Vertical evacuation planning to reduce a risk of a tsunami disaster in teluk segara district, bengkulu city

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Abstract. Bengkulu Province is classified as a province that is very prone to earthquakes and tsunamis. In order to minimize the impact of the tsunami hazard, preparedness to mitigate the tsunami hazard is needed. One of the ways is by providing information about the optimal evacuation route, assembly points and evacuation shelter buildings (ESB) and ESB capacity. The purpose of this study is to obtain an optimal evacuation route model to minimize the impact of the tsunami hazard in Teluk Segara District, Bengkulu City. The determination of the minimum evacuation route using the Floyd Warshall algorithm based on the minimum time of evacuation. In determining the minimum evacuation time, several factors are considered i.e. road width, road density, road capacity, walking speed of evacuees and group walking speed. This research produces the horizontal and vertical tsunami evacuation routes equipped with ESB capacities.

1. Introduction
Bengkulu Province is located on the west coast of Sumatra Island with Bengkulu as the capital. The location of Bengkulu Province between the junction of two very active plates in the world, namely the Eurasian Continent plate and the Indo-Australian Ocean plate along the west coast of Sumatra. This is why Bengkulu Province is classified as a province that is very prone to earthquakes and tsunamis. Bengkulu Province has experienced several earthquakes with the potential for a tsunami, including earthquakes in 1811 and 1833 with a magnitude of 8.8 on the Richter scale [1]. In the decade 2000-2010, there have been twice a large magnitude earthquake and potential for a tsunami, on June 4th, 2000 with a magnitude of 7.3 Mw and on September 12th, 2007 with a magnitude of 7.9 Mw [2]. From this data it can be concluded that Bengkulu is very vulnerable to tsunami hazards so that it is one reason that tsunami hazard mitigation readiness is urgently needed.

In evacuating the tsunami hazard, there are two methods that can be done i.e. horizontal evacuation and vertical evacuation. Horizontal evacuation, moving residents to a safe place based on the distance or higher areas such as hills although vertical evacuation, evacuating people to the nearest taller building which is safe from the tsunami, known as the Evacuation Shelter Building (ESB) [3], [4].

Research on evacuation planning in Bengkulu City has produced a horizontal evacuation route model in some coastal areas of Bengkulu City [5]. Based on the results of this study, there are several locations that require a long evacuation time to reach predetermined assembly points. In the coastal area of Bengkulu, especially Teluk Segara District, there are 5 clusters of 48 clusters that take more than 15 minutes to the assembly point where 15 minutes is the time available after the tsunami early warning set by the government to arrive at a safe place [5]. Some of these clusters are located in Sumur Melele and Kampung Kelawi Subdistrict in Teluk Segara District, where Sumur Melele is included in the high risk
category tsunami hazard, densely populate and directly adjacent to the Indian Ocean [6]. Therefore, a vertical evacuation location that can be reached in a shorter time is needed.

In this study, a vertical evacuation plan was made to complement the horizontal evacuation in [5] by providing information about ESB and its capacity to accommodate the surrounding community in facing the tsunami hazard in Teluk Segara District, where Teluk Segara is a district in the city of Bengkulu which is prone to tsunami disaster [7].

2. Basic Theory
2.1. Floyd Warshall algorithm
One algorithm that is quite popular for finding the shortest path is the Floyd Warshall algorithm. This algorithm is quite popular because the level of accuracy always shows a value of 100%, but this algorithm is quite complicated because the number of iterations that must be done depends on the number of points on the path, so the use of this algorithm for a large number of points must be accompanied by the help of computer programming [8]. This algorithm calculates the smallest weight of all paths connecting a pair of points and does it all at once for all point-by-point pairs until it reaches the destination point with the minimum number of weights [9]. The steps in the Floyd Warshall algorithm can be seen in [5].

