ON-FOOT EVACUATION MODEL USING VIRTUAL TESSELLATIONS NETWORK:
A proposed method for tsunami evacuation planning

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仮想テセレーションネットワークを用いた徒歩避難モデル
津波避難計画のための提案方法

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This study aims to analyze the tsunami disaster evacuation model using the current existing method, which uses only existing road, and compared with the proposed method using three types of tessellation as virtual network. The research is using Network Analysis solver within ArcGIS environment to compare 4 types of network distance with the real-world path as the standard. The result of this study has shown that the use of tessellation as a hexagon tessellation as a virtual network can help justify the real situation in the evacuation process much more precise rather than using the current existing method (standard method).

1. INTRODUCTION

Currently, most planners propose existing road network as the evacuation path/route to reach the designated temporary evacuation shelter (TES), but this standard method has their limitations in predicting other possible routes such as bare land, park and other available paths which are not identified as the road network. The aim of this research is to measure 4 different methods which are the current existing methods (standard method) which only use existing road network, the 3 types of tessellations as virtual network methods and finally compare these 4 types of evacuation route models with the real situation or real-world path (ideal distance) on the ground. To find the answer, this research comes up with two objectives, which are: a. to measure an on-foot walking distance using three different tessellations model and compared with the standard method, and b. To evaluate the four network models compared with the ideal distance in the field.

As mentioned previously, the general network analysis uses existing road network as the path to calculate the time and the distance for person/evacuee in the built environment [1], [2] from their "origin" location the nearest TES. However, there are some limitations if the model only uses the existing road network.

There are at least two reasons why the existing road network reduces the effectiveness of the model results. Firstly, during a disaster, evacuees instinctively move as fast as possible to the nearest TES, with a very limited time, the pedestrian-based evacuation (on-foot evacuation) is one possible method [3]. The evacuee on foot has more freedom to select their pathway: for example, the evacuee could cross a park which is not part of the road network, the evacuee could also possibly access private yards which are open at the time of tsunami hazard. Secondly, the availability of network data of existing road/pathway is sometimes not available in the existing masterplan due to the scale of the data. For example, in Indonesia, the urban masterplan documents (RTWR) only provide 1:50,000 scale of map data. This implies that small alleys in between houses cannot be identified in the existing masterplan maps. To overcome these limitations, several studies have proposed an additional network called the virtual network, for example, Budiarjo [4] and Mardin [5] proposed a hexagon tessellation network as a virtual network to optimize the analysis on evacuation and transportation distance respectively.

The virtual network is an additional road network added in the model. Both Budiarjo and Mardin used hexagon tessellation as their virtual network. Tessellation is a form of geometric iteration that forms a tile pattern without leaving a gap in between the interest area/map. The purpose of this tessellations is to divide a large area into smaller and in equal size. This is to uniform the unit of analysis or network length and avoid geographic differences within a sub-area. [6].

There are two types of tessellations, which are irregular tessellation and regular tessellations. The irregular tessellations appear in GIS such as the land unit between the road, administration unit, and the spatial units of a choropleth map [7]. Regular tessellations are very well known in the GIS environment as grid tessellations. The grid tessellation usually appears in raster data from a satellite image or other raster maps. Although rarely used for GIS analysis, the other regular tessellations are triangle and hexagon [7].

2. METHOD

2.1 Study Area

The study is undertaken in Palu Central Sulawesi where the massive disaster just happened on 28 September 2018. The earthquake, tsunami, and liquefaction caused 2,113

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people to lose their lives [8]. Although the information of the initial earthquake is still debatable between 7.4-7.7 Richter Scale, the result is massive, in a very short time and leave so small time window for evacuation [9]. The tsunami hit the coastal area with an estimated height of 11.4 m [10]. According to "Badan Meteorology dan Geofisika" Map, [11], Tsunami prone area in Palu lies from the west to the east, at the coast of Palu Bay area. Therefore, this research is carried out in the most affected area during the earthquake and tsunami disaster in 2018.

As one of the most populated area in Palu [12], this study area can give a sense of the emergency situation of people running/fast walking to the nearest shelters. With the settlement configuration like other regions in the city, the study area can become an appropriate case study representing to represent a disaster-prone area model. The land-use typology of this area is a combination of residential areas, commerce, offices and interspersed with health facilities, education (schools), and religious facilities such as mosques and churches.

2. Simulation Procedure

This research introduces a four steps process to find the results. The steps are 1. Creating and building the network in ArcGIS environments: 2. Determining the Origin (evacuee starting) points and Destination (temporary evacuation shelter) points and running the model using Closest Facility solver in network analysis tools; 3. Creating sample using equation; 4. Creating a real-world distance.

2.2.1 Creating and build the network

There are two stages in this step, which are creating the network using the standard method and the other three tessellation methods. The process is explained in the following part.

a. Creating the existing road network and Tessellation as virtual network

Since the research is trying to configure four different methods, which are the standard method and three tessellation models, a different process is taken for each method. This research starts by creating four different network models. The first one is creating the existing road model. This model is a standard method which is mainly used by urban planners in their planning projects. This model only utilizes the existing roads on the available maps. The other three models are developed by using different types of tessellations which are grid tessellations, the hexagon tessellations, and the triangle tessellations. Since the shape of each tessellation is different, the best way to create the similarity between this model is using the same circumscribed radius. The size of this circumscribed radius geometry is 20m, depicting the average size of parcels in Palu as the study area. These networks are developed using CAD-Software and later imported by ArcMap Software to be placed right in the study area. Figure 1 shows the 4 networks model.

