# Tsunami Run-Up Assessment Toward Human Lives Around Meuraxa Sub-District, Banda Aceh, Indonesia

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**Abstract.** The 2004 Indian Ocean tsunami caused dreadful damage in the Meuraxa sub-district, Banda Aceh, Indonesia. After a decade, human population and land settlement growing in the tsunami prone area especially in Meuraxa sub-district. The COMCOT model was applied to simulate the tsunami wave. The building shape in simulation area was developed by using the Building Block model from the Open Street Map data. The study is aimed at investigating the impact of 2004 Indian Ocean Tsunami on human lives with the building shape condition in 2017 based on the Open Street Map. The result indicated that Meuraxa sub-district area have hazard ratio with value about 1. The local community, who stay in this prone area, cannot survive from the future of tsunami disaster. The human casualties in this area are able to reach as same number as in the 2004 event without a proper of mitigation program from local government.

**Keywords:** Tsunami, human lives, building block model, and COMCOT.

## 1 Introduction

Flooding due to extreme events such as tsunami and storm surges frequently cause severe impacts toward coastal communities. Tsunami event, such as the 2004 Indian Ocean Tsunami in Banda Aceh city, lead adverse impacts by causing physical damage on constructions, human casualties, and economic losses. Post 2004 tsunami disaster, the damage had left land cover around coastal areas becoming open grounds where houses and facilities destroyed, and also caused in decrease of population. Most of coastal area communities work as fisherman for their primary occupation before tsunami occurred. Few months later, the remaining fisherman coming back to their land and re-starting their live and activities back. Therefore, the human population and economic activities were gradually growing in this area. The growing of population have generated economic improvement and land cover change from pre to post disaster state. More than a decade later the land cover of Banda Aceh coastal areas, especially houses and public facilities, have returned to its initial state as before the tsunami occurred.

The building, which lies around the coastal area, are able to influence the hydrodynamic of tsunami wave by reducing the inundation distance into coastal area. Several studies based on

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numerical modelling showed that the inundation distance decrease due to the existence of local building. However, the building in the coastal area also able to induce swift current on the street. The current of tsunami wave can carry debris of destroyed building or material, car, and human. By the growth of population and land cover especially houses, it able to make the coastal area become more vulnerable toward the extreme event such as the tsunami wave [1]. Therefore, study regarding the tsunami impact on human life due to swift current on the street in the past affected area is expected to be important for evacuation program in order to mitigate the impact.

In recent decades, tsunami numerical simulations have been developed by applying a hydrodynamic model to simulate a tsunami wave, from its generation and propagation until inundation, such as Method of Splitting Tsunami (MOST) [2], Tohoku University's Numerical Analysis Model for Investigation of Near-field tsunamis (TUNAMI-N2) [3], Cornell Multigrid Coupled Tsunami Model (COMCOT) [4][5]. Those models are open-source models which developed based on Shallow Water Equations (SWE). Several benchmark studies for COMCOT model were conducted in previous studies to evaluate the numerical model's validity with analytical solution, laboratory, and field measurements [6][7][8]. The COMCOT model has been used to estimate the inundation area and time of arrival known as Estimate of Inundation Area (EIA) and Estimated Time of Arrival (ETA), which contributes to the mitigation concept of creating a tsunami hazard map and incorporation with a tsunami early warning system [9].

However, the building shape is difficult to reproduce in the area simulation due to the low resolution of topography data. The low resolution of topography data only gives information for ground elevation without providing building elevation. Therefore, the building arrangement method needs to be applied to obtain high resolution result from numerical simulation in urban area. The tsunami waves propagation progress during inundation to urban area can be observed more detail with building condition. There are several methods to treat building condition in the simulation area such as the building block (BB), building hole (BH), building resistance (BR), and building porosity (BP) model. These models have been used to investigate the tsunami inundation distance and impact on urban area. The BR model is generally applied in tsunami simulation by giving the Manning's roughness coefficient on building area based on the land-use type. The BH model have been applied by [10] to investigate tsunami flooding in Kamaishi city due to the 2011 Tohoku earthquake and tsunami. The BP model have been adopted by [11] to evaluate tsunami impact in urban area of Onagawa city, Japan. The BB model have been used by [12] to investigate the inundation distance in Banda Aceh city due to the 2004 Indian Ocean Tsunami. The BB model treat the building by increasing a ground elevation as same as rooftop height for the topography data in the simulation area. These models showed good performance for simulating the tsunami propagation in the urban area.