2.2. Tsunami evacuation methods
In evacuation, the important principle is to ensure the safety of the people when moving from a dangerous place to a safe place [10]. In essence, the main strategy in evacuation is to save. There are two methods of evacuating from a dangerous tsunami zone to a safe place, namely: horizontal evacuation and vertical evacuation [3], [4]. Horizontal evacuation is carried out if the time available between tsunami early warning and arrival is sufficient for the community to evacuate to higher ground. In addition, the topography of the area where there are many hills also allows for horizontal evacuation. In coastal area, as an alternative to horizontal evacuation, we need vertical evacuation. This is because usually the population and building density are high and limited available evacuation time in coastal area [4], [10]. In vertical evacuation against tsunami hazards, people are directed to the nearest evacuation building in their vicinity by walking or running through a network of roads, pedestrian paths, or passages within the limited evacuation time. One alternative that can be used as a vertical evacuation location is the Evacuation Shelter Building (ESB), the building as a destination for people to save from tsunami in vertical evacuation.

In planning and determining the ESB, the most important thing to pay attention is that the building must be earthquake resistant and have the floor that is higher than the tsunami inundation level. The ESB should be located within accessible distance to the community and along a road that is accessible to the community. ESB must have the following conditions [4]:
1. The structure of the building must be earthquake and tsunami resistant because this building is expected to last until after the tsunami.
2. The building usually a multi-storey, so that the height of the floor building is higher than the height of the wave.
3. Design function, because the tsunami period is quite long, there is no building that functions only as an ESB in order to save space and costs.
4. The building must be large enough to accommodate many people.
5. Horizontal access, the buildings should be located in such a place that all refugees can reach it within the time available.
6. Vertical access, the buildings must have adequate vertical access such as stairs or inclines.

2.3. Building capacity
The ESB capacity can be calculated based on the following calculations and table [4], [11]:

$$ESBC = (CS \times BA \times NrF)/SpP$$

(1)
Information:

\( \text{ESBC} \): Capacity of evacuation shelter building (number of person)

\( \text{CS} \): Score capacity (%)

\( \text{BA} \): Area of building (m\(^2\))

\( N_{fF} \): Number of floor

\( S_{pP} \): Spaces needed for one person (m\(^2\))

**Table 1.** The capacity of evacuation shelter building types

| Building type          | Capacity of Evacuation Shelter Building |
|------------------------|----------------------------------------|
| Mosque/worship         | 78% * BA/ 1m\(^2\)                     |
| School                 | 30% * BA/ 1m\(^2\)                     |
| Office                 | 23.6% * BA/ 1m\(^2\)                   |
| Market building/mall   | 23% * BA/ 1m\(^2\)                     |
| Hotel                  | 26.3% * BA/ 1m\(^2\)                   |
| Hall/gallery            | 100% * BA/ 1m\(^2\)                    |

Source:[4], [11]

2.4. Tsunami Early Warning System-TEWS

Tsunami Early Warning System (TEWS) is a system for detecting tsunamis and announcing warnings to prevent loss of life and property [10]. TEWS has been developed by the Indonesian government with assistance from donor countries [6]. TEWS in Indonesia is known as InaTEWS which is directly controlled by the Meteorology, Climatology and Geophysics Agency (BMKG) in Jakarta. Using this InaTEWS, BMKG can send a tsunami warning in case of an earthquake that has the potential to cause a tsunami. This tsunami warning system only provides a short time for residents to search for and reach the evacuation site.

