Preliminary Identification of Road Network Vulnerability Due to Expansion of Status of Mount Merapi Eruption-Impacted Areas in Yogyakarta Special Region

Imam Muthohar*, Hardiansyah†, Budi Hartanto*, Sigit Priyanto*

*Civil and Environmenntal Engineering, Faculty Of Engineering, Universitas Gadjah Mada, Jalan Grafika No.2, Yogyakarta, 55281, Indonesia  
E-mail: imam.muthohar@ugm.ac.id

†Civil and Environmental Engineering, Faculty Of Engineering, Universitas Gadjah Mada, Jalan Grafika No.2, Yogyakarta, 55281, Indonesia  
E-mail: hardiansyah13@gmail.com

Abstract—The eruption of Mount Merapi in Yogyakarta, Indonesia in 2010 caused many casualties due to minimum preparedness in facing disaster. Increasing population capacity and evacuating to safe places become very important to minimize casualties. Regional government through the Regional Disaster Management Agency has divided disaster prone areas into three parts, namely ring 1 at a distance of 10 km, ring 2 at a distance of 15 km and ring 3 at a distance of 20 km from the center of Mount Merapi. The success of the evacuation is fully supported by road network infrastructure as a way to rescue in an emergency. This research attempts to model evacuation process based on the rise of refugees in ring 1, expanded to ring 2 and finally expanded to ring 3. The model was developed using SATURN (Simulation and Assignment of Traffic to Urban Road Networks) program version 11.3. 12W, involving 140 centroid, 449 buffer nodes, and 851 links across Yogyakarta Special Region, which was aimed at making a preliminary identification of road networks considered vulnerable to disaster. An assumption made to identify vulnerability was the improvement of road network performance in the form of flow and travel times on the coverage of ring 1, ring 2, ring 3, Sleman outside the ring, Yogyakarta City, Bantul, Kulon Progo and Gunung Kidul. The research results indicated that the performance increase in the road networks existing in the area of ring 2, ring 3 and Sleman outside the ring. The road network in ring 1 started to increase when the evacuation was expanded to ring 2 and ring 3. Meanwhile, the performance of road networks in Yogyakarta City, Bantul, Kulon Progo and Gunung Kidul during the evacuation period simultaneously decreased in when the evacuation areas were expanded. The results of preliminary identification of the vulnerability have determined that the road networks existing in ring 1, ring 2, ring 3 and Sleman outside the ring were considered vulnerable to the evacuation of Mount Merapi eruption. Therefore, it is necessary to pay a great deal of attention in order to face the disasters that potentially occur at anytime.

Keywords—Model, Evacuation, SATURN, vulnerability.

1. INTRODUCTION

Soil fertility and natural wealth on the slope of Mount Merapi (Indonesia) are among of the reasons why people living in this risky area are reluctant to move although a potential threat of disaster is present at any time. It can be said that people living in this area are greatly exposed to social vulnerability and danger of disaster [1][2]. Mount Merapi is one of the world’s most active volcanoes and has exploded more than 80 times and the last eruption in 2010 claimed more than 400 lives [3]. Increased population capacity and evacuation to safe places are crucial to save them from the danger of disaster [4][5]. An optimum evacuation plan by involving road network of evacuation routes and safe shelters are absolutely required to ensure the safety of refugees [6][7].

Evacuation is a process in which people move from a dangerous place to a safer place to reduce health problems and the lives of vulnerable affected people. It is also an effort to completely reduce the number of victims, so that it requires various coordinated aspects in determining the policy. Transport modeling for evacuation has been developed in several studies to obtain optimum evacuation movement results, which can provide an alternative solution to disaster problems, especially in minimizing casualties, such as design of evacuation routes to relieve congestion during evacuation [8][9].

Macroscopic transport modeling can be used to optimize road network performance as an evacuation route, such as an attempt to examine the correlation between evacuation process and road network performance [10][11]. This paper aims at examining the performance of road networks resulted from...
the expansion of the affected area of Mount Merapi which increased the number of refugees, as an attempt to identify initial vulnerability of surrounding road networks.