There are still few studies to re-assessing the tsunami impact on human lives several years after the disaster in affected area. This paper is aimed at investigating the impact of the 2004 Indian Ocean Tsunami on human lives with the building shape condition in 2017 based on the Open Street Map (OSM) data [13]. The BB model was adopted to create the building area on the simulation area. The study was performed to depict the tsunami wave velocity on the street during propagation into the Meuraxa sub-district of Banda Aceh city, Aceh Province, Indonesia. The results of this study are expected to contribute in tsunami evacuation program at rebuild area in order to mitigate the tsunami impact in the future.

## 2 Study Area

Banda Aceh is the capital city of the Aceh Province, Indonesia. Banda Aceh city is one of the cities that receive massive impact due to the 2004 Indian Ocean Tsunami. It is lied near the Sumatran subduction zone which make the city to be vulnerable toward tsunami disaster. The tsunami wave able to inundate the city in range 3-4.5 km from the coastline due to its relatively flat topography. The casualties was reach about 77,000 people in Banda Aceh as one-third of total victims in Indonesia. There are about 8 sub-district in Banda Aceh city including Meuraxa, Kuta Raja, Kuta Alam, Syiah Kuala, etc. Meuraxa is one of sub-district in Banda Aceh that located facing the open sea. The Meuraxa sub-district has chosen as study area due to high population growth after the tsunami event. The population was estimated about 34,000, 2,000, and 20,000 in 2004, 2005, and 2015, respectively. The number of population in 2005 decreased due to the 2004 tsunami wave impact. Several months after tsunami, the remaining people were choosing to return back to their own land where they do not to purchase new lands to live. The population increased around 10 times from 2005 until 2015 due to the lower price of purchase or rent house [14] in this area. The population growth also can be indicated by the land use cover change by the satellite image in the affected area especially Meuraxa sub-district. **Figure 1** shows the land cover change of settlement in 2004, 2005, and 2017. The land use was covered with the building in 2004. The land use in 2005 mostly was turned into a land type because the tsunami wave destroyed the building in 2004. However, the land use of structure was returned to re-dominate the land cover of Meuraxa sub-district after 13 years.

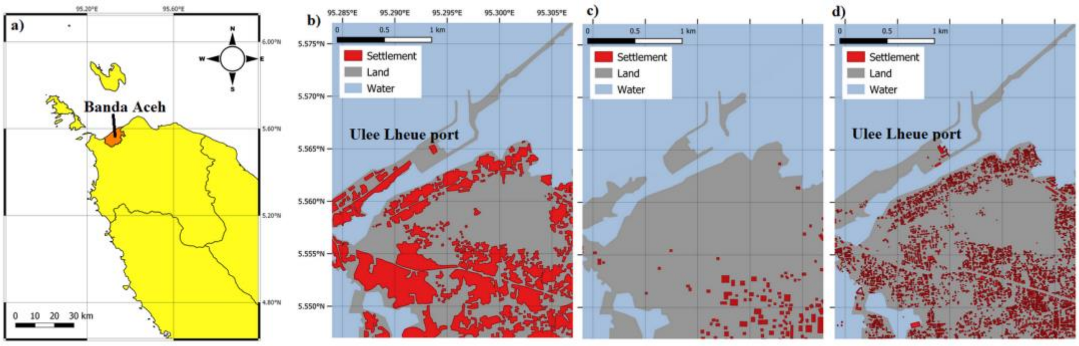

**Fig. 1.** a) Study area and Meuraxa sub-district: b) Before tsunami (2004), c) After tsunami (2005), and d) After tsunami (2017).