2.5. Evacuation time

Evacuation time is defined as the remaining time it takes for refugees to evacuate from the time BMKG officially announces a tsunami early warning until the tsunami waves arrive at the coastline [12]. The more refugees who can reach a safe place during this evacuation time, the more people who can be saved from the tsunami disaster. Based on various study documents, as well as the ability of the tsunami early warning system, the average response time of the community to carry out an evacuation is 7 minutes after an earthquake occurs [4], [10]. In this study, the calculation of evacuation time is influenced by several factors including: road width, road density, number of pedestrians in groups and the walking speed of refugees. Determination of the walking speed of refugees based on the Institute of Fire Safety & Disaster Preparedness (1987) after Sugimoto et al, (2003) in [10] uses the following formula:

\[
V = (C_0/C_1) \times V_s \tag{2}
\]

\[
C_0 = W/S \text{ (round-in value)} \tag{3}
\]

\[
C_1 = W/S \text{ (round-up value)} \tag{4}
\]

Information:

\( C_0 \) : The road base capacity

\( C_1 \) : The road actual capacity during disaster

\( V \) : Walking actual speed during disaster \((m/sec)\)

\( V_s \) : Walking speed a group of elderly person during disaster \((0.751 \ m/sec)\)

\( W \) : The road width \((m)\)

\( S \) : Person space requirement \((0,625 \ m^2)\)
3. Results and discussion

3.1. Road network graph

In this study, there are 48 clusters (cluster 1, 2, ..., 48) and 3 assembly points (A, B, C), data of road networks and horizontal evacuation routes with equipped with travel time were obtained from [5] as shown in the following figure.

![Road network graph](image)

**Figure 1.** Horizontal evacuation route

Source [5]

From each cluster to the assembly point, the travel time is calculated using the Floyd Warshall algorithm. The following table shows the travel time in Figure 1.

|    | Assembly Point | Travel time (min) |    | Assembly Point | Travel time (min) |    | Assembly Point | Travel time (min) |    | Assembly Point | Travel time (min) |
|----|----------------|-------------------|----|----------------|-------------------|----|----------------|-------------------|----|----------------|-------------------|
| 1  | A              | 3.44              | 13 | A              | 10.10             | 25 | B              | 5.23              | 37 | B              | 3.58              |
| 2  | A              | 2.73              | 14 | A              | 12.63             | 26 | B              | 7.79              | 38 | B              | 0.99              |
| 3  | A              | 5.69              | 15 | A              | 14.93             | 27 | B              | 4.47              | 39 | B              | 6.47              |
| 4  | A              | 6.01              | 16 | B              | 16.15             | 28 | B              | 2.90              | 40 | B              | 9.56              |
| 5  | A              | 7.18              | 17 | A              | 15.64             | 29 | B              | 4.23              | 41 | B              | 10.74             |
| 6  | A              | 12.15             | 18 | B              | 17.01             | 30 | B              | 6.95              | 42 | B              | 13.86             |
| 7  | A              | 12.62             | 19 | B              | 14.87             | 31 | B              | 3.42              | 43 | C              | 6.63              |
| 8  | A              | 12.6              | 20 | B              | 15.71             | 32 | B              | 3.56              | 44 | C              | 4.76              |
| 9  | A              | 7.80              | 21 | B              | 14.17             | 33 | B              | 6.10              | 45 | C              | 7.16              |
| 10 | A              | 11.36             | 22 | B              | 6.22              | 34 | B              | 5.30              | 46 | B              | 6.86              |
| 11 | A              | 12.43             | 23 | B              | 5.96              | 35 | B              | 3.85              | 47 | B              | 5.80              |
| 12 | A              | 17.04             | 24 | B              | 4.99              | 36 | B              | 0.53              | 48 | B              | 8.34              |

Information:

C : Cluster

3.2. Horizontal evacuation route analysis
Bengkulu Province has the potential for a tsunami event with a maximum height of 8m with a tsunami arrival time of 20 minutes [12]. Assuming that the community response to carry out an evacuation is 7 minutes after the earthquake occurred [4], [10], this means that the community only has 13 minutes to evacuate to a safe place. Based on Table 2, it can be seen that there are 9 clusters that require an evacuation time of more than 13 minutes to reach an assembly point so that an alternative assembly place is needed for these nine clusters in order to reach a safe place in less than 13 minutes. The clusters are 12, 15, 16, 17, 18, 19, 20, 21 and 42. 

