ASSESMENT OF TSUNAMI PREPAREDNESS MEASURES IN EAST COAST OF SRI LANKA BASED ON 2004 TSUNAMI EVENT

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ABSTRACT

The 2004 Indian Ocean tsunami is the worst natural disaster ever recorded in Sri Lankan history. Due to the present active tectonic activities in the subduction zone beneath Sumatra, there is a possibility of occurring tsunamis in the Indian Ocean again by bringing devastation for coastal countries in the Indian Ocean. Thus, proper understanding about possible tsunami inundation levels is a prerequisite for disaster prevention and management activities. The present study was carried out for the Batticaloa, a major city in east coast of Sri Lanka which was severely devastated by the 2004 tsunami. Even though tsunami awareness programs and post disaster field surveys have been carried out a decade ago, there are no any studies assessing the present conditions of tsunami disaster preparedness of Batticaloa City yet. Therefore, in this study, a numerical model was established to predict the tsunami propagation and inundation in the interested area. A field survey was carried out to collect the information on established facilities such as early warning systems and evacuation strategies. Delft3D-FLOW module was used to carry out the numerical simulations. There is a good agreement between simulated inundations by Delft3D modeling system and field investigated values. From the field survey, it was identified that present conditions of disaster management methods, techniques and strategies are inadequate in the study area and recommended to improve them to prepare for future tsunami events.

Keywords: Tsunami, simulation, Delft3D, inundation, evacuation

1. INTRODUCTION

Island countries have been experiencing coastal hazards such as typhoon, storm surges and sea level rise during the recent past. However, extreme coastal disasters such as 2004 Indian Ocean tsunami, 2010 Chile tsunami and 2011 Tohoku tsunami have left a regretful memory to world community during the last decade by emphasizing the safety of the coastal communities in vulnerable tsunami prone areas. Sumatra-Andaman subduction zone is one of the well-known region for the frequent higher magnitude earthquakes and tsunamis. These phenomena highlight the importance of disaster management and preparedness for future occurring tsunamis along the coastal regions of Indian Ocean, including the island country, Sri Lanka. Hence, proper understanding of basic five key processes such as tsunami generation, propagation, possible inundation areas, warning issuing techniques and evacuation methods are needed to be considered in order to minimize the devastation from future tsunami events.

Reconnaissance survey data of past tsunami disasters and numerical modeling methods assist coastal community to understand the hydrodynamic effects of tsunami waves. Accuracy and reliability of tsunami wave models depend on the selection of proper earthquake source parameters and numerical scheme. Tsunami can be triggered and generated due to natural destructive phenomena such as earthquakes, submarine landslide, volcanic eruption, asteroid impact or meteorological effect such as extreme pressure differences in ocean surface. Okada (1985) has provided equations to determine the sea surface displacement resulted from the subsea earthquakes by considering rectangular shape, finite width shear and tensile fault planes. In the scientific literature, there are various schemes of numerical techniques to compute tsunami propagation and inundation available such as Boussinesq equations (Grilli et al., 2007), shallow water models (Koshimura et al., 2009) and nonlinear long wave equations (Josiah et al., 2019). Systems with pre-installed deep water wave buoys (e.g. DART system) are used to capture seismic signals of earthquakes and then to identify the magnitude and the strength of shaking from the initial P wave. Thus, processed seismic signals are transmitted to warning towers to issues warnings. Nevertheless, tsunami evacuation facilities have a pivotal role of saving lives and properties in the tsunami prone areas. Evacuation facilities can be determined by either vertical or horizontal approach. Where, vertical approach achieved through evacuation towers constructed in the tsunami zones as well as horizontal approach achieved through evacuating people via safe and optimal route to a safer area before the arrival of tsunami soon after receiving the tsunami warning (Scheer et al., 2011).

According to the disaster risk index of 2017, Sri Lanka has gained a highest score of 8.2 due to the exposure to tsunami disaster while other natural hazards such as earthquake, cyclone and flood have the risk index of 0.1, 3.5 and 6.2 respectively (DMC, 2018), which reflects the vulnerability of coastal areas of Sri Lanka for tsunamis. Therefore, proper assessment of existing disaster management methods is required to develop new facilities or improve existing facilities. The Batticaloa City, a major city of eastern Sri Lanka is one of the worst hit areas by 2004 tsunami (Figure 1(b)). Batticaloa area consists with low lying land area and is being gradually developed after prevailed civil war during 1983 - 2009 periods. The powerful waves of 2004 tsunami swept the Batticaloa City bringing extensive damages for lives and properties. Though tsunami awareness programs, identification of hazardous areas and proposing evacuation measures were carried out in Batticaloa area, so far, there is no any study assessing the present conditions of tsunami early warning and evacuation measures based on predicted inundations in the Batticaloa City. Hence, it is very important to understand the possible vulnerable areas of future tsunamis to prepare and implement disaster mitigation and management plans. In recent literature, tsunami wave propagation and land area inundation were simulated using ELIMO and Nays2DFlood model system for Batticaloa area (Josiah et al., 2019). Though tsunami wave propagation was well simulated, inundation levels were underestimated by Nays2DFlood model in the same study. Considering the identified research gaps of the study area, present study was carried out (i) to reassess the tsunami inundation areas in Batticaloa City from 2004 tsunami by establishing a numerical model and (ii) to assess tsunami preparedness measures on the basis of identified hazards areas and available measures.

