Study on Volcanic Ash Fall Hazard and Road Network Disruption Risk due to Eruption of Fuji Volcano

Kazuaki TORISAWA[a] * and Harumi YASHIRO[b]
[a] Kanto Gakuin University, Yokohama, JAPAN
[b] National Defense Academy, Yokosuka, JAPAN

Abstract: In large-scale natural disasters, road network disruption has a tremendous effect on emergency response activities in affected areas. In recent years, concern about the influence on the metropolitan area at the time of the eruption of Fuji volcano is growing, and countermeasures against disruption of road network accompanying large-scale volcanic ash fall are also required. In this study, the probabilistic hazard map of ash fall caused by the eruption of Fuji volcano was evaluated. In addition, we examined the risk of road network disruption due to volcanic ash fall and evaluated the influence of the eruption of Fuji volcano.

Keywords: Volcanic Ash Fall, Hazard Map, Road Traffic Regulation, Risk Curve.

1. INTRODUCTION

In large-scale natural disasters, road network disruption has a tremendous effect on emergency response activities in affected areas. In recent years, concern about the influence on the metropolitan area at the time of the eruption of Fuji volcano is growing, and countermeasures against disruption of road network accompanying large-scale volcanic ash fall are also required. In this study, we evaluated the probabilistic hazard map of ash fall caused by the eruption of Fuji volcano and examined the risk of road network disruption due to volcanic ash fall.

2. EVALUATION METHOD

2.1. Evaluation Flow

The authors [1] have been studying estimation of the road network disruption risk by earthquake and tsunami. There, the road traffic regulation probability with input of the measured seismic intensity and tsunami flooding depth was evaluated, and the probability distribution of the affected traffic volume considering the unavailable road link based on it was evaluated by the Monte Carlo method.
In this research, the road traffic regulation probability with input of the ash fall layer thickness and the probability distribution of the affected traffic volume are evaluated with the same ideas as above.
Figure 1 shows the evaluation flow of the road network disruption risk due to volcanic ash fall in this study. First, evaluate the ash fall layer thickness for each unit cell, then evaluate unavailable road per road link, and lastly evaluate affected traffic volume for each road link. They are repeated a certain number of times to obtain the probability distribution of the affected traffic volume. Here, probabilistic calculation is performed in the evaluation of ash fall layer thickness distribution and unavailable road link. These will be described in detail from the next section onwards.