![Network Models](image-url)
b. Build the network on ArcGIS environments:
To gain the capability of network analysis in ArcGIS software, all the previous data should match the data standard of this software, the "Network Dataset" under ArcGIS 10.0, the network dataset is stored in a geodatabase folder and ready to be used.

2.2.2 Determine the origin (evacuee starting) points and Destination (Temporary evacuation shelter) points; and The Network Results
a. Origin and Destination (OD) Points
During the earthquake and followed by tsunami, people should be ready to evacuate from their place to the nearest temporary evacuation shelter. The location of the people as origin point is scattered around the area. To mimic the situation, this model created 200 random points which symbolized the evacuee locations. These scattered points became the origin point of our evacuation model.
For Destination Points, the TES location was chosen in several buildings that were considered to have strong structure and had at least 2 floors. Another requirement was that the building used as shelters were a public building, that is, in everyday life can be accessed by public such as places of worship (mosque and church), and education facilities such as school.
Total number of vertical TES as much as 15-point shelter, in addition, the selection of a number of these shelters is a result of a brief analysis of the strength of the building structure. The location of origin points can be found in Table 1 and Figure 2.

b. The Network Results
Having the Origin and destination and Tessellation and existing network, the model analyzed the path between the origin points to the nearest TES using Closest distance tools in ArcGIS Network Analysis solver. The result can be found in following Figure 2.

Table 1. Location of Destination (Temporary evacuation shelter) points

| No | Building          | Destination Id | X Coord. | Y Coord. |
|----|------------------|----------------|----------|----------|
| 1  | Courthouse       | 1              | 819542.2 | 9902051  |
| 2  | Education        | 2              | 818544.4 | 9901816  |
| 3  | Institution      | 3              | 819158.0 | 9901610  |
| 4  | Police Hospital  | 4              | 819375.6 | 9901448  |
| 5  | Office           | 5              | 819210.2 | 9901039  |
| 6  | Police Office    | 6              | 819455.2 | 9901507  |
| 7  | Police Office    | 7              | 818572.6 | 9901886  |
| 8  | Hospital         | 8              | 819111.0 | 9901889  |
| 9  | Hospital         | 9              | 819046.8 | 9901749  |
| 10 | Hospital         | 10             | 819097.8 | 9901740  |
| 11 | Parliament Office| 11             | 819371.0 | 9901350  |
| 12 | Mosque           | 12             | 818945.6 | 9901376  |
| 13 | Hotel            | 13             | 819300.7 | 9902077  |
| 14 | Hotel            | 14             | 819349.1 | 9902113  |
| 15 | Local Mosque     | 15             | 818643.4 | 9901674  |
| 16 | Local Mosque     | 16             | 818677.8 | 9901362  |
2.2.3 Selecting Sample

Since there are 200 routes created by the analysis for each model (800 routes for existing road model, grid tessellation, hexagon tessellation, and triangle tessellation), it is necessary to simplify these routes for further process. This research selects 25 most different route distance for each model from the same origin to the same destinations. There are 2 steps in this process, which are:

1. Filtering the 200 route which shares only the same behaviors:
The results from the different network models show a variation in the route. For example, the route of the standard method from origin position 2 ended at destination point 16 (at the mosque with coordinate x:818677.8 and y:9901362, but the other tessellation methods model, ended at destination point no 12 which is another mosque (coordinate x:818945.6 and y:9901376). From all 200 route of each model (total 800 route from all the 4 type models), only 60.5% or 121 points are showing the same behavior where all the models share the same route of their origin and their destination.

2. Filtering the 25 most different route as samples
Due to a large number of routes, this research carried out another filtering process. This second filtering process selected only the identified 25 points which were most different in terms of distance. The method is comparing the average of three tessellation route distance \((T_a, T_b, T_c)\) with the existing model distance \((T_h)\) using with the following equations,

\[
D_f = \left( \frac{T_a + T_b + T_c}{3} \right) / T_h
\]

Where \(D_f\) : the percentage of difference distance value

The result is shown in the following Table 2.