2. STUDY AREA

Figure 1 (a) shows the epicenters of earthquakes occurred between 2004 and 2012 period in the Andaman-Sumatra subduction zone which moment magnitudes are greater than 7.0. In this study, impact due to 2004 Indian ocean tsunami on Batticaloa City in the eastern coast of Sri Lanka is mainly considered. Coastal areas of eastern Sri Lanka, including Batticaloa area is dominated by lagoons and low-laying lands. Batticaloa City is surrounded by Batticaloa Lagoon and the Indian Ocean (Figure 1(b)).

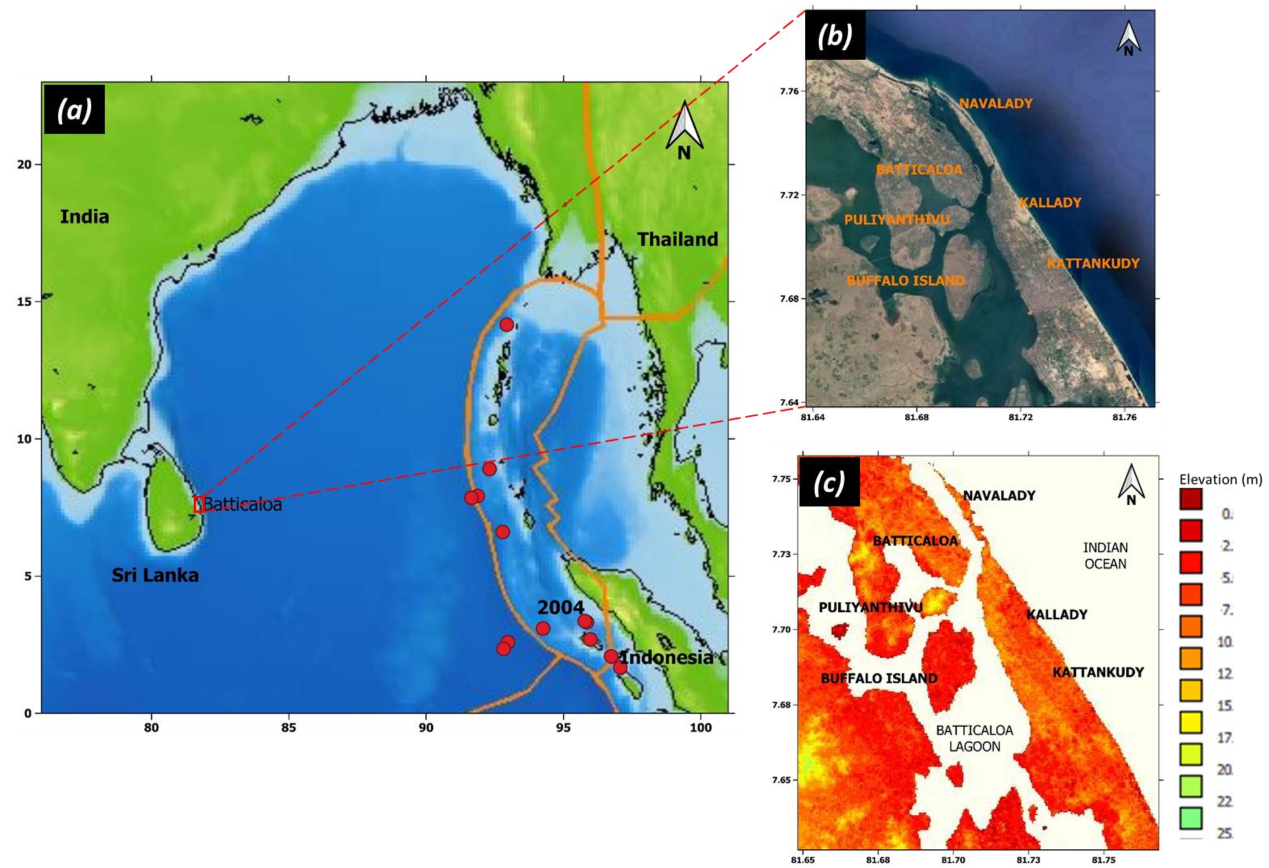

Figure 1. (a) Locations of the earthquakes ($M_w > 7.0$) in Indian Ocean between 2004-2012 (b) Study Area: Batticaloa area in Sri Lanka; (c) Topography variation in Batticaloa City (*Source: https://www.globalcmt.org/ and http://maps.google.com*)