* *tori@kanto-gakuin.ac.jp*

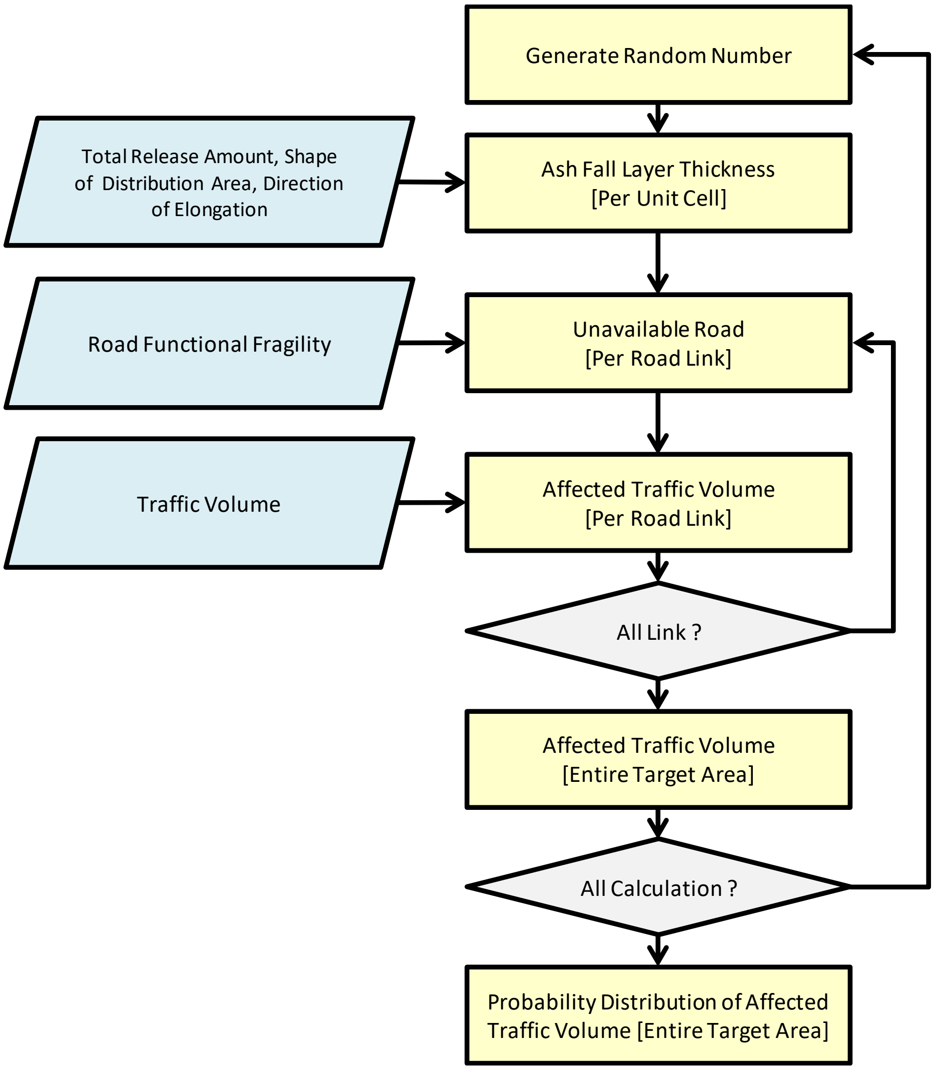


Fig. 1: Evaluation Flow of Road Network Disruption Risk due to Volcanic Ash Fall

2.2. Probabilistic Evaluation of Ash Fall Layer Thickness Distribution

Regarding the probabilistic evaluation of the ash fall layer thickness distribution over a wide area at the time of eruption, Sudo et al. [2] compiled the data on the shape of the distribution area and the direction of elongation from the ash fall layer thickness distribution data of the past eruption, and they studied a method for evaluating statistically the ash fall layer thickness distribution. Here, the probabilistic evaluation of the ash fall layer thickness distribution means calculating the probability of the volcanic ash fall layer thickness, which is the surrounding point, when a certain amount of ash is ejected from a certain volcano. And, Itoi [3] formulated it.

In this research, we evaluated the probabilistic hazard map of ash fall layer thickness by extending part of these previous studies [2], [3] when spatially evaluating with GIS (Geographic Information System). The evaluation method will be described below.

First, it is empirically obtained that the total release amount V of volcanic ash can be approximately expressed as the product of the thickness T of the ash fall layer and the area S surrounded by the isopach in the following equation [4].

$$V = kST \tag{1}$$

Here, k is a constant. When the k value [4] in the past eruption is summarized, the distribution follows a lognormal distribution, and the median and the logarithm standard deviation σ are 11.94 and 0.202, respectively [3].

When the equation (1) is sorted out for T, we obtain the equation (2).

$$\log T = \log V - \log S - \log \bar{k} + \sigma\varepsilon \tag{2}$$

Here, ε is a random variable according to the standard normal distribution (the average and the standard deviation are 0 and 1, respectively), and the constant $\bar{k}$ is 11.94.

On the other hand, when approximating the region enclosed by the isopach with an ellipse and taking the crater position at the major axis end point of the ellipse, under the assumption that the ratio of the minor axis diameter to the major axis diameter of the ellipse is constant in all layer thickness, it is possible to evaluate the layer thickness based on the total release amount and the elliptical area of the isopach from the relation of the above equation (1) [5].

Figure 2 shows the positional relationship of evaluation points when isopach in the ash fall layer distribution is approximated by ellipse and the volcanic vent position is taken at the origin of the x axis and the y axis. We assume a plane orthogonal coordinate system. The coordinates of the evaluation point (East and North are positive of x axis and y axis, respectively) is (x_s, y_s). In the figure, L_a and L_b are the radii of the long axis and the short axis of the ellipse, respectively, and the ratio of the minor axis radius to the major axis radius is called the ellipticity flatness R_E. Θ_E is the direction (counterclockwise from the east is positive) of elongation of the ash fall layer distribution (long axis of the ellipse). Suto et al. [2] summarized the statistics of the flatness R_E and long axis angle Θ_E at the time of eruption in the past (Fig. 3), and in analysis these statistical trends are equal in all layer thickness at the time of one eruption.