II. METHOD

Demand model and supply model are transport modeling methods that can be used in evacuation modeling. When the disaster takes place, the number of users of the road networks increases significantly because there are self-rescuing efforts. Large number of travelers and possibility of damage to several roads due to disaster make road networks very vulnerable. Evacuation modeling using user equilibrium (UE) can analyze flow and travel times of road network due to emergency conditions has resulted in a conclusion that the measurement of evacuation performance is highly dependent on the structure of road network and the number of vehicles in the emergency planning zone [12][13]. Several evacuation models have been used to identify critical networks, by taking congestion or ratio between flow and capacity of the road into consideration [14].

Rise of travel is a central aspect of transport modeling process. Travel is once movement made by a per-son by using one or more modes and each travel has one origin and one destination [20]. The final stage of transport studies is to make a regression technique more widely. Several travels of trip ends (dependent variable) were observed in each zone and each zone had measurable characteristics in which the rise of travel might be correlated. A regression analysis to analyze changes in road network performance burdened by evacuation process including flow and travel times as dependent variables and the number of refugees in affected area as independent variable is expressed in equation 1.

\[ Y = b_0 + b_1 x X_1 + b_2 x X_2 + \ldots + b_n x X_n \] (1)

where,
- \( b_0 \) = constant (result of regression analysis)
- \( X_1, X_2 \) = independent variable

Travel distribution is a central aspect of transport modeling process. Although travel, distribution and loading are often discussed separately, human behavior makes the three phases correlated to each other. In regard to travel distribution, it is important to know two things about the end of the travel, namely connected together, without determining actual route and sometimes without reference to travel mode, with a travel matrix between origin and destination known. The Furness method generates flow from the first equilibrium zone and pull into a balanced zone, as expressed in equation 2.

\[ t'_{ij} = \frac{t_{ij} x P_i}{P_i} \] (2)

\[ t''_{ij} = t'_{ij} x \frac{\sum \text{trips attracted to } j \text{ in first iteration}}{A_i} \]

\[ t'''_{ij} = t''_{ij} x \frac{\sum \text{trips produced by } i \text{ second iteration}}{P_{ij}} \]

The utilization of existing road network as an evacuation traffic facility can be very difficult when such road network is considered not to have adequate readiness to deal with emergency. In practice, the concept of road network performance-based evacuation transport model has several advantages, such as its ability to analyze traffic performance for evacuation process on a large scale, and several results of simulation in the form of evacuation time and solid path identification can produce a measurement of network vulnerability. Impacts of changes in natural conditions and of human hands, increased intensity of disasters in recent years has become an interesting research object as a study material, especially concerning road vulnerability networks due to disasters. Changes in road network performance due to an event can be identified as network vulnerability and toughness and can be expressed by index [15][16][17]. A methodology of analyzing of road network vulnerabilities is developed based on consideration of socio-economic impact of network degradation and search for determining the most important location as a result of network failure [18]. The vulnerability of road transport system is considered not from a security standpoint, but rather as an issue of reduced accessibility for various reasons. It emphasizes on system function and not physical network, although some of the reasons causing road network discontinuity are caused by physical damage [19]. Therefore, increased network performance can be identified as network vulnerability as a results of an event or disaster...

The evacuation model was built and developed using SATURN (Simulation and Assignment of Traffic to Urban Road Networks) software version 11.3.12W, a network analysis software developed by Institute for Transport Studies, University of Leeds. This model focused on the road networks in the Province of Yogyakarta Special Region, involving 140 centroids consisting of 73 zones based on subdistricts of 6 external zones and 61 evacuation zones. Meanwhile, the buffer node consisted of 449 nodes and involved 851 links consisting of state roads, provincial roads and regency/municipal roads. The scenario was de-signed based on disaster prone areas that had been determined by the regional government through the Regional Disaster Management Agency (BPBD) by dividing the areas into three parts, namely ring 1 with a distance of 10 km, ring 2 with a distance of 15 km and ring 3 with a distance of 20 km from the peak of Mount Merapi. The road networks were then drawn with the help of the ArcGis program to make the data input process on SATURN easier. The picture of the road network model using ArcGis is shown in Figure 1.
Figure 1 shows road networks and rise zone and pull of travel. Evacuation zone and some regency road network were placed in Sleman Regency, the closest area from the peak of Mount Merapi, as alternative evacuation routes for refugees. Furthermore, each ring was limited to make simulation process and analysis of results easier.