## 3 Method and Materials

### 3.1 Hydrodynamic Model

Cornell multi-grid coupled tsunami model (COMCOT) was applied to simulate the tsunami wave propagation process into the urban area at Meuraxa sub-district. COMCOT is an open source model and a tsunami model that capable of simulating tsunami propagation and inundation at coastal areas. This model has been benchmarked with analytical, laboratory, and field measurement data for validation [4] and was used to investigate the 2004 Indian Ocean tsunami [6]. COMCOT can simulate tsunami in specific areas, and parameters can be inputed to configure layers like the shallow water equation (SWE) that was used in this simulation. In this study, the COMCOT model, which consist of two SWEs namely the linear (LSWE) and nonlinear (NLSWE) with a leap-frog explicit finite difference method, was used. For tsunami in deep ocean, tsunami amplitude is much smaller than the water depth and linear shallow water equations in Spherical Coordinates can be applied. It is not a proper method for calculating sea wave hydrodynamics in shallower shore areas (including those areas where tsunamis may propagate). NLSWE is used in shallow conditions to solve convective inertia force and bottom friction terms. The LSWE formulated in COMCOT is as follows (the detail equations can be seen in [5]:

$$\frac{\partial \zeta}{\partial t}+\frac{1}{Rcos\varphi}\left(\frac{\partial P}{\partial \psi}+\frac{\partial}{\partial \psi}(\cos\varphi Q)\right)=0 \tag{1}$$

$$\frac{\partial P}{\partial t}+\frac{gh}{Rcos\varphi}\frac{\partial \zeta}{\partial \psi}-fQ=0 \tag{2}$$

$$\frac{\partial Q}{\partial t}+\frac{gh}{R}\frac{\partial \zeta}{\partial \psi}+fP=0 \tag{3}$$

where $\zeta$ is free surface elevation; $R$ is radius of earth; $\varphi$ and $\psi$ are latitude and longitude of the earth; $P$ and $Q$ are volume fluxes in West-East and South-North direction; $g$ is the gravitational acceleration; $h$ is still water depth; and $f$ represents the Coriolis force coefficient.

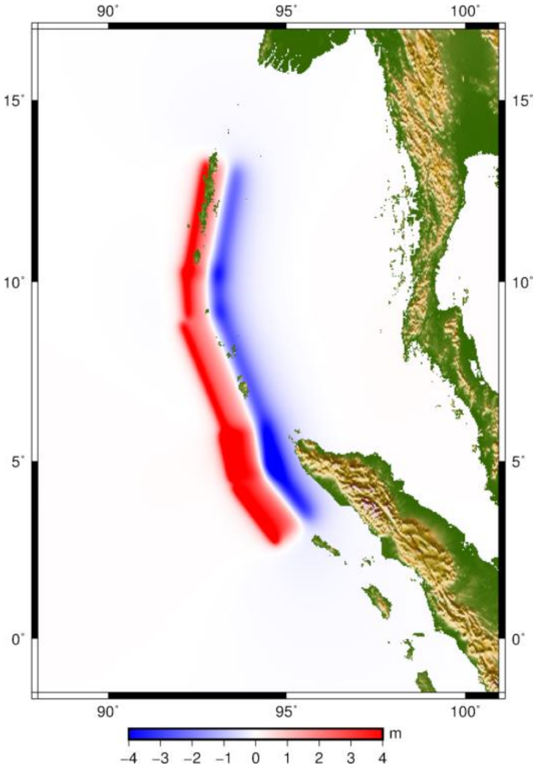

**Fig. 2.** The initial condition (water surface elevation) for the 2004 Indian ocean earthquake.

### 3.2 Initial Condition

A multi-fault model was proposed by several researchers to represent the 2004 Indian Ocean earthquake due to its complexity. The earthquake's rupture area extended approximately 1200 km from the epicenter, in western Aceh Province, to the Andaman Islands. The fault parameters published by [15] were applied in this study to generate the bottom deformation as an initial condition to generate the tsunami wave, as shown in **Figure 2**. The source was divided into five segments with a total seismic moment equivalent to Mw = 9.22. The fault parameters were validated by comparing the simulation results to satellite transect, tide gauge, and run-up height measurements near the Banda Aceh coast. The bottom deformation was generated using the deformation model proposed according to [16]. The COMCOT model assumed that the sea surface changes instantaneously followed the deformation of the sea bed as the initial condition for the tsunami wave in 2004. This is the same model that was used to investigate the morphological changes to the Khao Lak coast in Thailand during the 2004 tsunami [17].