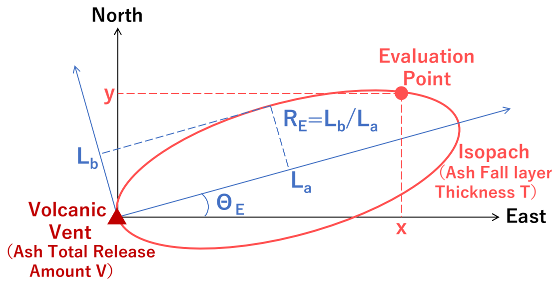
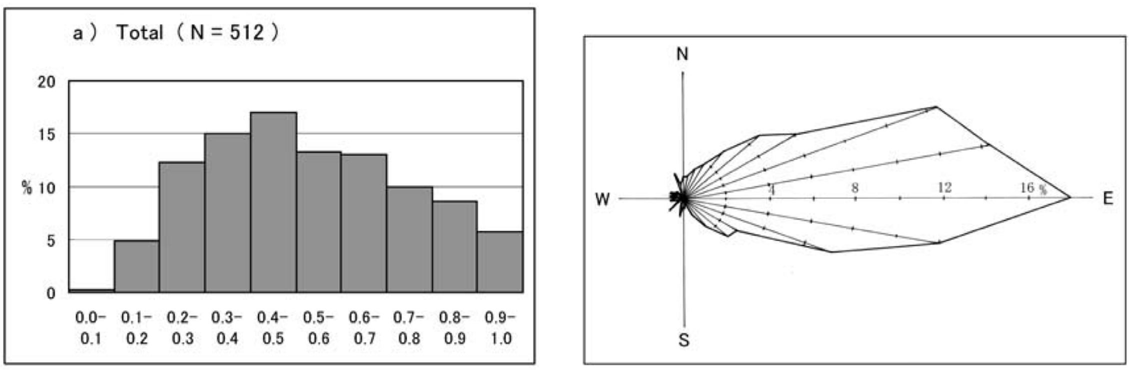


Fig. 2: Elliptical Approximation of Ash Fall Isopach and Coordinates of Evaluation Points [3]



(a) Ellipticity Flatness R_E
(Shape of Distribution Area)

(b) Long Axis Angle of Ellipse Θ_E
(Direction of Elongation)

Fig. 3: Historical Statistics on Ash Fall Layer Distribution [2]

Considering the coordinate system whose axis is the major axis and the minor axis of the ellipse, the coordinates (x_s', y_s') of the evaluation point are given by the expression (3).

$$\begin{Bmatrix} x_s' \\ y_s' \end{Bmatrix} = \begin{bmatrix} \cos\Theta_E & \sin\Theta_E \\ -\sin\Theta_E & \cos\Theta_E \end{bmatrix} \begin{Bmatrix} x_s \\ y_s \end{Bmatrix} \tag{3}$$

The above equation (2) can be represented as the equation (4) by elliptic approximation. And, L_a can be represented as the following equation (5) by x_s', y_s', R_E.

$$\log T = \log V - \log \pi R_E L_a{}^2 - \log \bar{k} + \sigma\varepsilon \tag{4}$$

$$L_a = \sqrt{(x_s' - L_a)^2 + \left(\frac{y_s'}{R_E}\right)^2}$$
$$\therefore L_a = \frac{1}{2}\left(x_s' + \frac{y_s'}{x_s' R_E{}^2}\right) \tag{5}$$

However, since trigonometric functions have periodicity, if the above expression is applied as it is, the same figure is drawn at a point symmetrical with respect to the origin. Therefore, in this research, cases are classified under a plurality of conditions as follows to perform spatial evaluation using GIS.

Case of $\Theta_E \leqq 90$ or $270 < \Theta_E$
When $x_s < (y_s / \tan(\Theta_E + \pi/2))$, $T = 0$
Otherwise, the expression (4)

Case of $180 < \Theta_E \leqq 270$
When $x_s > (y_s / \tan(\Theta_E + \pi/2))$, $T = 0$
Otherwise, the expression (4)

Case of $90 < \Theta_E \leqq 180$
When $y_s < (x_s / \tan(\Theta_E + \pi/2))$, $T = 0$
Otherwise, the expression (4)

From the above, the probability distribution of the ash fall layer thickness T becomes evaluable spatially by the probability distribution of the volcanic ash total release amount V, the shape of the distribution area R_E (ellipticity flatness), and the direction of elongation Θ_E (long axis angle of ellipse). The value of each random variable is determined by an independent random number, and iterative calculation is performed at the evaluation point which is the centroid of the unit cell in the target area.

2.3. Evaluation of Road Unavailable Probability (Road Functional Fragility)

There are many cases where the road is no longer available due to ash fall during the eruption, and the Japan Meteorological Agency [6] summarizes them as shown in figure 4. In the fig. 4, ○ indicates the ash fall layer thickness of the actual case where it was unavailable, but it can be seen highly variable from 0.1 cm to 7.5 cm. In addition, ◇ is a setting value in damage prediction by the Fuji volcano hazard map review committee [7], and it shows that it will become unavailable by ash fall layer of 5 cm at the time of drying and 0.5 cm at the time of rainfall. According to the Cabinet Office, Government of Japan [8], considering the criteria for disaster assessment of roads at the time of eruption in the past, the ash fall layer of 1 to 2 cm interferes with traffic. As it rains, the ash fall layer of just a few millimeters interferes with traffic.

