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# Typhoon-induced roof damage probability based on aerial survey and WRF

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**SUMMARY:**
The roof damage distribution obtained from the aerial conducted out two months after the damage caused by Typhoon Jebi in 2018 was analyzed using GIS data and the maximum wind speed distribution obtained using the WRF model. Investigating the damage ratio ($R_d$) with 250 × 250 m meshes showed that the variation in $R_d$ at the same wind speed ($V$) was considerably large, and therefore, a quantitative evaluation based on $R_d$ was considerably difficult. However, focusing on damaged meshes, including one damaged roof, clarified that the cumulative number of damaged meshes for the squared maximum $V$ could be expressed by superimposing two Weibull distributions, and the Weibull parameters could be given by the building area ratio ($\varepsilon$). Moreover, the modelled values indicated a good approximation. This result indicated that the typhoon-induced roof damage probability could be estimated by $\varepsilon$ and maximum $V$ when typhoons pass through the focused area.

*Keywords: building area ratio, Weibull distribution, damage probability estimation*

## 1. INTRODUCTION

On September 4, 2018, Typhoon Jebi made landfall in Japan with an extremely high intensity and caused great damage over a wide area. This was the first time in 25 years that an extremely strong typhoon hit Japan. This typhoon killed 14 and injured 980 people, 46 of whom were seriously injured. It also damaged 97,910 houses, of which 68 were completely destroyed and 833 were partially destroyed. Damage to more than 70,000 houses was concentrated in Osaka Prefecture. Two months after the disaster, an aerial survey was conducted to determine the distribution of roof damage. In this study, the distribution of roof damage by typhoons was investigated using a geographic information system (GIS), and the distribution of the maximum wind speed ($V$) was obtained using the Weather Research and Forecasting (WRF) model.

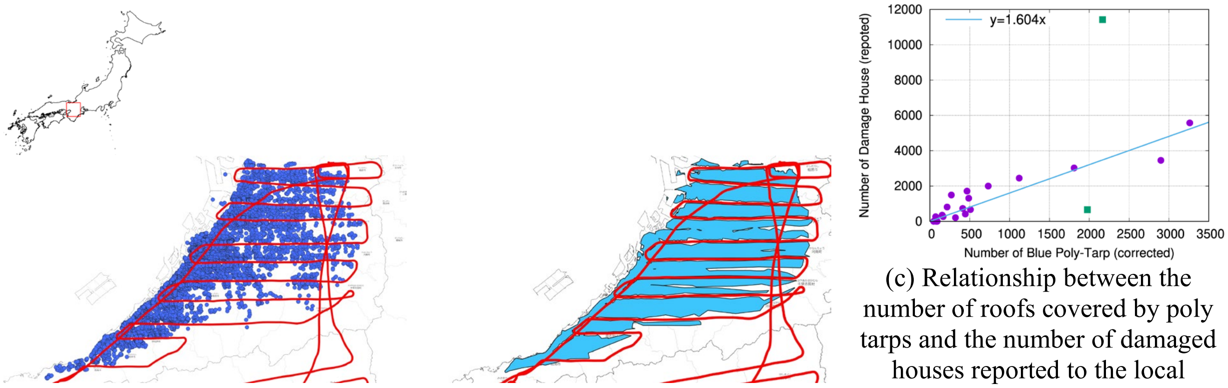
## 2. ANALYSIS CONFIGURATION

### 2.1. Aerial Survey

The aerial survey was conducted on November 13, 2018, 70 d after the disaster. Two 4K video cameras were set at the side window of the rear seat of a small propeller plane (Cessna 172R) to capture the footage. The shooting altitude was 600 m, and the shooting position was recorded using a global navigation satellite system (GNSS) receiver. Roofs covered with blue tarps were visually selected from the captured images, and the locations of the damaged roofs were identified by comparing them with satellite photographs on GIS. Figure 1 shows the survey results. In this figure, the solid lines, points, and polygons indicate the flight course, positions of roofs covered by blue poly tarps, and region of the aerial survey, respectively. Figure 1 (c) shows that the relationship between the number of roofs covered by blue poly tarps and the number of damaged houses reported to the local governments is approximately linear. Therefore, the distribution of blue poly tarps can be considered a substitute for the distribution of damaged houses.