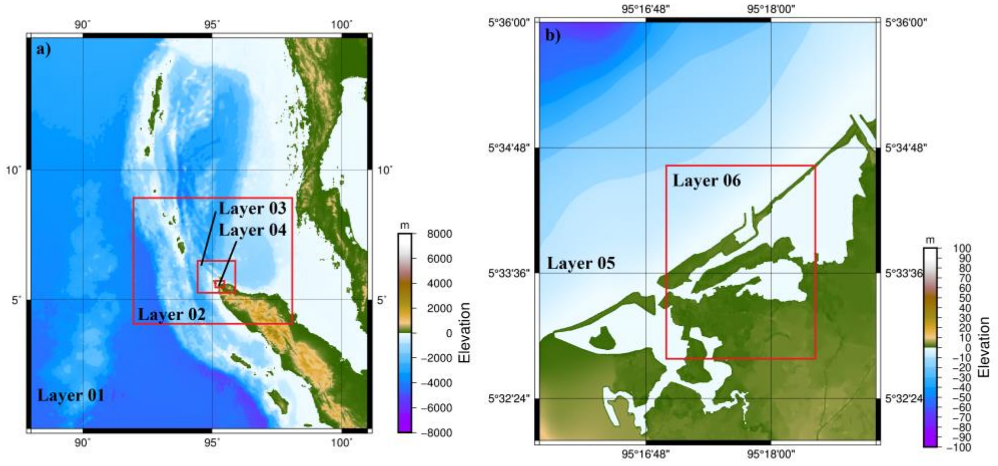

**Fig. 3.** Nested grids for the COMCOT simulation domain showing a) Layers 01-04 and b) Layers 05-06.

### 3.3 Grid Setup and Input Data

The multi later system in COMCOT model was adopted to obtain accurate and detailed hydrodynamic process in the urban area. The tsunami velocity and height can be observed more detail based on high-resolution data. Six nested grid layers were used to simulate the tsunami wave from the 2004 source to the Meuraxa as shown in **Figure 3**. The input parameters implemented on each layers such as grid size, extent area, and SWE type can be seen in **Table 1**. General Bathymetric Chart of the Ocean (GEBCO) data [18] were adopted for bathymetry and topography data in layers 1-4. The GEBCO data are open source for general bathymetry and topography data with resolution about 0.5 arcminute. The Generic Mapping Tools (GMT) [19] were applied to interpolate the GEBCO data for layers 2-4 due to implementing a smaller grid size than the GEBCO data. The bathymetry and topography for layers 5-6 were developed with nautical chart data measured by Dishidros of TNI AL Indonesian with scale about 1:100,000 in 2001. The Quantum GIS (QGIS) [20] software were used to digitizing the nautical chart data. The GEBCO and nautical chart data were combined by applying Quickin and Refgrid software in Delft3D open source [21]. The manning values for water and land were specified with value about 0.013 and 0.025 on layers 1-6. The tsunami wave was prevented to overtop the building in the simulation area. The building in the simulation area were assumed have elevation that higher than the tsunami inundation depth. Hence, the manning roughness value for the settlement cover were assumed similar with the land cover.

**Table 1.** Information on the setup of the six layers for simulation.

| | Layer 01 | Layer 02 | Layer 03 | Layer 04 | Layer 05 | Layer 06 |
|---|---|---|---|---|---|---|
| Number of grids | 974 X 1124 | 898 X 748 | 745 X 740 | 930 X 935 | 1044 X 1744 | 1412 X 1764 |
| Lati. (degree) | 88-101 | 92-98 | 94.7-95.7 | 95.2-95.4 | 95.3-95.33 | 95.28-95.31 |
| Longi. (degree) | 0-15 | 4-9 | 5.3-6.2 | 5.5-5.75 | 5.53-5.65 | 5.55-5.58 |
| Grid size (m) | 1480.8 | 740.4 | 148.08 | 29.616 | 7.404 | 1.851 |
| Grid size ratio | - | 2 | 5 | 5 | 4 | 4 |
| Coordinate system | Spherical | Spherical | Spherical | Spherical | Spherical | Cartesian |
| SWE | Linear | Linear | Linear | Linear | Linear | Non-linear |