Figure 1(c) shows the topography variation of Batticaloa City together with tsunami affected main areas such as Navalady, Kallady and Kattankudy. Navalady area was completely destroyed during the tsunami event. All administrative buildings of Batticaloa City are situated in Puliyanthivu area. This is quite elevated area than other regions of Batticaloa City. Generally, the land elevations of study area vary between 0 *m* to 14 *m MSL*. Somehow, land elevations in Batticaloa coastal area is generally flat and lies between 1.2 *m* and 4.0 *m* above *MSL* (UNHABITAT, 2013). Further, Batticaloa has a long straight sandy beach (Josiah et al., 2019) and has a large brackish lagoon extend towards the south.

3. METHODOLOGY

3.1 Field survey and data collection

Filed survey was carried out during the period between 15th and 17th December 2019 to identify the present conditions of tsunami evacuation measures in the study area. Activities such as field observations and key informant survey were included in the field survey. During the field survey, special attention was given to identify the available tsunami warning signs, hazard maps and warning towers and evacuation facilities. Further, required details pertained to 2004 Indian Ocean tsunami were collected from secondary data sources such as published reconnaissance survey data.

3.2 Numerical simulation

3.2.1 Numerical model

Simulation of tsunami wave generation and propagation was carried out with Delft3D-FLOW module together with Delft dashboard tools (Deltares, 2019). After simulating initial tsunami condition by using Delft dashboard tools, Delft3D-FLOW module was used to simulate the hydrodynamic effect during the tsunami propagation and inundation processes. Delft dashboard uses Okada (1985) equations to generate initial sea surface displacement. In Delft3D-FLOW module, 3D shallow water wave equation is used to resolve the wave propagation. Earthquake source parameters of 2004 Indian Ocean tsunami was considered from different studies for initial tsunami condition simulation. These parameters have been derived by inversion methods using tide gauge data and satellite altimetry data (e.g. Fujii and Satake, 2007; Grilli et al., 2007; Koshimura et al., 2009 and Suppasiri et al., 2011). Among them, fault parameters provided by Koshimura et al. (2009) demonstrated a good agreement for the desired simulation and hence used for simulation. Simulation was carried out for a period of six hours starting from 00:58:00 *GMT* on 26th December 2004.

3.2.2 Data and computational domain

Land elevation and bathymetry data were taken from the SRTM global one arc-second and GEBCO 30 arc-second databases respectively. Further, recent field survey of nearshore depth data (Dastgheib et al., 2018) was used to enhance the accuracy of near shore depths. Computational domain consisted with three level of nested grid setup as shown in Table 1 and Figure 2(a). Open boundary conditions were specified for Grid 1. Subsequent boundary conditions of nested Grid 2 and Grid 3 were extracted from the immediate Grids 1 and Grid 2 respectively.

Table 1. Details of nested grid setup

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	81.000 ~ 82.500	6.450 ~ 8.850	750 x 1200	0.002 (~200*m*)
3	81.400 ~ 81.820	7.550 ~ 8.100	1050 x 1375	0.0004 (~40*m*)

3.2.3 Verification of the model

For the verification of model, simulated tsunami wave heights were compared with the tide gauge data recorded during the 2004 Indian Ocean tsunami event. Tide gauge data was obtained from Fujii and Satake (2007) and Grilli et al. (2007). Figure 2 (a) shows the locations of the considered tide gauges in Indian Ocean. Figure 3 shows the comparison of simulated tsunami waves at selected seven gauging stations with observed values where time axis represents the arrival time of waveform from the initial wave generation together with the Root Mean Square Error (*RMSE*) and Correlation Coefficient (*r*) values. In overall, by the visual observation on peak values and patterns of the tsunami waves, it is identified that observed and simulated values are in good agreement at considered points. Further, these results are agreed with recent studies (e.g. Grilly et al., 2007; Supppasiri et al., 2011; Josiah et al., 2019). Agreeing with the low values of *RMSE*, prediction of tsunami waves at Kuraburi, Belawan and Colombo stations have shown higher agreeableness with observed data than other stations (i.e. Pradip, Vishakapatnam, Chennai and Mercator). The possible reasons for the discrepancies and higher *RMSE* would be the selected values of earthquake source parameters and phase differences of simulated waves with the observed values. Further, Figure 2(b) shows the tsunami wave propagation two hours after the initial wave generation together with the arrival time contour for two hours derived by Satake et al. (2006). It also shows a good agreement of tsunami arrival time in the Sri Lankan coast.

