TSUNAMI DAMAGE ESTIMATION ALONG THE COAST OF LAOAG CITY USING TSUNAMI FRAGILITY FUNCTIONS

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ABSTRACT

The objective of this study is to assess the tsunami hazard and to estimate the tsunami damage in Laoag City. The scenarios used for the assessment of tsunami were obtained from different studies of the Manila Trench. For damage estimation, tsunami fragility functions developed for Banda Aceh were used. The worst scenario S2 has a magnitude of M_w 8.4, with a fault length of 277 km, a fault width of 91 km and a top depth of 5 km. The slip amount was set to 3.72 m with strike, dip and rake angles of 20°, 41°, and 79°, respectively. The maximum uplift and subsidence obtained for this scenario were 2.08 m and 0.25 m. The maximum tsunami height resulted on 4.47 m and the arrival time to 20 min after the earthquake. Also, the inundation area and maximum inundation depth values were 6.79 km^2 and 6.8 m. The estimated damage on exposed buildings and casualties were 93%, and 70%, respectively. These findings can be used as a reference by local governments, however careful assessment of uncertainties not considered here are necessary for future disaster planning and mitigation.

Keywords: Tsunami simulations, Fragility Functions, Damage Estimation, Laoag City.

1. INTRODUCTION

The archipelago of the Philippines is located an active seismic region where tsunamis may also occur. Events like the 1976 Moro Gulf M 8.1 and the 1994 Mindoro Ms 7.1 earthquakes generated tsunamis and damage on structures and loss of human lives. Studying tsunami hazard as well as estimating the damage to exposed infrastructure and people would be the key to prepare for a future possible disaster. The study area chosen for this research is Laoag City which is one of the chartered cities in the Philippines. Various studies using Manila Trench as a tsunami generator were taken into consideration to develop earthquake source models. The subduction beneath this trench has been in the process of strain accumulation over a period of 440 years in which could be a source of Mw 9.0 earthquake (Megawati et al., 2009). The scenario which generates the highest output data for seafloor deformation, tsunami heights, inundation depth and area will be used as the worst case scenario. The maximum inundation depth value for each “barangay” is used for damage estimation. Barangay is the smallest administrative division in the Philippines. The damage probability and death ratio were collected per barangay using the maximum inundation depth and fragility functions. The results to be presented are limited by the resolution and quality of the data used such as the bathymetry and topography, together with the exposed data. Thus, these results can only be used as a guide and not as exact values for disaster planning.

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2. THEORETICAL CONCEPTS

2.1. Tsunami Modeling

In this study, the governing equations were derived based on the nonlinear long wave theory (Yanagisawa, 2018). The differential equations for continuity and momentum conservation in the spherical coordinate system discretized using the staggered leapfrog method. Moreover, to attain stability in the simulation, the program code follows Courant-Freidrichs-Lewy (CFL) condition.

2.2. Fragility Functions

Tsunami Fragility functions are used to estimate the damage probability on structures and human loss using the hydrodynamic features of tsunami such as inundation depths, current velocity and hydrodynamic force (Koshimura et al., 2009a).

This study only uses the inundation depth values to obtain the damage probabilities. The equation (1) is the formulation for finding the probabilities while Table 1 presents the constant parameters used for this study which were obtained from Banda Aceh damage data after the 2004 Indian Ocean tsunami.

$$P(x) = \Phi\left(\frac{x-u}{\sigma}\right) \tag{1}$$

where parameter x is for the inundation depth while μ and σ are for the mean and standard deviation, respectively.

Table 1. Parameters for fragility functions (Koshimura et al., 2009b).

x for fragility functions P(x)	μ	σ
Building Damage	2.99	1.12
Casualty	3.75	1.35

3. DATA AND METHODOLOGY

3.1. Tsunami Hazard Modeling

The bathymetry and topography data used in this study were the GEBCO 30 arc-sec and SRTM 3 arc-second. The computational domains are presented in Figure 1. The grid sizes for Regions 1 to 4 were approximately 810 m, 270 m, 90 m and 30 m respectively. Region 4 contains the study area.