After the design of the road network model was completed, the next step was process to input network and travel matrices into SATURN. The input of road network consisted of number of nodes connecting links, free flow speed, speed during capacity, capacity of road link, number of directions and length of link. Meanwhile, the input of travel distribution consisted of daily OD matrices and evacuation travel, i.e. evacuation route of refugees in ring 1 which was obtained from the daily OD matrix modification added by the number of refugees to be evacuated with a variation of 50%, 60%, 70%, 80%, 90% and 100%. Similarly, the expansion of evacuation to ring 2 was a combination of variation of refugees in ring 1 by 80%, 90%, and 100% with 50%, 60%, 70%, 80%, 90% and 100% of the population in ring 2. Furthermore, the expansion of evacuation to ring 3 was a combination of variation of evacuation travel in ring 1 by 90% and 100% and ring 2 added by 80%, 90% and 100% with 50%, 60%, 70%, 80%, 90% and 100% of the population moving to ring 3.

Before the simulation on the disaster condition, daily travel modeling was firstly made as the basic model for the next process. The basic model should have a similarity with the real condition as evidenced by statistical testing with certain value limits. The following is the inputs of the road network model in SATURN as shown in Figure 2.

Figure 2 shows the road network models to be loaded under several conditions for analyzing performance. The road network performance observed in the analysis was total volume and travel times on the road network included in ring 1, ring 2, ring 3, Sleman outside the ring, Yogyakarta City, Bantul, Kulon Progo and Gunung Kidul.

III. RESULTS AND DISCUSSION

Before the simulation process, the model was firstly validated by comparing the results of daily travel model to traffic counting in the field. The results of model validation in 60 national and provincial roads are shown in Figure 3.

The result of validation show that R Square was 0.761, meaning the similarity of the model was 76% with actual condition. Some models could have similarity close to 100%, but it was difficult to obtain for macroscopic models. After the validation process was accepted, the next process was performing a predefined scenario simulation. The results of the evacuation scenario of evacuating refugees in ring 1, which consisted of 6 variations of the model, obtained regression equations to
determine flow and travel times in the observed areas as shown in Table 1.

**Table 1.**

EQUATIONS TO DETERMINE FLOW AND TRAVEL TIMES DUE TO REFUGEES IN RING 1

<table>
<thead>
<tr>
<th>Road Network</th>
<th>Equation for Determining Flow</th>
<th>R Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>Y = 3,163.967 - 2.773 X1</td>
<td>0.132</td>
</tr>
<tr>
<td>Ring 2</td>
<td>Y = 62,795.522 + 115.645 X1</td>
<td>0.904</td>
</tr>
<tr>
<td>Ring 3</td>
<td>Y = 178,699.163 + 220.444 X1</td>
<td>0.951</td>
</tr>
<tr>
<td>Sleman (outside the ring)</td>
<td>Y = 501,562.304 + 174.213 X1</td>
<td>0.783</td>
</tr>
<tr>
<td>Yogyakarta City</td>
<td>Y = 129,712.163 + 7.416 X1</td>
<td>0.261</td>
</tr>
<tr>
<td>Bantul</td>
<td>Y = 214,892.707 + 4.925 X1</td>
<td>0.058</td>
</tr>
<tr>
<td>Kulon Progo</td>
<td>Y = 92,570.859 - 13.229 X1</td>
<td>0.538</td>
</tr>
<tr>
<td>Gunung Kidul</td>
<td>Y = 106,773.467 + 13.703 X1</td>
<td>0.487</td>
</tr>
</tbody>
</table>

When the evacuation scenario of the refugees was extended to ring 2 consisting of 18 variations of simu-lation model, the regression equations were obtained as shown in Table 2.