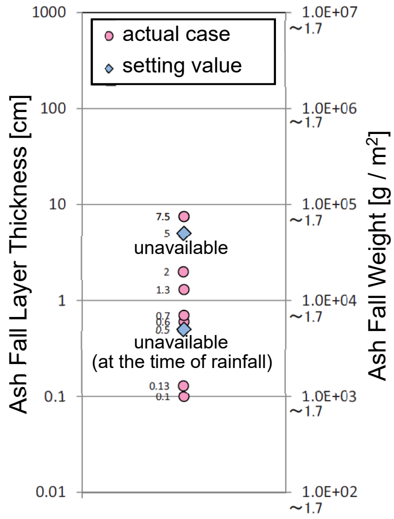


Fig. 4: Ash Fall Layer Thickness Which Makes Road Unavailable [6]

From the above, it seems that the occurrence of a road unavailable event is not uniquely determined against the ash fall layer thickness and has uncertainty. For the evaluation, it is desirable to predict probabilistically with input of the ash fall layer thickness. The road traffic regulation caused by ash fall can be represented as road functional fragility because it is a functional aspect of the road such as a slip accident or movement difficulties accompanying ash deposition on the road surface, poor visibility due to rolled ash, etc. As a previous study, Tamaki et al. [9] constructed data on the ash fall layer thickness distribution and road traffic regulation at the Kirishimayama Shinmoedake eruption in 2011, and the traffic regulation probability $P(x)$ when the ash fall amount x [kg / m^2] was modeled by the following equation using the cumulative distribution function Φ of the standard normal distribution. μ_x and σ_x obtained by regression are 21.8 and 10.1, respectively.

$$P(x) = \Phi\left(\frac{x-\mu_x}{\sigma_x}\right) \tag{6}$$

The ash fall amount in the above equation (6) converts to the ash fall layer thickness and the road functional fragility curve to ash fall at the time of drying is shown in figure 5. It is expressive that the traffic regulation begins to occur by the ash fall layer of about several millimeters, the event occurs with 50% probability at about 2 cm or more, and it occurs almost certainly at about 5 cm. These are roughly consistent with the past case mentioned above.

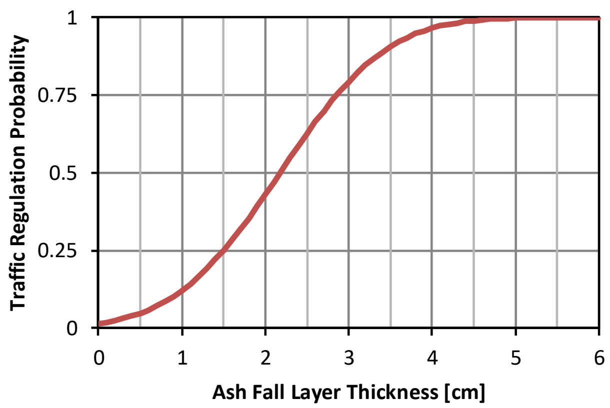


Fig. 5: Road Functional Fragility Curve to Ash fall Layer Thickness [9]
(Ash weight 1 kg / m^2 converted to 0.1 cm thick)

In this study, the unavailable road link is evaluated by using the road functional fragility curve. More specifically, the traffic regulation probability $Pi(x)$ of the road link i is calculated by using the road

functional fragility curve, and the road link i is determined to be unavailable when $Pi(x)$ greater than u_i which is the uniform random number generated in the range of 0 to 1.
It is necessary to validate the road functional fragility curve by another eruption case and investigate the fragility curve at the time of rainfall in the future.

3. CASE ANALYSIS

3.1. Analysis Target

Case analysis by the evaluation method described above was conducted to evaluate the influence of the eruption of Fuji volcano on the road network in the metropolitan area. The scope of the case analysis was set to the range shown in figure 6. The red line in the figure is the expressway, the blue line is the national highway, the orange line is the local road, and the green line is the prefectural road.