To perform a tsunami simulation, earthquake source is needed. The source models adopted for this study are listed in Table 2.

Different output points of tsunami waveforms are assigned for each region in which one point is placed in Region 4.

The simulation code introduced by Yanagisawa (2018) during the IISEE training class was used for this study. Most of the outputs can be plotted in maps through QGIS. The scenario which has the highest results will be identified as the worst

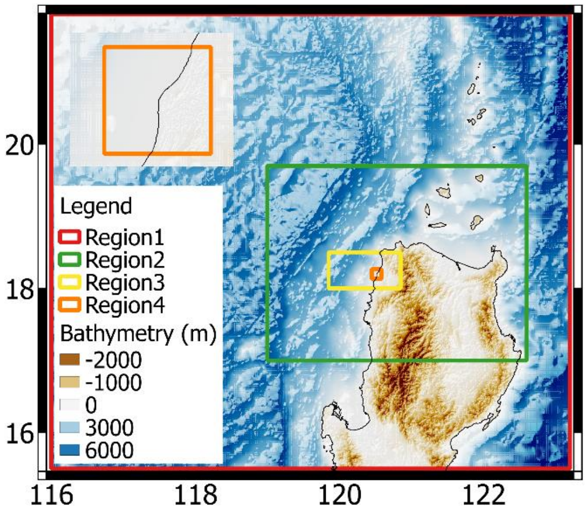

Figure 1. Overview of computational domains.

case scenario and be used for the damage estimation part.

3.2. Tsunami Damage Estimation

The methodology for the damage estimation was adopted from Vera (2015). The maximum inundation depth at each barangay is needed to be obtained from the worst-case scenario. Using the equation (1), the probability of building damage and casualty can be identified per barangay. Multiplying these values to the number of exposed data will lead to an estimated number of building damage and casualties. This methodology will be used for both Methodologies A and B but using a different set of exposed data.

The data set provided by Philippine Statistics Authority (PSA) which is the Census for 2015 will be used for Methodology A. For Methodology B, building points were identified inside the inundated grid data. In the case of the population, data from PSA (2015) was uniformly distributed inside the barangay and only the population inside the inundation area.

Table 2. Earthquake source parameters.

Code	M	Location		Depth (km)	Fault		Slip Amount (m)	Angle (°)		
		Long. (°E)	Lat. (°N)		Length (km)	Width (km)		Strike	Dip	Rake
S1	8.4	119.2	17.75	0	277	91.00	3.72	20	41	79
S2	8.4	119.2	17.75	5	277	91.00	3.72	20	41	79
S3	8.4	119.2	17.75	10	277	91.00	3.72	20	41	79
S4	8.4	119.1	16.06	5	254	91.16	3.69	1	36	95
W1*	8.1	119.36	17.65	40	180	75.08	2.46	22	20	90
N1*	8.3	119.36	17.65	5	250	90.35	3.63	22	20	90
N2*	8.3	119.36	17.65	10	250	90.35	3.63	22	20	90
N3*	8.3	119.36	17.65	20	250	90.35	3.63	22	20	90
N4*	8.3	119.36	17.65	30	250	90.35	3.63	22	20	90

4. RESULTS AND DISCUSSION

4.1. Seafloor Deformation

The seafloor deformations were computed using Manshinha and Smylie (1971) equations which is part of the TUNAMI code by Yanagisawa (2018). The ranges of the results were from 0.77 m to 2.08 m and -0.52 m to -0.19 m for uplift and subsidence, respectively.

Scenario S2 reported the highest uplift value of 2.08 m and subsidence of 0.26 m (Figure 2). The results were affected by large fault geometry and also the focal mechanism of this scenario. While scenario W1 resulted in the lowest uplift of 0.77 m among all the scenarios.