### 2.2 Maximum Wind Speed Distribution

The meteorological analysis in this study was performed using the WRF model for Typhoon Jebi when it passed through the Kinki region (Takemi et al., 2019). The horizontal grid size was approximately 900 m. $V$ was calculated as a 10 min mean value, and the maximum $V$ at a height of 10 m was obtained from this calculation. $V$ at an arbitrary location was obtained using planar linear interpolation. The distribution of maximum $V$ is shown in Figure 2 (a).



(a) Blue poly tarp distribution

(b) Region of the aerial survey

(c) Relationship between the number of roofs covered by poly tarps and the number of damaged houses reported to the local governments

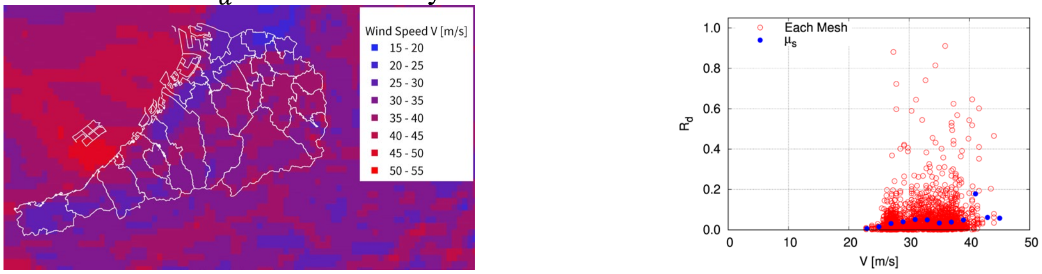
**Figure 1 Aerial survey results**

### 2.3 Damage Assessment Mesh

The damaged houses were analyzed using an evaluation mesh generated by an orthogonal grid arranged at intervals of 250 m on an orthogonal coordinate system. In this study, the meshes overlapped with the area of the aerial survey shown in Figure 1 (b).

## 3. MAXIMUM WIND SPEED ($V$) VERSUS DAMAGE RATIO ($R_d$)

The data obtained are often analyzed to determine the damage rates. Therefore, the damage ratio ($R_d$) was investigated. $R_d$ is defined as the ratio of the number of roofs covered by blue poly tarps to the total number of houses. Figure 2 (b) shows the relationship between $V$ and $R_d$, including each mesh. In this figure, the filled circles indicate the average ratio for each wind speed class. Notably, the variation in $R_d$ at the same $V$ was significantly large. Consequently, a quantitative evaluation based on $R_d$ is considerably difficult.



(a) $V$ distribution (10m height)

(b) $V$ vs. $R_d$

**Figure 2 Maximum wind speed when the typhoon passed through the Kinki area and the Relationship between the maximum wind speed, $V$, and the damage ratio, $R_d$**

## 4. DAMAGE PROBABILITY

### 4.1 Application of the weakest link model

The weakest link model shows the probability that when a chain made by connecting the same rings is pulled, the chain breaks if one of the rings is broken. This probability distribution is represented by a Weibull distribution (Weibull, 1951). Assuming that multiple buildings are designed according to the same design criteria within a single mesh, and that the same $V$ blows through the mesh, the house, mesh, and $V$ correspond to the ring, chain, and tension in the weakest link model, respectively. Therefore, a mesh that includes even one damaged house is defined as a damaged mesh. The cumulative number of damaged meshes ($P_d$) with respect to the maximum $V$ squared value was evaluated (Oda et al., 2022). The cumulative number was evaluated because the mesh that suffers damage at a $V$ lower than a certain $V$ naturally suffers damage, even at that $V$. The Weibull probability density distribution for explanatory variables $X$, $F(X)$ can be defined as follows (Equation 1):

$$F(X) = A\left[1 - \exp\left\{-\left(\frac{X - X_{\min}^2}{X_0^2}\right)^m\right\}\right] \tag{1}$$

where, $A$ denotes the convergence value, $X_{\min}$ denotes damage-start $V$, $X_0$ denotes the scale factor, and $m$ denotes the shape factor.