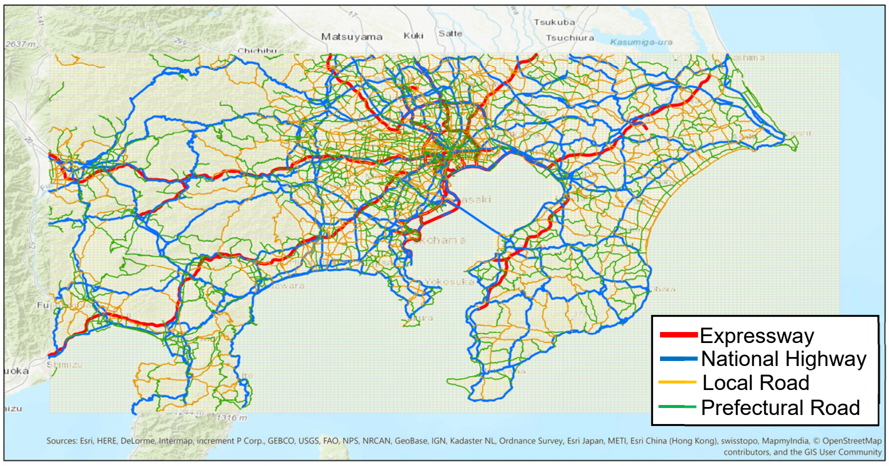
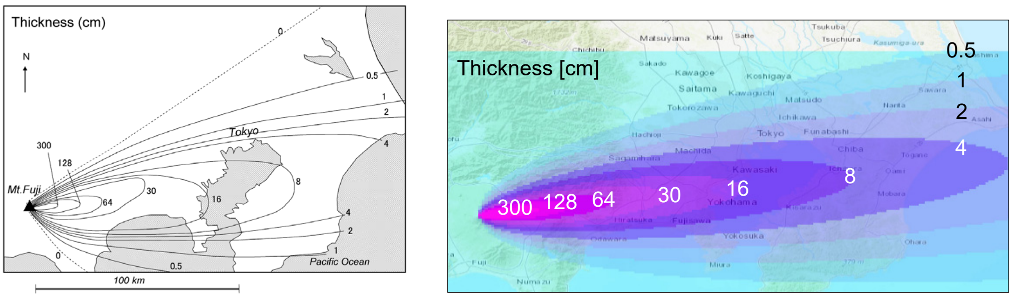


Fig. 6: Analysis Target Road Network

3.2. Hazard Map of Volcanic Ash Fall Layer Thickness

Since there are several different interpretations about the occurrence frequency of the Fuji volcano eruption, we decided to evaluate the probability distribution of the ash fall layer thickness under the condition that Fuji volcano eruption occurred without considering the occurrence frequency in this research.
First, for testing the efficacy of this method approximating ash fall isopach with an ellipse, the ash fall layer thickness was estimated assuming the same total release amount 1.7 km^3 [10] as the 1707 eruption of Fuji volcano (under the condition that the ellipticity flatness R_E and the long axis angle Θ_E were constant). The estimated result by this method and the contour drawing based on ash deposition records are compared as shown in figure 7. It was confirmed that almost reasonable result can be obtained by this method.



(a) Contour drawing based on ash deposition records [10]

(b) Estimated result using the same total release amount as the 1707 eruption

Fig. 7: Comparison of Ash Fall Layer Thickness of the 1707 Eruption of Fuji Volcano

Next, the probability distribution of the ash fall layer thickness was estimated according to the probability distribution of the volcanic ash total release amount V. In this study, the probability distribution of V was assumed as shown in figure 8. The number of calculation repetitions was 5,000.

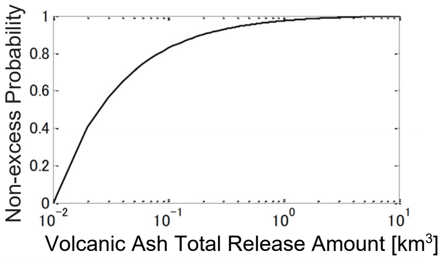


Fig. 8: Assumption of Probability Distribution of Volcanic Ash Total Release Amount V of Fuji Volcano Eruption [3]

Figures 9 and 10 show the map of the expected value and the map of the 95% non-excess value, respectively, estimated using the obtained probability distribution of the ash layer thickness. The shape of the ash fall layer distribution is characteristic, which is the result of reflecting the above statistics of the flatness R_E and the long axis angle Θ_E. For example, in Odawara city, it can be seen that the expected value of the ash fall layer thickness is 0.5 cm to 1 cm, while its 95% non-excess value is 2 cm to 4 cm.