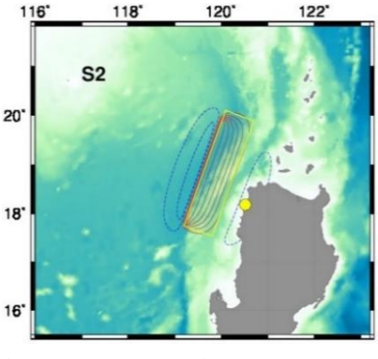

Figure 2. Seafloor deformation map of scenario S2 calculated using the formula of Okada (1985).

4.2. Tsunami Heights

The maximum tsunami height gives us the idea of the possible tsunami inundation that can happen to a certain area. The tsunami caused by scenario S2 can be the result of the larger geometry of the earthquake source. Scenario S4 was also comparable. Since this scenario or the fault area does not directly face the study area, the tsunami height was not as high as scenario S2. Lastly, the tsunami of scenario W1 was relatively low due to the deep depth (40 km) of the source. The maximum tsunami height in Laoag City in each scenario was obtained (Figure 3). The ranges were from 2.31 m (scenario W1) to 4.67 m (scenario S2).

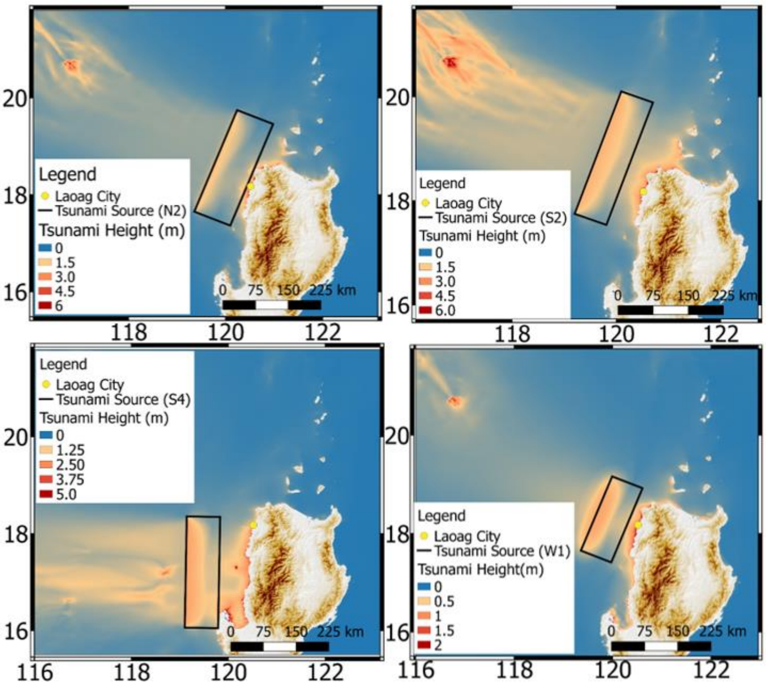

Figure 3. Maximum tsunami height map of scenarios N2 (top left), S2(top right), S4 (bottom left) and W1(bottom right) processed in QGIS.

4.3. Tsunami Propagation and Waveforms

Figure 4 shows the tsunami waveform in the output point of Laoag City which is placed in the smallest regions which have a grid size of 1 arc second from scenario S2. After 20 mins, the Laoag City will experience the arrival of the tsunami (positive amplitude). The arrival times are the key factor for the evacuation planning, giving the community the idea of how much time they need to evacuate and also for the establishment of evacuation shelters.

The shape of the coastline affected the propagations of the tsunami as well as the tsunami heights and inundation in the coastal areas.

The initial negative waves are the effect of the subsidence pattern of the seafloor deformation after the earthquake. It can be identified that there are sharp peaks that can be related to the grid size. Moreover, its location allowed the propagation of tsunami to the area which leads to almost two peaks of 4 m.