**Table 2.**

EQUATION TO DETERMINE FLOW AND TRAVEL TIME DUE TO REFUGEES EXPANDED UNTIL RING 2

<table>
<thead>
<tr>
<th>Road Network</th>
<th>Equation for Determining Flow</th>
<th>R Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>Y = 18,818.489 - 27.288 X1</td>
<td>0.128</td>
</tr>
<tr>
<td>Ring 2</td>
<td>Y = 517,846.707 + 1,183.305 X1</td>
<td>0.891</td>
</tr>
<tr>
<td>Ring 3</td>
<td>Y = 1,389,174.076 + 2,436.103 X1</td>
<td>0.942</td>
</tr>
<tr>
<td>Sleman (outside the ring)</td>
<td>Y = 2,751,714.837 + 1,251.416 X1</td>
<td>0.765</td>
</tr>
<tr>
<td>Yogyakarta City</td>
<td>Y = 707,362.750 - 68.605 X1</td>
<td>0.227</td>
</tr>
<tr>
<td>Bantul</td>
<td>Y = 1,384,230.913 + 36.679 X1</td>
<td>0.064</td>
</tr>
<tr>
<td>Kulon Progo</td>
<td>Y = 560,867.402 - 97.408 X1</td>
<td>0.586</td>
</tr>
<tr>
<td>Gunung Kidul</td>
<td>Y = 778,016.087 - 113.059 X1</td>
<td>0.507</td>
</tr>
</tbody>
</table>

Similarly, when the evacuation scenario of refugees was expanded to ring 3 consisting of 36 variations of the simulation model, the regression equations were obtained as shown in Table 3.

**Table 3.**

EQUATION TO DETERMINE FLOW AND TRAVEL TIME DUE TO REFUGEES EXPANDED UNTIL RING 3

<table>
<thead>
<tr>
<th>Road Network</th>
<th>Equation for Determining Flow</th>
<th>R Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>Y = 3101.357 + 23.882 X1 + 4.597 X2 + 0.716 X3</td>
<td>0.607</td>
</tr>
<tr>
<td>Ring 2</td>
<td>Y = 63987.326 + 584.049 X1 + 87.487 X2 + 117.084 X3</td>
<td>0.962</td>
</tr>
<tr>
<td>Ring 3</td>
<td>Y = 177983.405 + 1628.380 X1 + 62.953 X2 + 104.676 X3</td>
<td>0.976</td>
</tr>
<tr>
<td>Sleman (outside the ring)</td>
<td>Y = 499037.797 + 219.280 X1 - 6.300 X2 - 410.418 X3</td>
<td>0.94</td>
</tr>
<tr>
<td>Yogyakarta City</td>
<td>Y = 128447.795 + 132.961 X1</td>
<td>0.761</td>
</tr>
<tr>
<td>Bantul</td>
<td>Y = 213805.068 + 153.412 X1 - 55.926 X2 + 151.268 X3</td>
<td>0.839</td>
</tr>
<tr>
<td>Kulon Progo</td>
<td>Y = 92384.347 + 7.300 X1 - 22.916 X2 - 75.769 X3</td>
<td>0.923</td>
</tr>
<tr>
<td>Gunung Kidul</td>
<td>Y = 106397.352 + 0.778 X1 - 23.295 X2 - 75.485 X3</td>
<td>0.889</td>
</tr>
</tbody>
</table>

The equations were then used to determine flow and travel time of the road network in the observed are-as based on the percentage of population moving in each disaster prone area of ring 1, ring 2 and ring 3.

The results of interviews conducted on those who lived in the disaster-prone areas of Mount Merapi, Sleman, Province of Yogyakarta Special Region indicated that those who would perform evacuation travel with vehicles were 91% of the total population, while the rest traveled by foot and answered “did not know”. Therefore, when the percentage of the refugees was analyzed using the equations, the total travel flow and travel times in the observed areas were obtained as shown in Figures 4 and 5.
Figure 4. Total flow in the observation areas

Figure 5. Total travel time in the observation areas
Figures 4 and 5 show the changes in road network performance due to the evacuation process compared with road network performance on daily travel. Accordingly, it can be seen that the total flow and travel times of each road network observed in all scenarios produced changes in values. The values increased in some observation areas, but decreased in other areas.