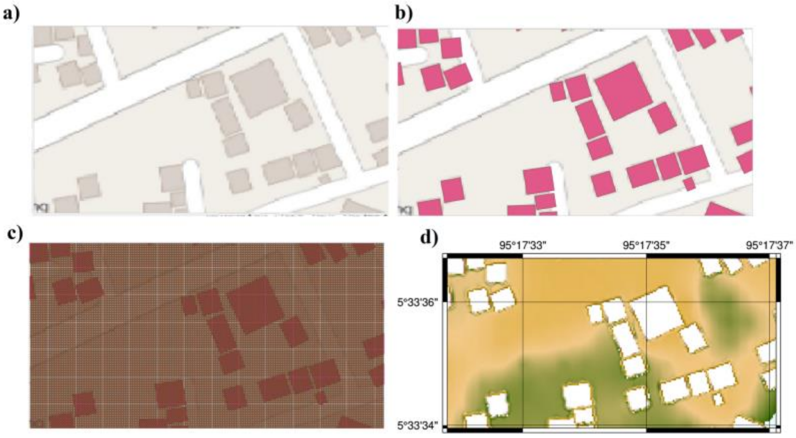

**Fig. 4.** Buildings locations in Meuraxa sub-district of Banda Aceh city. a) OSM data, b) Extracted building shape from OSM data as polygon, c) Divided topography data inside the polygon, and d) Topography data with building shape on the simulation area.

### 3.4 Building Treatments

The low resolution topography data, which developed based on the GEBCO data and nautical chart data, was used for Layer 06 as the innermost layer. The building shape and height information did not available from this data. Therefore, the BB model was applied to updating the topography data with the building condition. The building parameters such as shape and location was obtained from the Open Street Map (OSM) data. **Figure 4** is show a method that applied to create the building block in the simulation area with structured meshes.

QGIS software was applied to obtain the OSM data. **Figure 4a** show the building shape and location on the Meuraxa sub-district area from the OSM data. The shape of building was extracted as the polygon in QGIS. The topography data, which located inside the polygon, was updated with elevation about 10 m. The topography data inside the polygon was assumed as building in the simulation area. The building was assumed have an elevation higher than the tsunami wave height and cannot destroyed by the tsunami wave in order to observe the tsunami velocity on the narrow street between each building. **Figure 4d** indicated that the structured meshes is capable to create the building shape similar with the OSM data in the simulation area.

### 3.5 Flood Impact Assessment on Lives

The tsunami flood able to give massive impact toward human lives in the urban area. The hydrodynamic force from the tsunami wave can produce a number of fatalities by sweeping away the residents far inland. The flood impact toward human lives can be calculated quantitatively based on the relationship between tsunami height and velocity. The human instability can be calculated by several formulas such as empirical and semi-analytical. The human instability is determined based on the relationship between the critical velocity and water depth. The equation based on weight and height of person is popular to calculating the human instability. The equation that proposed by [22] was adopted to calculate the human instability due to hydrodynamic force as follow:

$$DUc = 0.004HM + 0.2 \tag{4}$$

where $D$ is water depth (m). $Uc$ is critical velocity (m/s). $H$ and $M$ are height (m) and weight (kg) of person, respectively. The human instability is shown based on a critical velocity. That means the human able to stand from the tsunami wave when its velocity lower than the critical velocity. The values of critical velocity are varies depend on the inundation depth. The critical velocity will be lower if the inundation become higher.