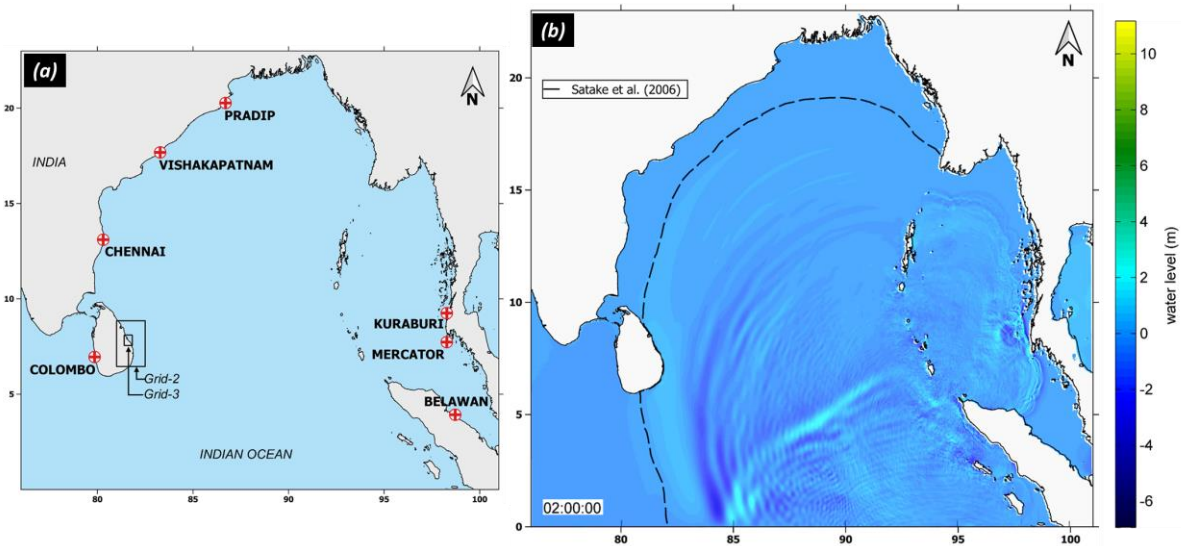

Figure 2. (a) Gauging stations used for model verification (b) Simulated tsunami wave propagation in Grid 1