3.3. Determination and analysis of buildings and buildings location that can be used as ESB and their capacities.

Determination and analysis of buildings and buildings location that can be used as ESB and ESB location and their capacities are carried out based on data of multi-storey buildings in the study area. Based on a survey conducted in the area around the 9 clusters (clusters 12, 15, 16, 17, 18, 19, 20, 21 and 42), there are several storey buildings located around the 9 clusters, but by considering the building requirements that can be used as ESB based on [4], one of the buildings that can be used as an ESB is the SMPN 3 building in Bengkulu City.

The SMPN 3 building is a two-floors school building which area of a floor approximately ±950m². This building looks strong and located on the main road making it easier for horizontal access, and there are stairs that can be used to get to the 2nd floor so vertical access is very easy to do. Based on Table 1, the scoring capacity of the school building is 30% and according to [3], to accommodate 1 person it takes an area of 1m², then using equation 2 can be calculated the capacity of the SMPN 3 building is \( \frac{0.3 \times 950m^2 \times (2-1)}{1m^2} \) = 285. This means that the capacity of the SMPN 3 building is 285 people. However, assuming full capacity and to accommodate 1 person, an area of 1m² is required, then the capacity of the SMPN 3 building can accommodate \( \frac{950m^2}{1m^2/\text{orang}} = 950 \) people.

3.4. Designing a road network graph model and vertical evacuation route in the research area

Analysis and study of road networks, assembly points and ESB are modeled using graph theory. The road network graph and horizontal evacuation route obtained from [5], with the addition the ESB that have been determined as a vertex and road network infrastructure as edges, are made into a new road network graph. Between the adjacent vertices is weighted with the travel time. In calculating the travel time from each cluster to ESB, several factors which are taken into consideration include: road width, road density, number of pedestrians in groups and the walking speed of refugees which are applied to equations (2), (3) and (4). The determination of evacuation routes from 9 clusters to ESB (denoted as S1) uses the Floyd Warshall algorithm. The travel time and evacuation routes from 9 clusters to ESB are as shown in the following table.

| No | C | ESB | Distance (m) | Travel time (min) | Evacuation route |
|----|---|-----|-------------|------------------|-----------------|
| 1  | 12| S1  | 415,37      | 10,75            | 12 → 15 → 19 → 16 → S1 |
| 2  | 15| S1  | 215,58      | 5,58             | 15 → 19 → 16 → S1 |
| 3  | 16| S1  | 40,42       | 1,05             | 16 → S1         |
| 4  | 17| S1  | 230,90      | 5,98             | 17 → 18 → S1    |
| 5  | 18| S1  | 113,47      | 2,94             | 18 → S1         |
| 6  | 19| S1  | 166,21      | 4,30             | 19 → 16 → S1    |
| 7  | 20| S1  | 252,37      | 6,53             | 20 → 16 → S1    |
| 8  | 21| S1  | 431,54      | 11,17            | 21 → 20 → 16 → S1 |
| 9  | 42| S1  | 541,47      | 12,87            | 42 → 17 → 18 → S1 |
The following figure shows the clusters, the assembly points and ESB in research area.

![Figure 2. Clusters, assembly points and ESB in research area](image)

The horizontal and vertical evacuation route models in Teluk Segara District, Bengkulu City are equipped with the required minimum evacuation time as shown in the following table.