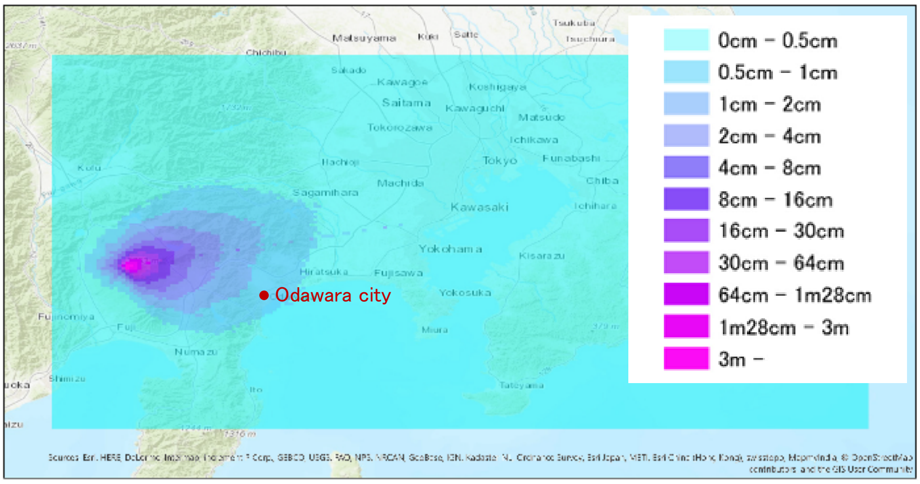


Fig. 9: Map of Expected Value of Ash Fall Layer Thickness due to Fuji Volcano Eruption

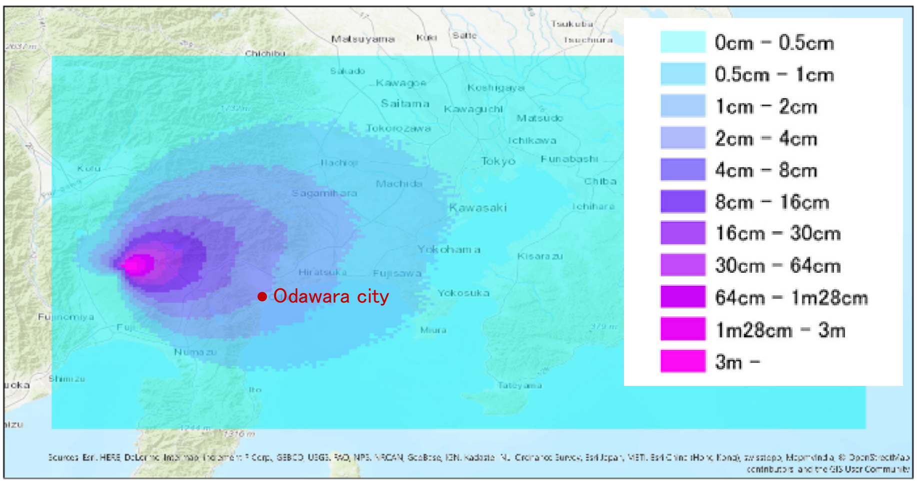


Fig. 10: Map of 95% Non-excess Value of Ash Fall Layer Thickness due to Fuji Volcano Eruption

It is also possible to estimate the probability to deposit above a certain thickness based on the probability distribution of the ash fall layer thickness. Figure 11 shows the map of the probability that ash fall layer thickness exceeds 0.5 cm. That probability in Odawara City is 10% to 20%.

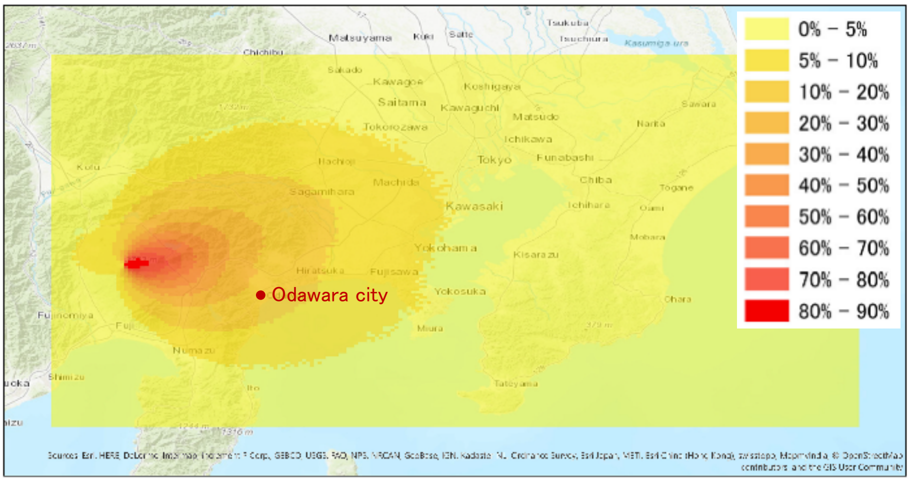


Fig. 11: Map of Probability that Ash Fall Layer Thickness Exceeds 0.5 cm due to Fuji Volcano Eruption

