickramarathne et al. 2013).

In order to deploy a more constructive early warning protocol, by the year 2007, two mobile phones in possession of Director-General, DMC and Deputy Director, Department of Meteorology (DoM) were directly linked to PTWC and received warning immediately after earthquakes above 6.5 Richter scale occurred. Another text message provided magnitude, time and location, later. When DoM receives the warning, a decision should be made within 15-20 minutes. Therefore, while looking for sea-level gauge data, DoM requests advisory from an independent source, which is, for most cases, California Integrated Seismic Network. Since limited access to sea level data was also a major problem during the tsunami event, after 2004, Sri Lanka subscribed for data from two gauges located in North Sumatra and West coast of Sumatra. To detect tsunamis, systems with deep-ocean tsunami detection buoys (e.g. DART system) are placed in tectonically active locations. Thus, detected and processed seismic signals are transmitted to tsunami early warning towers to issues warnings. Upon the information received about the magnitude, alerts are issued to the public in the following order. Mass media, police communication towers, military camps, District Disaster Coordinators and District Secretaries are incorporated in disseminating the particular advisory or warning as illustrated in Figure 5. 6.5-7.0 Earthquake advisory; no tsunami warning and situation is being monitored. 7.0-7.5 Tsunami advisory; a chance in tsunami event and the public should stay alert about evacuation measure. Above 7.6 Tsunami warning; immediate evacuation (if above 7.8) (SLIPS, 2013).

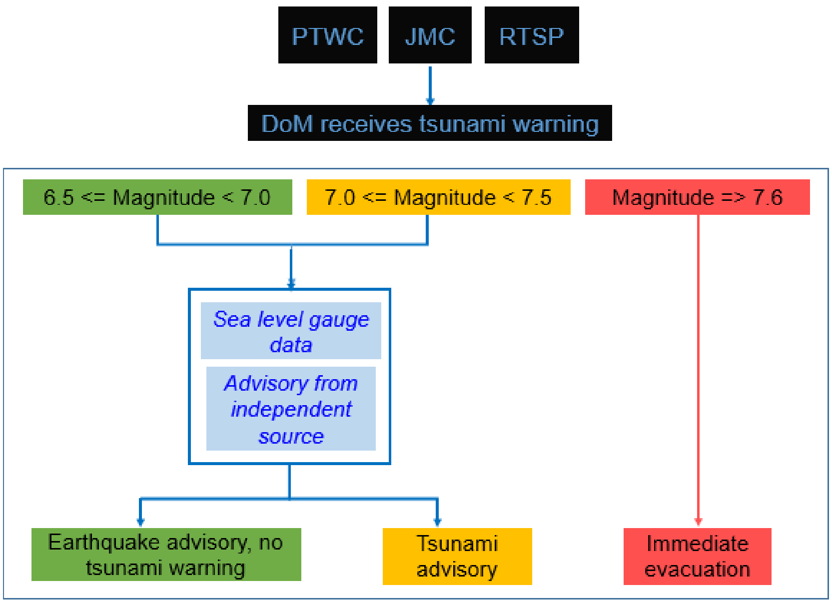

Figure 5: Present early warning dissemination mechanism practised by DoM, Sri Lanka

As per the identified gaps in last-mile dissemination of early warning systems, "Sri Lanka Comprehensive Disaster Management Programme 2014 – 2018" enhanced mechanisms to disseminate early warning messages. At present, DMC has upgraded its communication systems considering early warning towers located at major population centres. In the context of the study area, Eventually, Galle city also deployed police and military for the purpose of executing evacuation orders. The benefits of assessing HF/VHF radio communication systems and mobile telecommunications in broadcasting tsunami evacuation orders are also available for Galle district community.

Identified safe areas, vertical and horizontal evacuation

Throughout the period of 2004-2020, DDMU-Galle has provided technical support in proposing warning dissemination priority routes, developed hazard maps for Galle city and proposed tsunami evacuation points.

Hettiarachchi et al. (2016) developed a hazard map for Galle city considering the risk level based on inundation and current speed. High- inundation level above 0.5m with high flow/current speeds (>1.5 m/sec), medium- inundation level between 1m to 2m with low flow speeds and low- Inundation level less than 1m and low flow speeds. Population, buildings and infrastructure, socio-economic fabric of society, ecosystems, services and infrastructure, and administering was considered for the vulnerability assessment of Galle city which resulted in high and medium vulnerability in Galle city area. Based on the population, residing elevation, and distance to seafront and evacuation conditions, Galle city was characterized with a high risk. All these assessments were conducted in the context of 2004 Tsunami event.