The results of flow calculation analysis show that the values increased in the road networks in ring 2, ring 3 and Sleman outside the ring. The values of flow in the road network of ring 2 consisting of daily travel scenario, evacuation scenario of refugees in ring 1, evacuation scenario of refugees until ring 2 and refugee evacuation scenario until ring 3 were 64,184; 73,319; 86,829; 135,752 pcu/hour respectively. The values of flow in the road network of ring 3 were 179,913; 198,760; 205,358; 341,393 pcu/hour respectively. Meanwhile, the values of flow in the road network of Sleman outside the ring were 504,959; 517,416; 515,374; 657,659 pcu/hour respectively.

The results of the analysis of travel time calculation show that there were changes in the form of increased values of travel time due to the evacuation scenario of the refugees compared with the daily travel scenario in the road network of ring 2, ring 3 and Sleman outside the ring. The values of travel times in the road network of ring 2 consisting of daily travel scenario, evacuation scenario of refugees in ring 1, evacuation scenario of refugees until ring 2, and evacuation scenario of refugees until ring 3 were 533,607; 625,527; 769,521; 1,310,867 seconds respectively. The increased values of travel time in the road network of ring 3 were 1,403,447; 1,610,859; 1,700,468; 3,148,267 seconds respectively. Meanwhile, the increased values of total travel time in the road network of Sleman outside the ring were 2,774,307; 2,865,594; 2,832,662; 3,927,639 seconds respectively.

Other obtained results show that there were changes in flow and travel times of the road network in ring 1 due to the influence of daily travel scenario, evacuation scenario of refugees in ring 1, evacuation scenario of refugees in ring 2 and evacuation scenario of refugees until ring 3, namely 3,236; 2,912; 3,996; 5,758 pcu/hour and 19,832; 16,335; 30,692; 46,835 seconds respectively. These results indicate that the values of flow and travel times of the road network increase when the evacuation scenario of refugees was expanded until ring 2 and ring 3. This indicates that there was a phenomenon of interference in the road network.

Furthermore, flow and travel times decreased from daily travel to evacuation travel as the evacuation status was expanded to ring 3, i.e. the road network existing in Yogyakarta City, Bantul, Kulon Progo and Gunung Kidul. The implementation of the evacuation scenario from ring 1, expanded to scenario ring 2 and until the scenario ring 3 made the values of flow and travel times continuing to decrease, indicating that some travels in these areas were delayed due to the disaster of Mount Merapi.

Therefore, the road networks were initially identified to experience vulnerability due to the increased values of flow and travel time as shown in Figure 6.

Figure 6 shows that in the implementation of scenario of refugees in ring 2 and ring 3, road networks existing in ring 1, ring 2, ring 3 and Sleman outside the ring were identified to be vulnerable. Meanwhile, due to the evacuation scenario of ring 1, the road networks identified to be vulnerable were only in ring 2, ring 3 and Sleman outside the ring. However, the road networks existing in ring 1 could be concluded to vulnerable because it had been identified in the scenario of ring 2 and ring 3.

IV. CONCLUSIONS

Based on the results of the discussion, it can be concluded that:

1. The expansion of refugee evacuation status from ring 1, ring 2 and until ring 3 increased the flow and travel times in the road networks include in ring 2, ring 3, and Sleman outside the ring.
2. The road network in ring 1 started to increase when the evacuation was expanded to ring 2 and ring 3.
3. The performance of road networks existing in Yogyakarta City, Bantul, Kulon Progo and Gunung Kidul simultaneously decreased when the evacuation zone was expanded.
4. The preliminary identification of vulnerability had determined that the road networks existing in ring 1, ring 2, ring 3 and Sleman outside the ring were considered vulnerable to the evacuation of Mount Merapi eruption.
5. The results of the analysis have proved that not all road networks in the Province of Yogyakarta Special Region are vulnerable to the disaster of Mount Merapi eruption.

ACKNOWLEDGMENT

would like express my sincere gratitude to The Ministry of Research, Technology and Higher Education, which provided scholarship for taking Doctoral Program at Universitas Gadjah Mada, Head of the Doctoral Program of Civil Engineering, Universitas Gadjah Mada, Supervisor who assisted in the preparation of this research article, and Co-Supervisor who assisted in.
REFERENCES