3.3. Road Network Disruption Risk due to Volcanic Ash Fall

According to the evaluation flow shown in Fig. 1 above, the affected traffic volume was evaluated every 5000 samples of ash fall layer thickness obtained in the previous section, and the probability distribution of the affected traffic volume as the road network disruption risk was evaluated. The average traffic volume per 12 hours of traffic census was used for traffic volume in this analysis.

Figures 12 and 13 show the map of the expected value and the map of the 95% non-excess value, respectively, estimated using the probability distribution of the affected traffic volume obtained for each road link. At the expected value the affected traffic volume is roughly constant throughout all road in the target area except the expressway which generally has more traffic than other roads, whereas at 95% non-excess value it becomes very large near the crater of Fuji volcano.

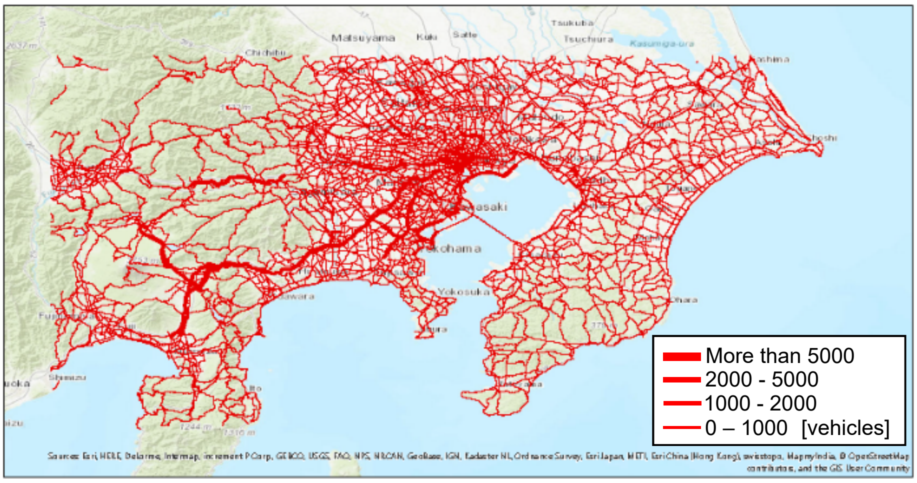


Fig. 12: Map of Expected Value of Affected Traffic Volume due to Fuji Volcano Eruption

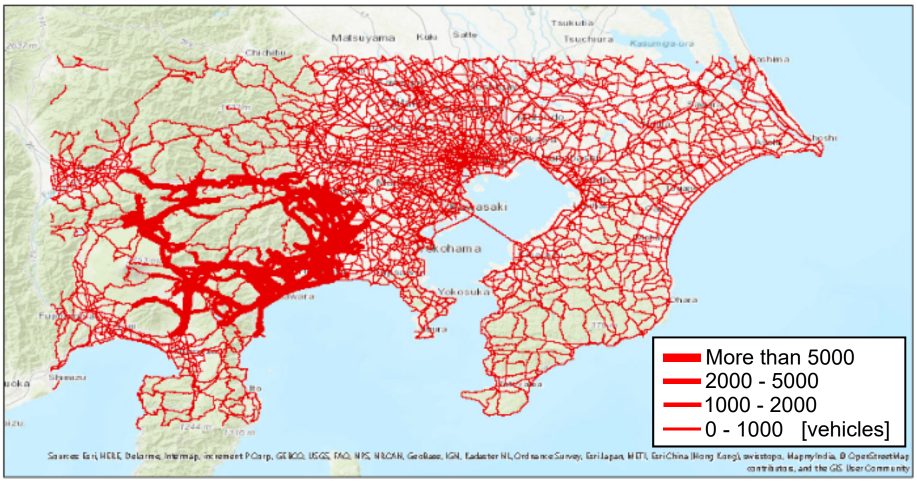


Fig. 13: Map of 95% Non-excess Value of Affected Traffic Volume due to Fuji Volcano Eruption

Figure 14 shows the risk curves of road network disruption due to volcanic ash fall. They represent the conditional excess probability of the affected traffic volume for each road type or the total of all types. For the total of all types, the affected traffic volume is over 3 million vehicles with the probability of 0.1, and it is over 30 million vehicles with the probability of 0.01. Though there is little difference in the road network disruption risk for each type of road, the risk in the prefectural road seems to be relatively low.