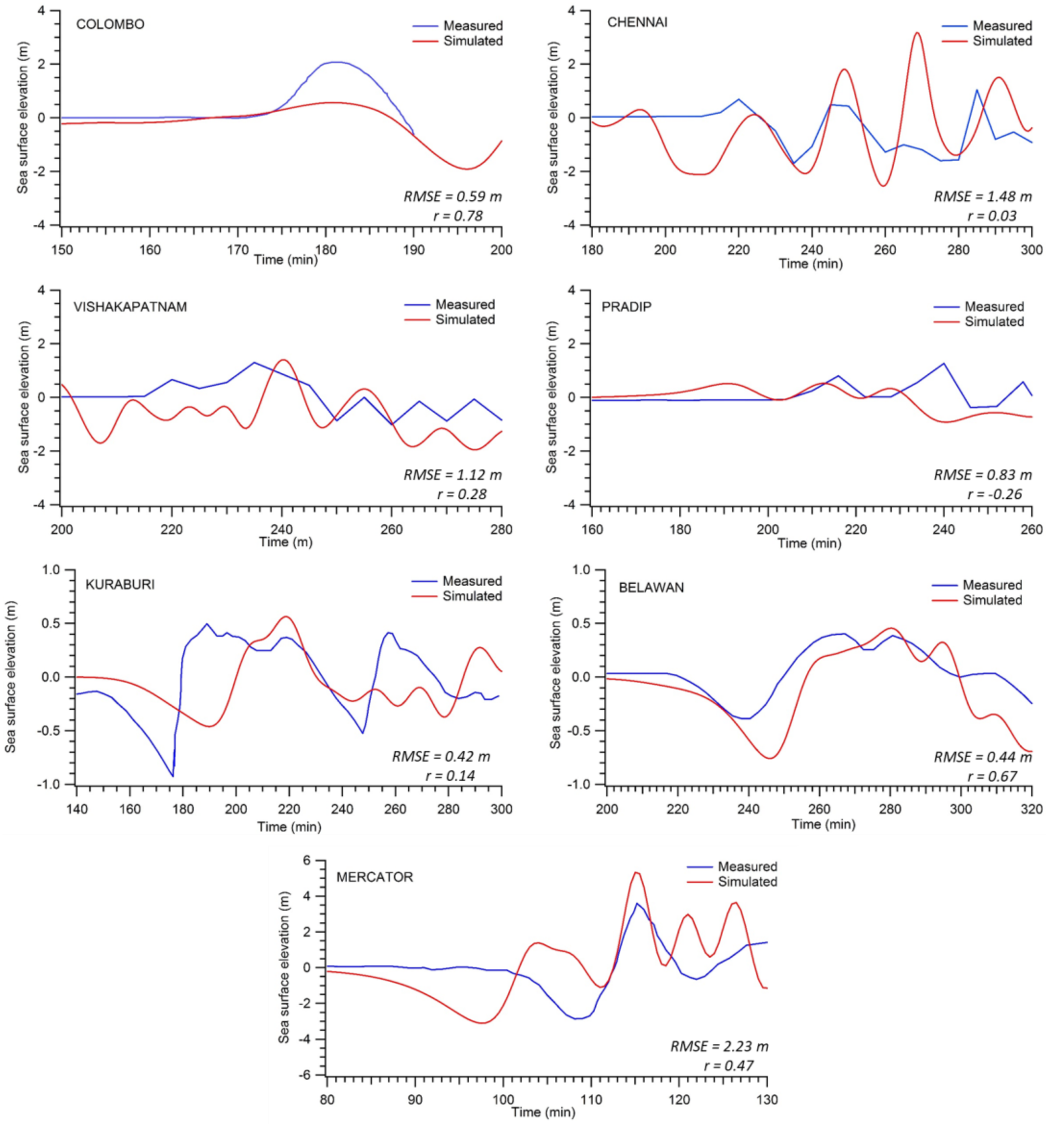

Figure 3. Comparison between measured and simulated tsunami waveforms. (Time in minutes, starting from 00:58:00 *GMT* on 26th December 2004)

4. RESULTS AND DISCUSSION

4.1 Simulated tsunami heights and inundation distance in the study area

Even though, few post-field survey data (e.g. Inoue et al., 2007; Wijetunge, 2006) are available for Batticaloa region, suitable numerical model which has a capability to simulate both tsunami propagation and inundation has not been established yet for the study area for disaster mitigation and management purposes. Hence, the simulated horizontal inundation distances and inundation depth by Delft3D-FLOW modeling system is useful for disaster related decision making processes. Accordingly, Figure 4(a) shows the computed inundation extent for the 2004 Indian Ocean tsunami event. Simulated inundation was compared with the UNHABITAT (2013) community map of tsunami inundation, which has been prepared by interviewing public. Further, simulated results were compared with the horizontal run up distances identified during the post field tsunami survey by Inoue et al. (2006).

Figure 4(b) shows the simulated inundation distances together with the inundation extents provided by the past field surveys (Inoue et al., 2006; UNHABITAT, 2013). Simulated inundation extents are agreed with the survey data of Inoue et al. (2006). However, inundation in the upper part of Puliyanthivu area (Figure 4(b)) has significantly underestimated. This might be due to the insufficient bathymetry data of the Batticaloa lagoon which limits the wave propagation through the lagoon. Inundation extent prepared by the UNHABITAT (2013) also shows a slightly higher estimation compared with the post tsunami field survey by Inoue et al. (2006). Thus, comparing with field investigated and numerically simulated results, Delft3D modeling system has simulated the inundation extent with a good agreement.