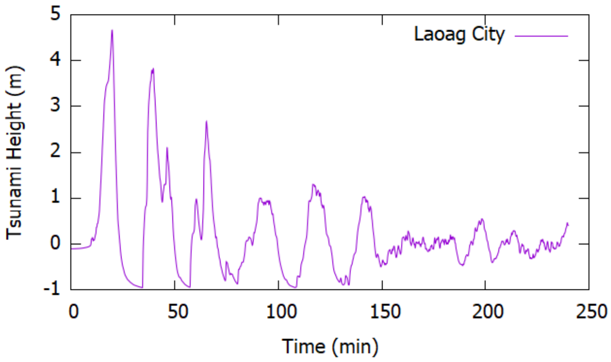

Figure 4. Calculated waveform in Laoag City.

4.4. Tsunami Inundation

The inundation simulation results were only taken in the smallest grid. Figure 5 presents the inundation map of scenarios N2, S2, S4 and W1. The maximum inundation depth was about 6.8 m at scenario S2 while the lowest one was 3.5 m at scenario W1. The scenarios S1-S3 and N1-N4 had the same parameters except for the depth that was varied in each scenario. It could be the reason that the results were almost the same with small differences from each other.

The inundation area should also be taken into consideration in finding the maximum credible scenario from the Manila Trench. Scenario S2 delivered the largest inundation area while W1 delivered the lowest. The inundation area and maximum inundation depth were almost at the coastline of Laoag City. One reason could be the topography of the study area. The land area at the coastline elevated made the inundation area smaller.

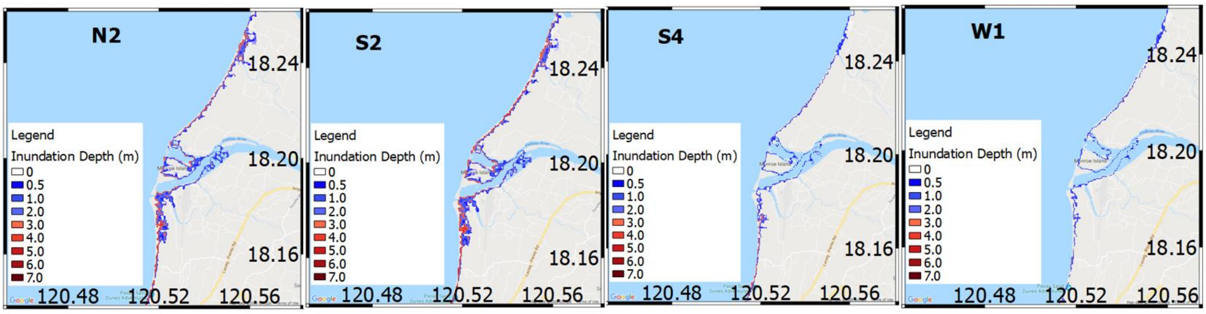

Figure 5. Inundation maps for scenarios N2, S2, S4 and W1.

4.5. Tsunami Damage Estimation

To estimate the potential damage from scenario S2, inundation depth values at each barangay are needed. Exposed data were different for Methodologies A and B. For exposed building, PSA data and identified building points in satellite imageries were used for Methodology A and B, respectively. The damage map for each methodology is presented in Figure 6.

The results using Methodology A produced the higher number. Since this methodology used aggregated data considering the inundated area, the approach may have led to overestimation. Most of the barangays' inundated area lies only on the coast, but the estimation was done for the whole area. In Methodology B, the estimation was done only to the inundated area which led to smaller values. In this approach, the buildings inside the inundation area were taken into consideration for the estimation and can lead to a more accurate estimation.

The maximum inundated depth was obtained at Barangay 37 with 6.7 m while at lowest in Barangay 32-C with 2.5 m due to its location. The estimated number of building damage and casualty results of Methodology A were 3,972 (77%) and 12,800 (59%), respectively. In the case of methodology B, the estimated damage on buildings and casualties were 538 (93%) and 3,144 (70%) respectively.