### 4.2 Squared maximum wind speed ($V^2$) vs. cumulative number of damaged meshes ($P_d$)

Figure 3 (a) shows the relationship between squared maximum wind speed $V^2$ and $P_d$ for each building area ratio, $\varepsilon$, class. As shown in this figure, two different Weibull distributions appeared to overlap in the relationship between $V^2$ and $P_d$. Therefore, a double Weibull distribution function that overlaps two Weibull distribution equations with ratio $a$ is defined as follows (Equation 2). The least squares method was used to obtain the Weibull parameters for each $\varepsilon$ class.

$$F(X) = A(\varepsilon)\left[a(\varepsilon)\left(1 - \exp\left\{-\left(\frac{X - X_{\min,1}^2}{X_{0,1}^2}\right)^{m_1}\right\}\right) + (1 - a(\varepsilon))\left(1 - \exp\left\{-\left(\frac{X - X_{\min,2}^2}{X_{0,2}^2}\right)^{m_2}\right\}\right)\right] \tag{2}$$

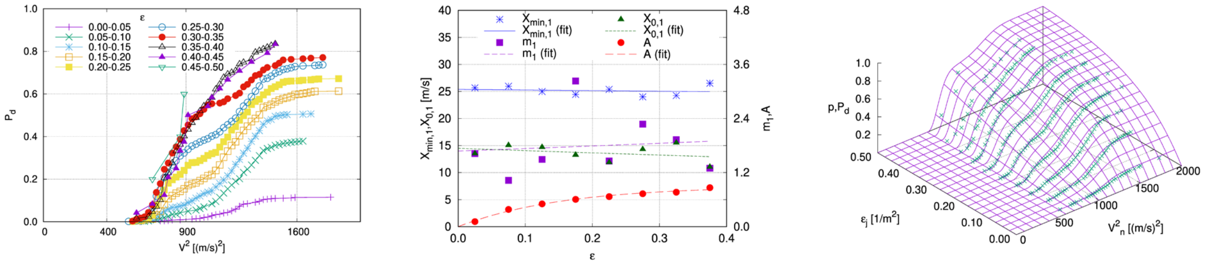
Figure 3 (b) shows the fitting results. The double Weibull distribution function provided a good approximation for each $\varepsilon$ class, as shown in Figure 3 (a). The relationship between $\varepsilon$ and these factors is shown in Figures 3 (c) and (d). Here, the factors are assumed to be controlled by $\varepsilon$ as follows (Equation 3):

$$A(\varepsilon) = \alpha_A\{1 - \exp(-\beta_A \cdot \varepsilon)\},\ a(\varepsilon) = (1 - \exp(-\beta_a \cdot \varepsilon)),\ X_{\mathrm{min,i}} = \alpha_{X_{\mathrm{min,i}}} \exp(-\beta_{X_{\mathrm{min,i}}} \cdot \varepsilon),$$
$$X_{0,i}(\varepsilon) = \alpha_{X_{0,i}} \exp\left(-\beta_{X_{0,i}} \cdot \varepsilon\right),\ m_i(\varepsilon) = \alpha_{m_i} \exp\left(-\beta_{m_i} \cdot \varepsilon\right) \tag{3}$$