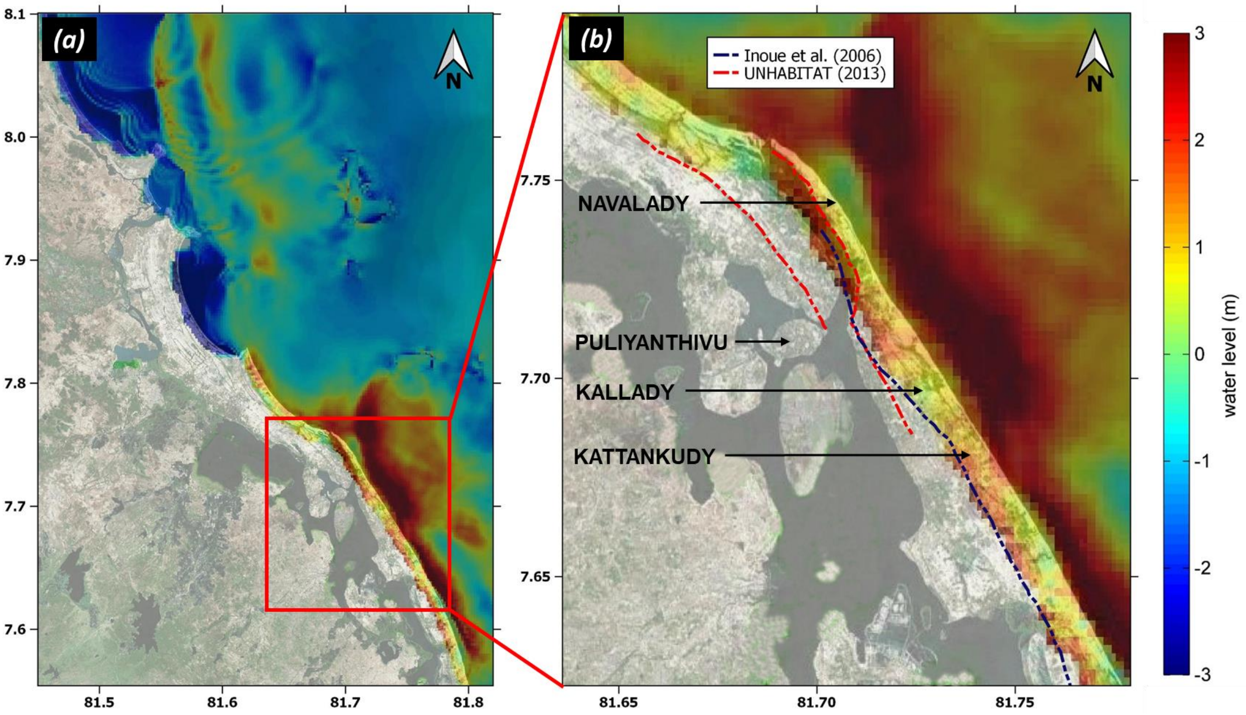

Figure 4. (a) Simulated tsunami inundation extent in Batticaloa City and (b) comparison with field survey data

Further, water levels at the shorelines were also compared with the measured data by Wijetunge (2006). Figure 5 shows the comparison between simulated and measured water levels along the shoreline together with *RMSE* and *r* values. Water levels between 7.80N and 8.00N has been underestimated by the model. However, at other locations, there is a good agreement between simulated results and observations.

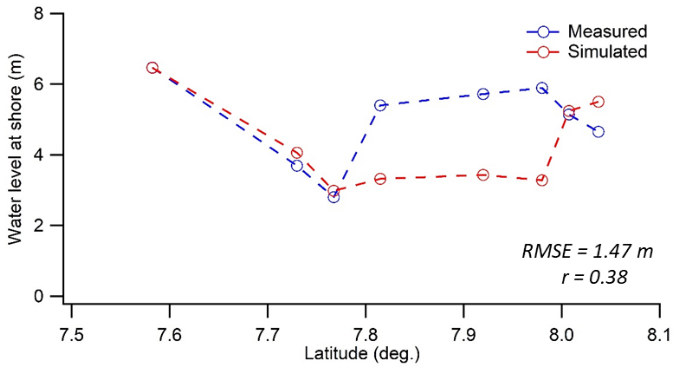

Figure 5. Comparison between measured and simulated wave heights at shoreline

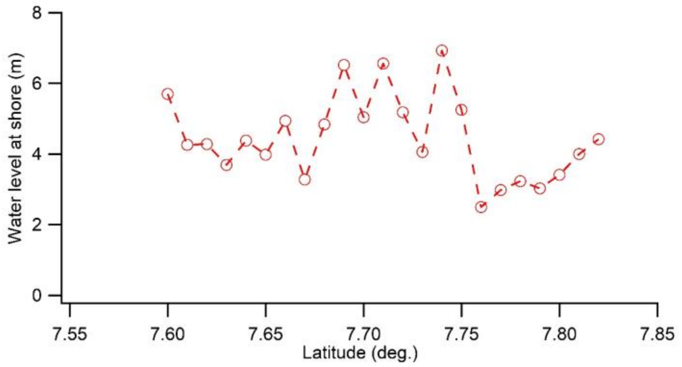

Figure 6. Approaching wave heights at the shoreline

Additionally, maximum waterlevels at shoreline from Kirankulam to Chenkalady (latitude: 7.6N to 7.82N in steps of 0.01^0 *deg.*) were extracted in order to distinguish the spatial distribution of the simulated tsunami wave heights. Figure 6 shows the extracted maximum water levels along the coastline. It was identified that tsunami water level varies between 3 *m* and 7 *m* along the Batticaloa coast line (latitude: 7.65N to 7.78N).

4.2 Assessment of tsunami preparedness measures in the study area

Assessment of the tsunami evacuation measures was carried out by using numerically simulated results, secondary data and key informant survey and field observations. In severely affected areas such as Navalady and Kallady (Figure 2), any warning signs or hazard maps are not available presently. During the field survey, it was identified that there is only one tsunami sign board in Batticaloa city (Figure 7(c)). Though tsunami sign and symbols can be used to provide information related to tsunamis and their impact, it was observed the inadequacy of tsunami sign board which provides information such as evacuation zones, routes and safe locations. So, further information is required to provide by means of sign board for the public to provide instructions, directions, or routes for evacuation at the time of evacuation during a tsunami warning.