Field survey data confirms the proposed assembly points by DDMU-Galle are mainly religious gathering places and community halls with a total capacity of holding 1770 families. The heights of the shelters are adequate and can be utilized for the vertical evacuation points while other locations can be employed as safe locations to evacuate.

Implementation issues, training, awareness programs

DMC, the responsible body in undergoing evacuations, focused on awareness programs targeting affected communities, schools and government organizations through DDMUs. Localized drills are being practised since 2007. Sri Lanka evacuated the entire coastal area within 45 minutes in response to a tsunami warning in 2007. The first island-wide tsunami drill was conducted in 2010, and it was possible to complete evacuations within 25-45 minutes in 13 districts, including Galle district, indicating satisfactory coordination in warning dissemination. About 90% of the population in tsunami-prone districts evacuated to safe locations during the 2012 tsunami warning (Wickramarathne et al. 2013). However, despite the improvements of early warning systems and evacuation measures lack of community participation for evacuation drills still remains as a key issue, probably due to the false alarms. For Galle district alone, almost 30% of 2004 tsunami-affected community has responded to a higher number of false alarms by the year 2006. The probability of a false alarm to reach the public is still higher since tsunami warnings are being issued despite the sea level gauge data during an earthquake with a 7.9 or higher magnitude. For instance, Sri Lanka issued official evacuation orders in 2005, 2007 and 2012, which reached the general public as false alarms. Unofficial warnings have triggered the number of false alarms and have consequently built up a lack of reliability in tsunami evacuation orders among the community (SLIPS, 2013).

Proposals for the improvement of existing preparedness plans and evacuation measures

In general, tsunami waves reach after about 3 hours from Sumatra-Andaman region, which ensures there is sufficient time to evacuate if the warning is received on time. From the developed inundation map in the present study, safe areas were identified, and some areas were agreed with the previously identified areas (Figure 6). In order to minimize the traffic congestions indicated by Hettiarachchi et al. (2016), evacuation routes were found to reach safe areas without much difficulties (Figure 6). Routes were determined based on easiness to access the safe areas. Hence, main roads can be utilized to reach for proposed assembly points. Proposed routes agree with previously identified horizontal routes. However, new routes have been proposed, for the area close to the Galle Fort, based on the numerically simulated results.

Other than the facilities situated in the safe areas, structures situated in the vulnerable area (i.e inundation area) such as buildings which can be used as emergency evacuation point, places such as hospitals and schools need to be preauthorized the evacuation was identified (Figure 6). Figure 6 also shows some important evacuation places identified in addition to Sakthiparan (2020). The suggested locations were observed through field survey and selected by coupling with the simulation results. The primary considerations were the number of stories (e.g. District Secretariat Office, Galle), inundation depths (e.g. Ripple Reach building), ground elevation (e.g. SL Telecom building) and higher vulnerability of the area. The proposed evacuation shelter buildings by Sakthiparan 2020 covers the majority of the vulnerable area and yet some high-risk prone areas were identified due to lack of suitable evacuation centres. Thus, thorough attention has been given for the rightmost area of