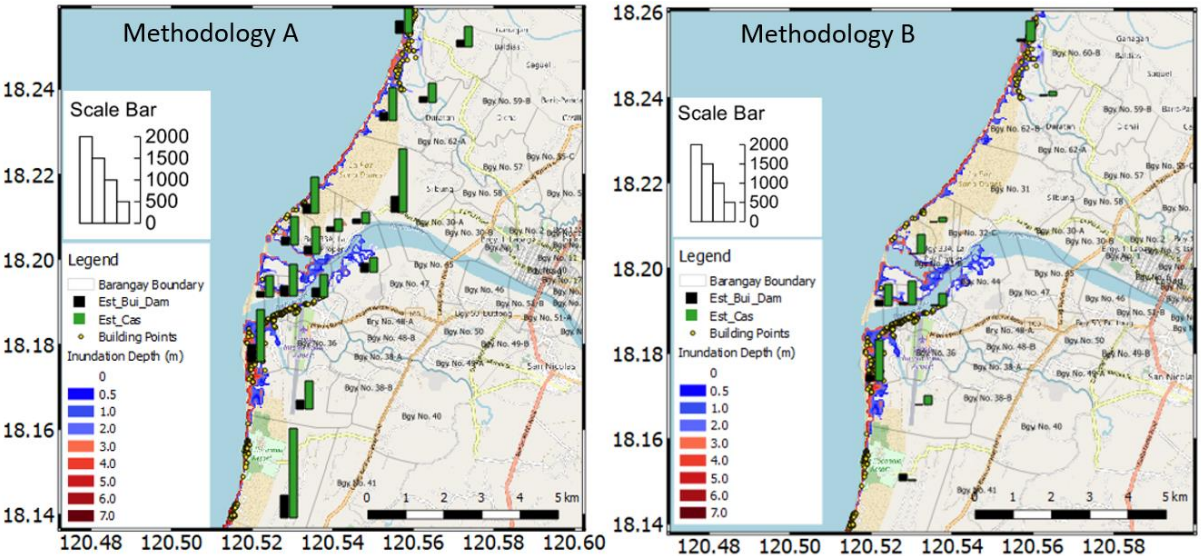

Figure 6. Tsunami Damage Map of Methodology A and B.

The estimation for the number of casualties in this study did not include the perception of the people about an evacuation. If the evacuation is to be considered, the estimation results for casualty will be smaller. Also, knowledge about the signs of a tsunami as well as alerting stations will also be one of the factors to lessen the estimates.

5. CONCLUSIONS

The tsunami hazard was assessed along the coast of Laoag City using single-fault models of the Manila Trench. The results such as the seafloor deformations, tsunami heights, inundation area and depth for each case were considered to produce a maximum credible scenario. In the worst case scenario, the damage was estimated using tsunami fragility functions developed for Banda Aceh in the 2004 Indian Ocean tsunami.

The fault dimension of scenario S2 was 277 km by 91 km, and its focal mechanism leads to the highest maximum uplift of 2.08 m among all the scenarios. Also, this scenario resulted in a maximum tsunami height of 4.67 m and led to a maximum inundation depth of 6.7 m. Since scenario S2 produced the highest values, its inundation map was used for the damage estimation.

The estimation of tsunami damage was done using the fragility functions in two different approaches. The information on satellite imageries and street maps were used as data in a new methodology. The identified number of the exposed building were 581 in which 93% (540) were expected to be damaged by the tsunami. For the exposed population, the data from PSA were distributed to each grid inside a barangay. The total number of the exposed population was 4,474 in which 70% (3,144) was expected to be affected by the tsunami. These findings can only be used as a guide and not as exact values for the disaster planning.

6. RECOMMENDATION

This research has certain limitations in terms of the data used. It is recommended to have accurate information about tsunami propagation and inundation. Finer and high-resolution data for bathymetry and topography should be used for the smallest region. For the exposure data such as building and population, a field survey should be done to have an exact number of these data.

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