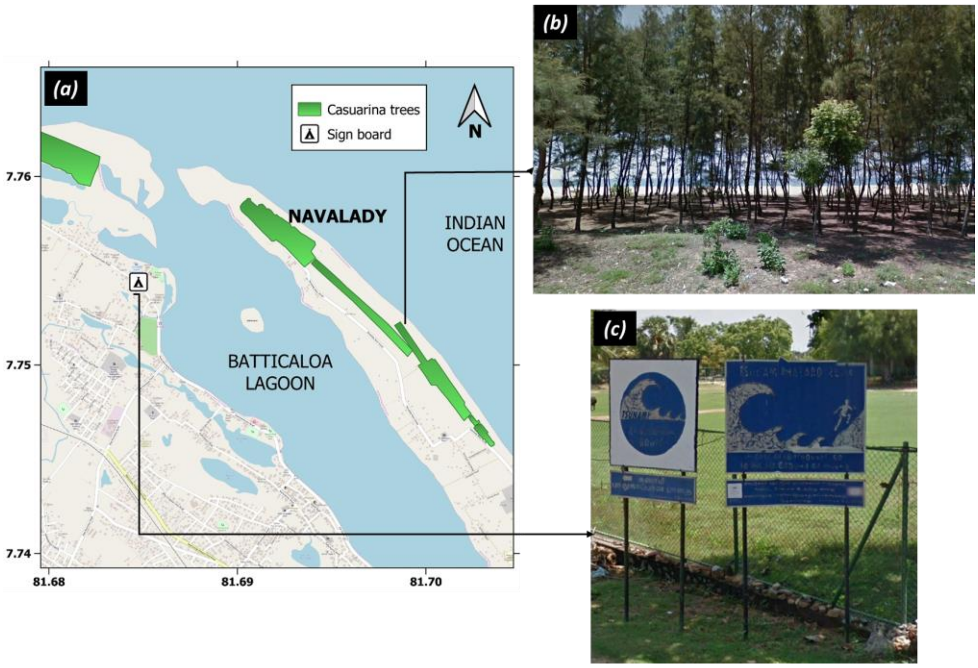

Figure 7. (a) Aerial map with locations (b) Casuarina trees along the coastline (c) Tsunami sign board (Source: Field Survey, 2019)

As observed, lot of Casuarina trees have been planted between beach and residential area of the Navalady and Kallady areas (Figure 7(b)). Generally, Casuarina trees provide greater resistance for tsunami wave by progressively dissipating energy by drag and other forces created by Casuarina trees, while tsunami passes through Casuarina trees areas (Dengler and Preuss, 2003). Hence, availability of Casuarina trees would be advantageous in terms of mitigation of tsunami damages.

Seven tsunami warning towers are currently available in the Batticaloa district as shown in Figure 8. Every tsunami warning tower is interconnected and managed by the Disaster Management Center (DMC) in Sri Lanka. Warning dissemination takes place through the prescribed administrative levels such as district level, divisional level and village level (DMC, 2018). DMC of Sri Lanka has conducted regional tsunami preparedness exercise in some other coastal cities which include training on warning receiving, issuing as well as increasing the awareness of the community about the disasters (DMC, 2018). However, it was recognized that there were no such training in the study area during the recent past highlighting the lack of preparedness for future tsunami events. Further, it was identified that, there are no facilities in the Batticaloa City such as evacuation buildings or assembly points other than tsunami warning towers.

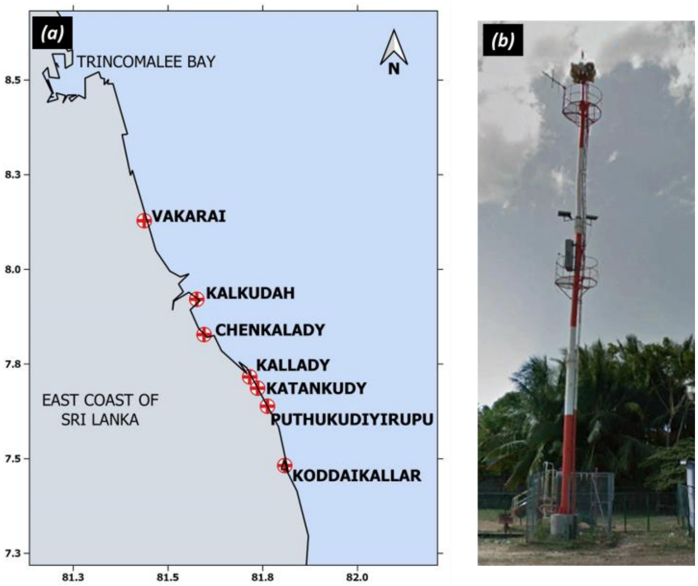

Figure 8. (a). Tsunami warning tower locations in Batticaloa district and (b) Tsunami warning tower at Koddaikallar (Source: Field Survey, 2019)

During the 2004 Indian Ocean tsunami event, school buildings at the Puliyanthivu (Figure 9) area were utilized as shelter for affected people. Because of present unavailability of designated facilities, public buildings such as schools and playgrounds in the study area can be utilized as assembly points. Figure 9 shows the maximum inundation area of the Batticaloa city for the 2004 Indian Ocean tsunami event together with the available school buildings. It can be observed that few schools are situated in the inundation zone. Many schools situated in the inundation area are made up of at least two story buildings which has a height greater than 3 *m*. By taking precautions and conducting proper assessment of buildings, safety of schools during future similar tsunami events can be achieved. As evacuation or assembly points for tsunamis, schools and playgrounds situated in the Puliyanthivu area can be utilized as its land elevation is higher than other areas of Batticaloa (Figure 1(c)).