The hazard ration (HR) can be calculated based on a comparison the critical velocity and the tsunami wave velocity. The critical velocity was obtained from the human instability formula. The tsunami wave velocity (Us) was simulated by the COMCOT model. The estimation of hazard ratio proposed by [23] was adopted with the equation as follow:

$$HR = \min\left(1, \frac{Us}{Uc}\right) \tag{5}$$

The maximum of HR was set with value about 1. The value show that the tsunami wave height exceeded the height of human body. The Statistic Bureau of Japan data that applied by [24] to calculate the human instability was adopted with value about 1.51 m and 52 kg for height and weight of an elderly, respectively.

# 4 Results and Discussion

## 4.1 Tsunami Wave Inundation Induced Current on the Street

**Figure 5** shows the tsunami wave propagation process and velocity during inundated toward the urban area. The tsunami wave arrived at the one of escape route in Meuraxa and propagated through the escape route after 44 minutes as shown in **Figure 5a**. The tsunami wave velocity and height reached more than 4 m/s and 4 m on the escape route, respectively. The urban area able to induce the higher velocity on the escape route due to the building closeness. After 50 minutes, the tsunami height and velocity were decreased. That can be happened because the existent of building able to reduce the tsunami wave force. The building able to reduce the hydrodynamic forces in the urban area [25]. Therefore after 54 minutes propagate far inland, the tsunami wave velocity decreased with value around 0.5 m/s.

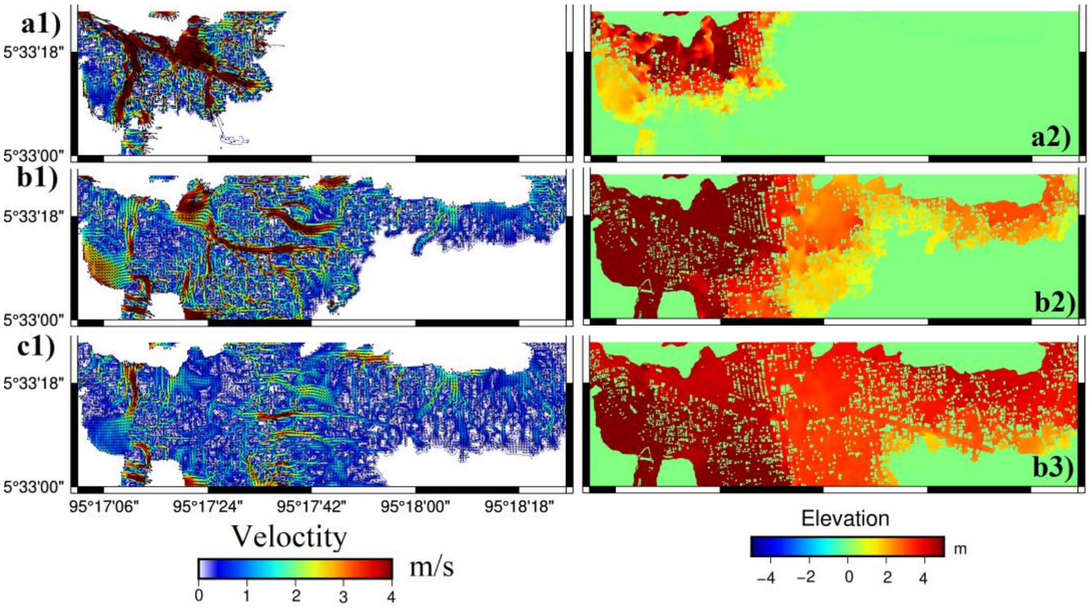

**Fig. 5.** Snapshots of tsunami propagation process at: a) t=44 mins, b) t=50 mins, and c) t=54 mins. The left side indicates tsunami wave velocity. The right side shows the tsunami wave height. The escape route is indicated by a purple polygon.

## 4.2 Evaluation of Tsunami Flood Toward Human Lives

**Figure 6** is show the HR results between the critical velocity and the tsunami wave velocity based on the Karvonen formula. The HR value is about 1 for the entire of simulation area. The critical velocity was calculated based on the elderly condition. Therefore, the Meuraxa sub-district have the maximum of the high risk for the tsunami wave impact toward not only for the elderly but also for children on this area. The people on this area will not be able to survive when the tsunami inundated into this area. The flood will be easily to wash out the local community due to the tsunami wave velocity was much higher than the critical velocity. Although the tsunami velocity reduce around 0.5 m/s far inland after about 54 minutes as shown in **Figure 5c1**, the tsunami wave height exceed the human height with value about 2 m as depicted in **Figure 5c2**.