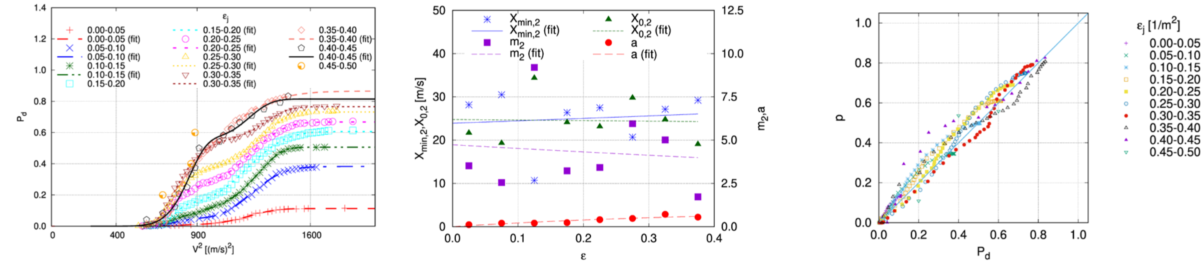
Table 1 lists the results of the least squares method. The relationship between $V^2$, $\varepsilon$, and $P_d$ is shown in Figure 3 (e) and calculated using Equations (2) and (3) with the values reported in Table 1. The relationship between the measured and modelled values is shown in Figure 3 (f). The estimated values indicated a good approximation of the measured values because the correlation coefficient was 0.989. The damage probability distribution was estimated using $\varepsilon$ and maximum $V$, as shown in Figure 3 (g). The relationship between the estimated damage probability class value ($p$) and the percentage of damaged buildings, $R_m$, in the mesh for the damage probability class is shown in Figure 3 (h).

Table 1 Parameters for Weibull distribution factors

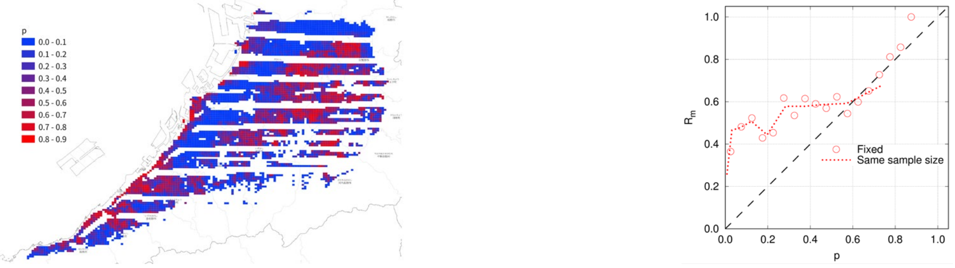
| $i$ | $\alpha_{X_{\min,i}}$ | $\beta_{X_{\min,i}}$ | $\alpha_{X_{0,i}}$ | $\beta_{X_{0,i}}$ | $\alpha_{m_i}$ | $\beta_{m_i}$ | $\alpha_A$ | $\beta_A$ | $\beta_a$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 25.4 | 0.045 | 14.5 | -0.300 | 1.679 | -0.324 | 0.9023 | 6.435 | 2.441 |
| 2 | 23.9 | -0.228 | 24.8 | 0.051 | 4.733 | 0.455 | | | |



(a) $V^2$ vs. $P_d$ (c) $\varepsilon$ vs. Weibull factors for Peak 1 (e) Cumulative number of damaged mesh and modeled distribution



(b) Fit curves (d) $\varepsilon$ vs. Weibull factors for Peak 2 (f) Measured value vs. estimated value



(g) Estimated damage probability distribution (h) p vs. Rm

Figure 3 Results of double Weibull distribution fitting and estimated damage probability

# 5. CONCLUSION

This study used GIS data and the maximum wind speed distribution to investigate the damage distribution of roofs covered by blue poly tarps that were captured by aerial surveys. The investigation clarified that the damage probability could be expressed using the double Weibull distribution density function and that these parameters were controlled by $\varepsilon$.

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