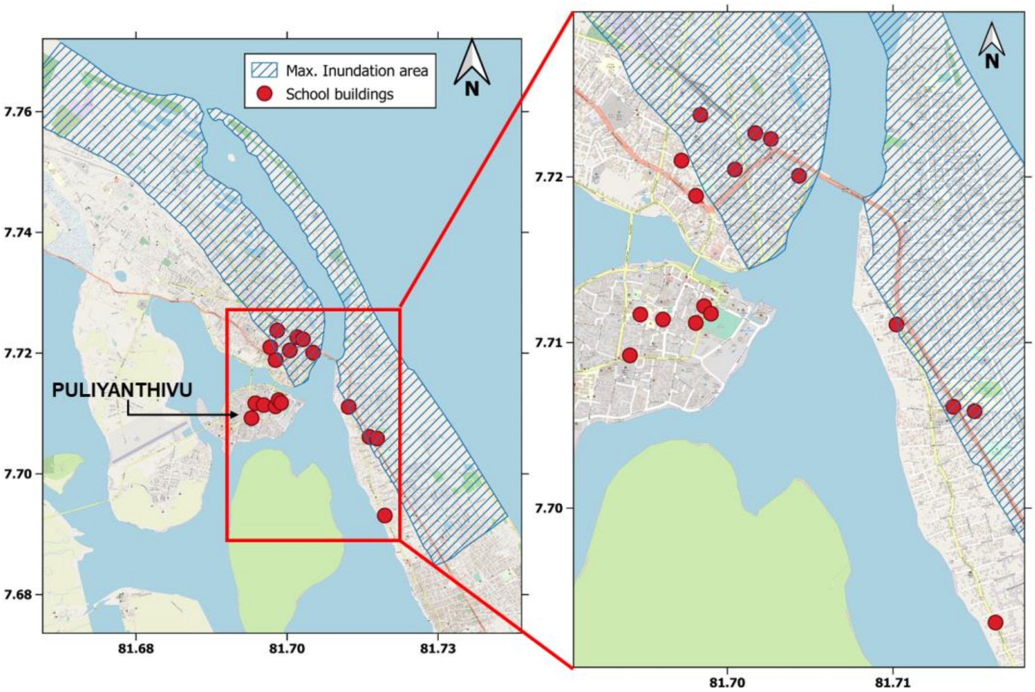

Figure 9. Inundation extent area of Batticaloa City with the available school building (*Source: UNHABITAT, 2013 and Field survey, 2019*).

Since the tsunami waves takes at least two hours to reach the Sri Lankan coast, much priority can be given for the design and implement horizontal evacuation measures than the vertical evacuation towers. However, as Batticaloa coastal area is constrained by Batticaloa Lagoon from other side, consideration on vertical evacuation towers is also recommended as the next priority. Since proper guidance such as hazard maps, evacuation routes and predestined assembly points are lacking in this region, the present study's findings would be helpful to identify hazardous/safe locations and propose suitable evacuation measure.

5. CONCLUSIONS

The present study was carried out for the Batticaloa City, a major city of eastern Sri Lanka. It is one of the worst hit areas by 2004 tsunami event. The main objective of the present study was to reassess the tsunami inundation areas in Batticaloa City from 2004 tsunami by establishing a numerical model. Further, it was required to assess the available tsunami preparedness measures based on identified hazards areas and the availability of present warning and evacuation measures. Accordingly, seven tsunami warning towers were identified as a preparedness measure for upcoming tsunamis. However, inadequate number of tsunami towers and lack of tsunami training/awareness programs were identified from the field survey. Further, there are no measures such as evacuation buildings/vertical evacuation towers, assembly points, and horizontal evacuation routes in the study area. Numerical simulation was carried out to understand the tsunami inundation heights and distances in the study area. Accordingly, a numerical modeling system was established to simulate the 2004 tsunami event. Thus, Delft3D-FLOW modeling system was verified and applied to simulate the hydrodynamic effect of the tsunami event. It was identified that, developed Delft3D modeling system has a capability for reproducing 2004 tsunami event, inundation extent and tsunami wave heights with a satisfactory level of accuracy. Thus, this model can be used for future disaster prevention and management processes for the study area, incorporating identified available and non-available tsunami preparedness/evacuation measure.

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