The HR results also indicated that the number of casualties will be similar with the past tsunami event in 2004 for this area. The risk toward human lives could become higher due to the cycle of the big earthquake occurrence with interval around 150-200 years and the population growth in the tsunami prone area especially the Meuaraxa sub-district. Several studies indicated that the tsunami wave height and the affected area will be increased due to the climate change that cause sea level rise in Banda Aceh city [26]. Therefore, a proper of evacuation program is needed in this area to mitigate the tsunami impact in the future.

### 4.3 Arrival Time

Despite the HR results is more than 1 for entire simulation area that indicated the human will be fall due to the tsunami wave, the arrival time results revealed that the local community still have a time about 40 minutes before the tsunami wave arrived at the coastal area. That can be seen in **Figure 7**. The local community able to escape to an escape building or designed place for escape when tsunami coming. The local comunity on other areas which have the arrival time more than 48 minutes and located far from the coastal area can be escape to the higher or unaffected area by the tsunami wave. This findings could be useful for local authorities and decision makers to develop more appropriate escape route zone and program such as enhancing the local community knowledge to mitigate the tsunami wave impact toward the human lives. However, the settlement area in this area have big probability to destroy again by the tsunami wave as shown in **Figure 1c** due to a height intensity of the hydrodynamic force. There are unavailable any structure to protect the coastal area from the tsunami disaster even the local government allow the local community for return to the affected area.

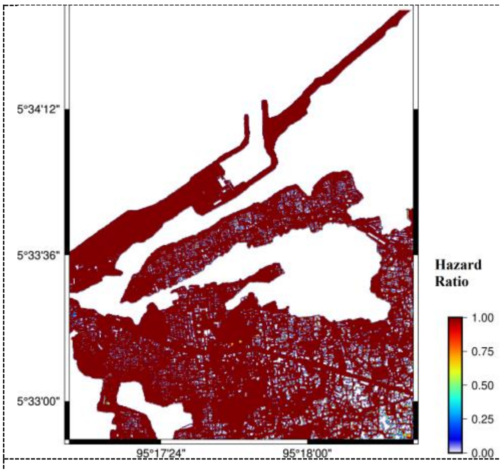

**Fig. 6.** HR result.

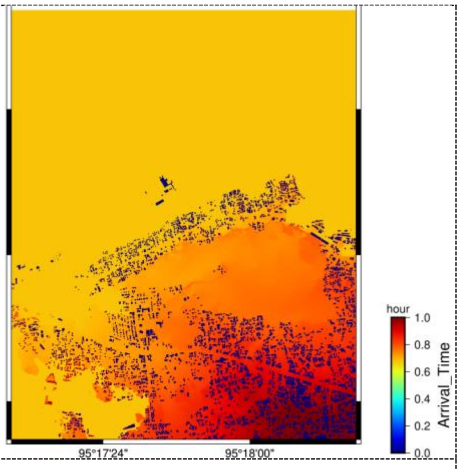

**Fig. 7.** Tsunami arrival time.

# 5 Conclusion

This study was conducted to assess the tsunami wave impact on human lives in the Meuraxa sub-district of Banda Aceh city. The COMCOT model was used to simulate the tsunami wave. The Building Block model was adopted to create the building shape on the simulation area. The OSM data was applied to obtain the building shape location in the simulation area. The main results obtained by this study is in the Meuraxa sub-district have the HR value about 1 for the entire simulation area. That indicated the local community, who stay in this area will not be able to survive if the tsunami wave hit this area. The tsunami wave velocity, which calculated as the critical velocity, was much higher compare with the human capability to stand from the flood. On the other hand, the tsunami wave will be arrived around 40 minutes to the coastal area. It gives enough time for the local community to escape from the tsunami wave. This finding could be useful for the local government to enhance the escape program in the affected area to mitigate tsunami wave impact in the future due to the population growth in the tsunami prone area.

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