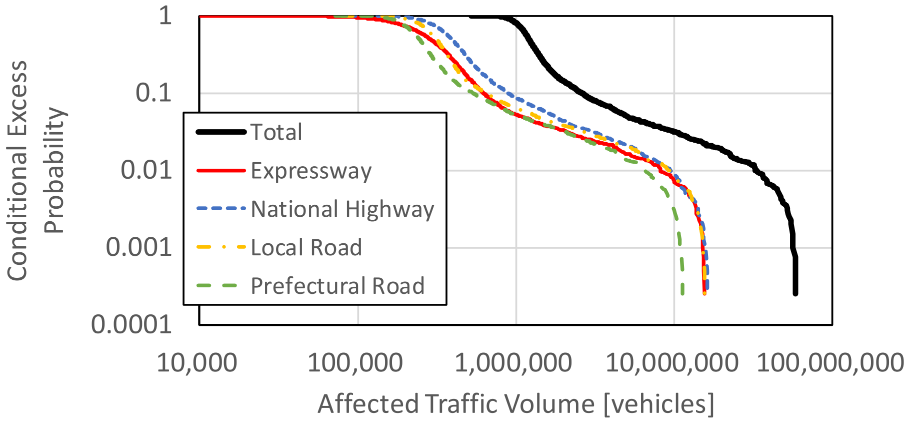


Fig. 14: Risk Curve of Road Network Disruption due to Fuji Volcano Eruption
(Excess Probability of Affected Traffic Volume under Condition that Fuji Volcano Eruption Occurred)

4. CONCLUSION

In this study, the evaluation method of the volcanic ash fall hazard map was developed by extending the previous studies, and we constructed the original method for evaluating the road network disruption risk using the obtained probability distribution of ash fall layer thickness.

The case analysis by the proposed method was also conducted to evaluate the influence of the eruption of Fuji volcano on the road network in the metropolitan area. We calculated the excess probability curve and the probability map of the affected traffic volume and clarified the total amount and the geographical distribution of them in the target area. It was confirmed that this method was effective for estimation the influence of road network disruption due to large-scale volcanic ash fall.

However, several factors influencing the ash fall layer thickness, such as the temporal change of ash falling and the effect of ash removal by road sweeper etc., are not considered in this study. These are future tasks. We will also try to calculate the loss amount from the affected traffic volume as a social influence.

References

[1] Torisawa, K., S. Yoshida, and S. Sadohara. "*A Study on Road Network Damage Prediction and its Influence Estimation to Business Continuity of Supply Chain*", Journal of Japan Association for Earthquake Engineering, Vol.14, No.2, pp.84-103, (2014).

[2] Suto, S., *et al.* "*Trial to Make Up the Probability Map of the Volcanic Ash Fall Deposit, Derived from the Published Ash Fall Data, in Japan*", Bulletin of the Volcanological Society of Japan, Vol.55, No.1, pp.13-20, (2010).

[3] Itoi, T. "*Probabilistic Volcanic Ashfall Hazard Analysis based on Statistical Data*", Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, Vol.B-1, pp.65-66, (2016).

[4] Hayakawa Y. "*Pyroclstic Geology of Towada Volcano*", Bulletin of the Earthquake Research Institute University of Tokyo, Vol.60, pp.507-592, (1985).

[5] Takezawa, N., *et al.* "*Volcanic Ash fall thickness distribution immediate estimation system for the initial action after an eruption*", Summaries of Technical Papers of Annual Meeting Japan Society of Civil Engineers, pp.879-880, (2008).

[6] Japan Meteorological Agency, "*The 1st Meeting Reference Material of Investigative Commission for the Effect of Ash Fall and Volcanic Countermeasures and Advancement of Ash Fall Forecast*", (2012).

[7] Fuji Volcano Disaster Prevention Council, "*Fuji volcano Hazard Map Review Committee Report*", (2004).

[8] Investigative Commission for the Volcanic Disaster Prevention Measures on Wide Area, Cabinet Office, Government of Japan, "*Recommendations for Measures against Large Volcanic Disasters*", (2013).

[9] Tamaki, T., and H. Tatano. "*An Evaluation Method for Road-blockage by Volcanic Ashfall and the Restoration*", Journal of Natural Disaster Science, Vol.33, Special issue, pp.165-175, (2014).

[10] Miyaji, N., and M. Koyama. "*Recent Studies on the 1707 (Hoei) Eruption of Fuji Volcano*", Fuji Volcano, pp.339-348, (2007).