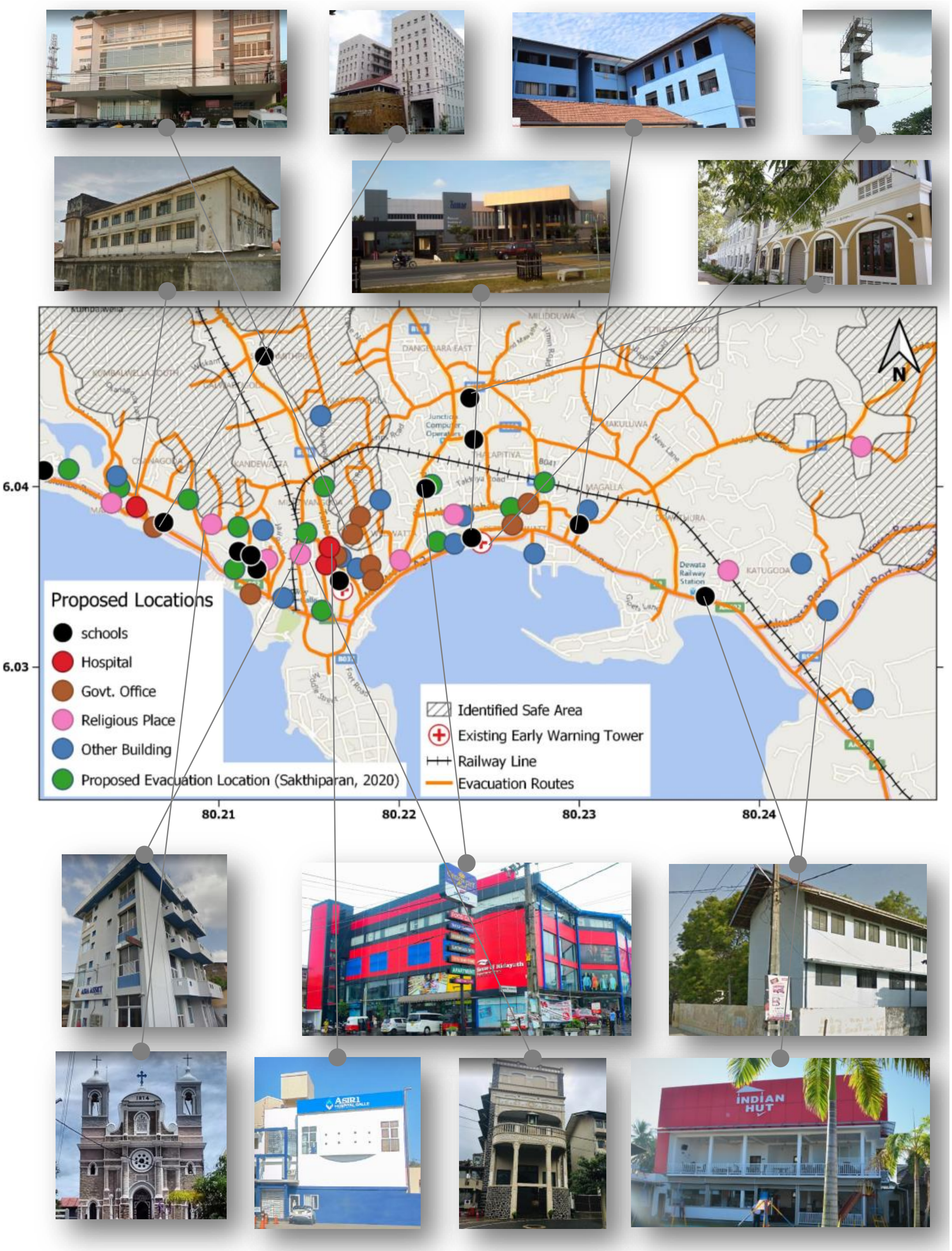

Figure 6: Proposed evacuation measures: Identified safe areas, locations of vertical evacuation locations and horizontal evacuation routes in Galle city to reach safe areas based on field investigation and numerical simulations results.

Figure 6 since limited buildings are proposed for the particular division. The buildings are suggested specially for the immediate evacuation in case of any failure of communication during a tsunami event. Incorporating service sectors that include health and electricity should be further developed in proposing evacuation plans. As highlighted in Wickramarathne et al. (2013), the evacuation procedures should be coupled with electricity which is a higher priority during nighttime evacuation such as 2005 evacuation. The provided routes should be properly analyzed about the traffic conditions, which became critical during the evacuation in 2012. This study does not propose extra early warning towers as it is already networked and predetermined by DMC.

CONCLUSION

The present study was carried out to identify and reassess hazardous areas for future tsunamis for Galle City of Southern Sri Lanka. According to the identified vulnerable areas and the availability of present evacuation measures, suitable evacuation plans were proposed. For the simulation of initial water levels, generated by the 2004 tsunami, the Tsunami Tool of Delft Dashboard developed by Deltares was used. The hydrodynamic effect induced by 2004 tsunami (i.e. tsunami propagation, coastal amplification of waves, and land inundation) was simulated using the Delft3D-Flow model. It was recognized that Delft3D-Flow model, together with Delft Dashboard Tsunami Tool, could successfully reproduce tsunami inundation. Further, availability and functionality of the available vertical and horizontal tsunami evacuation facilities with safe evacuation routes were investigated from the field investigations and key informant surveys. Field investigated data was used to propose additional tsunami evacuation assembly points and potential immediate vertical evacuation pathways. Based on the simulation results, safe and hazardous areas were identified. Generally, previously developed tsunami hazard maps are agreed with the area identified from numerical simulations. Based on the outcome of the field investigations and numerical simulation, evacuation measures were proposed for areas where safe evacuations plans are currently unavailable. Thus, safe areas are proposed, and suitable horizontal evacuation measures were proposed based on easy access. Vertical evacuation points were suggested primarily considering the identified zones with lack of proposed buildings in previous studies. Currently, tsunami early warning and evacuation in Sri Lankan disaster management is in a favourable condition. However, a lack of community awareness and receiving false alarms are still in needs consideration. Since traffic congestion is critical during the evacuation time, it is recommended to analyse the traffic conditions for the provided routes properly.

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