| No | C | AP/ESB | Travel time (min) | Evacuation route   |
|----|---|--------|-------------------|--------------------|
| 1  | 1 | A      | 3.44              | 1 → A             |
| 2  | 2 | A      | 2.73              | 2 → A             |
| 3  | 3 | A      | 5.69              | 3 → 2 → A         |
| 4  | 4 | A      | 6.01              | 4 → 3 → 2 → A     |
| 5  | 5 | A      | 7.18              | 5 → 3 → 2 → A     |
| 6  | 6 | A      | 12.15             | 6 → 1 → A         |
| 7  | 7 | A      | 12.62             | 7 → 10 → 6 → 1 → A |
| 8  | 8 | A      | 12.60             | 8 → 6 → 1 → A     |
| 9  | 9 | A      | 7.80              | 9 → 2 → A         |
| 10 | 10| A      | 11.36             | 10 → 6 → 1 → A    |
| 11 | 11| A      | 12.43             | 11 → 5 → 3 → 2 → A|
| 12 | 12| S1     | 10.75             | 12 → 15 → 19 → 16 → S1 |
| 13 | 13| A      | 10.10             | 13 → 9 → 2 → A    |
| Source | Number | Type | Distance | Route |
|--------|--------|------|----------|--------|
| 14     | 14     | A    | 12.63    | 14→13→9→2→A |
| 15     | 15     | S1   | 5.58     | 15→19→16→S1 |
| 16     | 16     | S1   | 1.05     | 16→S1 |
| 17     | 17     | S1   | 5.98     | 17→18→S1 |
| 18     | 18     | S1   | 2.94     | 18→S1 |
| 19     | 19     | S1   | 4.30     | 19→16→S1 |
| 20     | 20     | S1   | 6.53     | 20→16→S1 |
| 21     | 21     | S1   | 11.17    | 21→20→16→S1 |
| 22     | 22     | B    | 6.22     | 22→24→32→B |
| 23     | 23     | B    | 5.96     | 23→29→28→B |
| 24     | 24     | B    | 4.99     | 24→32→B |
| 25     | 25     | B    | 5.23     | 25→28→B |
| 26     | 26     | B    | 7.79     | 26→25→28→B |
| 27     | 27     | B    | 4.47     | 27→28→B |
| 28     | 28     | B    | 2.90     | 28→B |
| 29     | 29     | B    | 4.23     | 29→28→B |
| 30     | 30     | B    | 6.95     | 30→37→38→B |
| 31     | 31     | B    | 3.42     | 31→36→B |
| 32     | 32     | B    | 3.56     | 32→B |
| 33     | 33     | B    | 6.10     | 33→35→36→B |
| 34     | 34     | B    | 5.30     | 34→32→B |
| 35     | 35     | B    | 3.85     | 35→36→B |
| 36     | 36     | B    | 0.53     | 36→B |
| 37     | 37     | B    | 3.58     | 37→38→B |
| 38     | 38     | B    | 0.99     | 38→B |
| 39     | 39     | B    | 6.47     | 39→31→36→B |
| 40     | 40     | B    | 9.56     | 40→34→32→B |
| 41     | 41     | B    | 10.74    | 41→34→32→B |
| 42     | 42     | S1   | 12.87    | 42→17→18→S1 |
| 43     | 43     | C    | 6.63     | 43→44→C |
| 44     | 44     | C    | 4.76     | 44→C |
| 45     | 45     | C    | 7.16     | 45→44→C |
| 46     | 46     | B    | 6.86     | 46→47→33→35→36→B |
| 47     | 47     | B    | 5.80     | 47→33→35→36→B |
| 48     | 48     | B    | 8.34     | 48→39→31→36→B |

Information:
- **C**: Cluster
- **AP**: Assembly point

According to Table 4, the horizontal and vertical evacuation route models in Teluk Segara District, Bengkulu City can be seen in Figure 3.
Figure 3. The horizontal and vertical evacuation route models in Teluk Segara District, Bengkulu City

4. Conclusion
The evacuation route resulting from this study is an evaluation of the evacuation route in [5]. In [5] obtained a horizontal evacuation route, where there are clusters that require an evacuation time of more than 13 minutes. This time of 13 minutes is assumed to be based on the time of arrival of the tsunami after deducting the average response time of the community to carry out an evacuation is 7 minutes after the earthquake occurred. The vertical and horizontal evacuation routes produced in this study indicate that no cluster takes more than 13 minutes to reach the assembly point or ESB.

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