| No | Route O-D | \(D_f\) | Route Name |
|----|-----------|--------|------------|
| 1  | Origin 125 Destination 16 | 1069%  | Route 1    |
| 2  | Origin 89 Destination 9    | 569%   | Route 2    |
| 3  | Origin 182 Destination 8   | 535%   | Route 3    |
| 4  | Origin 80 Destination 13   | 321%   | Route 4    |
| 5  | Origin 58 Destination 8    | 309%   | Route 5    |
| 6  | Origin 92 Destination 3    | 252%   | Route 6    |
| 7  | Origin 165 Destination 13  | 245%   | Route 7    |
| 8  | Origin 178 Destination 3   | 243%   | Route 8    |
| 9  | Origin 156 Destination 7   | 237%   | Route 9    |
| 10 | Origin 68 Destination 7    | 234%   | Route 10   |
| 11 | Origin 34 Destination 12   | 230%   | Route 11   |
| 12 | Origin 133 Destination 2   | 221%   | Route 12   |
| 13 | Origin 27 Destination 9    | 215%   | Route 13   |
| 14 | Origin 159 Destination 1   | 209%   | Route 14   |
| 15 | Origin 199 Destination 5   | 75%    | Route 15   |
| 16 | Origin 81 Destination 5    | 75%    | Route 16   |
| 17 | Origin 18 Destination 12   | 74%    | Route 17   |
| 18 | Origin 23 Destination 5    | 74%    | Route 18   |
| 19 | Origin 16 Destination 15   | 69%    | Route 19   |
| 20 | Origin 22 Destination 15   | 68%    | Route 20   |
| 21 | Origin 172 Destination 5   | 68%    | Route 21   |
| 22 | Origin 13 Destination 5    | 62%    | Route 22   |
| 23 | Origin 107 Destination 15  | 55%    | Route 23   |
| 24 | Origin 112 Destination 5   | 51%    | Route 24   |
| 25 | Origin 176 Destination 16  | 49%    | Route 25   |

The result is shown in the following Table 2.

Table 2. The 25 Selected route sample based on the percentage of the difference distance value

![Figure 3. Route Map of selected sample](image)
2.2.4 Creating the real-world path (Ideal Model)

From the selected route, this research retraced the real route distance of each origin and distance of the 25 selected routes which is called the real-world distance. The real-world path should be logical and mimic the people evacuating. To draw the real-world route, the origin point and destination point were connected using all the available real-world path such as road, small alley, open land and all other possible path that could be used as pathway in an emergency situation. In this case, during the tsunami disaster evacuations. Later, the 25 real-world routes will become the standard of the following measurements steps.

All the routes can be found in Table 3 and Figure 3, the result of the retraced routes and the distance can also be found at the same table.

### Table 3. Routes distance of the selected sample

| Route Name | a | b | c | d | e |
|------------|---|---|---|---|---|
| Route 1    | 7.62| 8.88| 88.21| 79.23| 114.78 |
| Route 2    | 16.12| 97.43| 106.57| 77.23| 87.88 |
| Route 3    | 33.02| 122.62| 105.66| 118.44| 106.19 |
| Route 4    | 20.33| 72.56| 63.2| 59.83| 83.6 |
| Route 5    | 38.18| 119.67| 129.17| 105.14| 126.74 |
| Route 6    | 34.71| 94.08| 88.68| 79.21| 75.68 |
| Route 7    | 34.73| 74.36| 81.69| 98.74| 89.33 |
| Route 8    | 57.24| 133.89| 146.54| 116.58| 113.93 |
| Route 9    | 88.43| 236.65| 213.73| 178.09| 226.89 |
| Route 10   | 135.69| 35.53| 33.97| 46.4| 32.22 |
| Route 11   | 39.33| 98.68| 81.23| 94.03| 89.8 |
| Route 12   | 38.98| 23.2| 16.62| 26.88| 12.71 |
| Route 13   | 98.99| 235.65| 198.22| 205.75| 241.32 |
| Route 14   | 27.09| 57.26| 50.43| 55.04| 65.51 |
| Route 15   | 370.98| 297.22| 302.33| 232.32| 273.23 |
| Route 16   | 377.4| 260.49| 325.34| 260| 281.98 |
| Route 17   | 394.18| 188.17| 178.69| 140.49| 233.59 |
| Route 18   | 95.32| 92.03| 78.64| 126.05| |
| Route 19   | 86.36| 186.26| 191.26| 170.96| 221.5 |
| Route 20   | 147.96| 131.08| 112.28| 191.87| |
| Route 21   | 281.95| 264.35| 209.07| 242.44| 262.06 |
| Route 22   | 436.17| 301.49| 258.7| 252.93| 285.74 |
| Route 23   | 260.7| 135.71| 161.57| 134.83| 181.28 |
| Route 24   | 146.73| 74.91| 81.05| 70.51| 65.59 |
| Route 25   | 379.89| 193.54| 193.16| 172.87| 281.04 |

The result of this research shows that the three tessellation methods perform better results (129.54; 128.49; and 225.44) to the real-world path compared to the standard method (994.18). Based on this finding, this research can conclude that the three tessellation models perform much better in predicting the distance of evacuation during the tsunami hazard compared to the model of the standard method.

4. Conclusion

The result of this research shows that the three tessellation models are much better compared to the standard method, which is mainly used by urban planners and researchers in recent days, for predicting the evacuation.
time. However, the three tessellation models also have some limitations. The main weakness is that the routes created by the tessellations are completely virtual and cannot be used as a real path for a person to evacuate. On the other hand, the real network which is used in standard method provides the best path for evacuee to move to the nearest TES. Combining these two methods could provide a better solution for evacuation planning. In future research, the possibility of the combination methods should be carried out to produce a more robust finding to overcome both methods limitations.

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