



EVACUATION ROUTE PLANNING UNDER AFTERSHOCK RISK CONSIDERING BUILDING-RELATED HAZARDS AND PEDESTRIAN DENSITY

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Abstract

Due to the impact of the 2011 Tohoku Pacific Offshore Earthquake (magnitude 9.0) that struck Japan, railway service in the Tokyo metropolitan area was suspended, leaving many people stranded and unable to return home. These stranded commuters congregated around railway stations and on major roads, causing massive congestion. Meanwhile, during the 2016 Kumamoto Earthquake in Japan, the largest mainshock (magnitude 7.3) occurred approximately 28 hours after the foreshocks, resulting in damage such as the collapse of many buildings and the falling of exterior walls. Based on these experiences, it can be said that crowd evacuation under conditions where aftershocks are expected is extremely dangerous. Therefore, evacuation strategies considering building characteristics (height and age), road conditions (width), and pedestrian density was examined in this study. The data regarding building height was obtained using 3D urban model PLATEAU [1] of the Ministry of Land, Infrastructure, Transport and Tourism, while the data regarding building age was derived from Zenrin's Residential Map. Regarding the risk of exterior wall collapse, the results of falling debris dispersion experiments previously conducted by the authors were utilized. Using this information, a risk index for each road link (road section) was created and the risk of evacuation routes based on the total risk of the road links traversed was evaluated. Using these datasets, a hazard index was calculated for each road link, and evacuation route risk was evaluated based on the cumulative hazard levels of the road links along the route. The findings of this study contribute to the examination of safe guidance strategies for people unable to return home in the event of a large-scale earthquake predicted to occur in the future.

Keywords: 3D urban model, project PLATEAU, risk level, pedestrian density

1 Introduction

Following a major earthquake, the basic policy recommends that people refrain from rushing home all at once and instead remain at their workplaces, schools, or other locations where they are at the time of the disaster, with the aim of preventing traffic congestion and secondary disasters [2]. However, a significant number of residents are expected to attempt to return home due to the need to check on the safety of family members, care for those requiring assistance, or protect and retrieve children, raising concerns about mass evacuations. Furthermore, since aftershocks are also anticipated, there are concerns about an increased risk of secondary disasters, such as the collapse of building facades. Furthermore, according to damage estimates by the Tokyo Metropolitan Government for a direct-hit earthquake in southern Tokyo (magnitude 7.3), 205 fatalities and 7,057 injuries are projected to result from falling objects outdoors [3].

However, these estimates do not account for the impact of aftershocks on people unable to return home, and the actual number of fatalities and injuries are expected to be even higher. In the Kita-Senju area of Adachi Ward, Tokyo, the site of this experiment - it is predicted that approximately 30,000 people would be stranded in front of Kita-Senju Station if public transportation, such as railways, were to cease operations following a major earthquake [4]. Therefore, this study focuses on Kitasenju Station, one of major transfer hubs in Japan, and its surrounding area. The objective is to develop a method for assessing the risk of wall collapse considering building age, height, and pedestrian density, and to propose evacuation routes capable of mitigating crowding.

2 Assessment of falling object hazards

2.1 Methods for assessing falling object hazards

Considering a situation in which exterior wall panels fall and fragments scatter horizontally, it is assumed that the kinetic energy gained during the fall is converted into the dispersion distance of the fragments. Based on the principle of conservation of energy, the velocity of an object falling from a height h immediately before it strikes the ground is given by equation (1):

$$v = \sqrt{2gh} \quad (1)$$

Let u be the initial horizontal velocity of the fragments after the collision, and v be the initial vertical velocity. If the horizontal and vertical velocities resulting from the collision are proportional to the velocity immediately before the collision, $\sqrt{2gh}$, and denoting the proportional constants as α and β , respectively, u and v are given by equations (2) and (3).

$$u = \alpha\sqrt{2gh} \quad (2)$$

$$v = \beta\sqrt{2gh} \quad (3)$$

$$t = \frac{2v}{g} = \frac{2\beta\sqrt{2gh}}{g} \quad (4)$$

Therefore, the horizontal dispersion distance d is given by equation (5) below.

$$d = 2vt = \frac{2vu}{g} = \frac{2\alpha\sqrt{2gh} \beta\sqrt{2gh}}{g} = 4\alpha\beta h \propto Kh \quad (5)$$

Thus, it can be seen that in the simple model of vertical free fall, dispersion distance d is proportional to height h .

$$d \text{ [m]} = Kh \text{ [m]} \quad (6)$$

The proportional coefficient K was determined using experimental results obtained in the authors' previous studies. Matsuoka et al [5] investigated the scattering characteristics of building materials expected to fall from roofs and exterior walls during earthquakes through drop tests. Their study examined both the overall scattering behavior of falling debris and the scattering characteristics associated with different material types. The experimental data were used to determine the proportional coefficient K in equation (6).

Specifically, the scattering distance equation was derived using data obtained from drop tests of concrete panels released from heights of 5 m, 15 m, and 20 m. From the experimental results, the maximum scattering distance of each 100 g fragment was extracted. Using the results shown in figure 1, a multiple regression analysis was conducted to determine the proportional coefficient K. As shown in table 1, the p-value was 0.01, indicating a statistically significant result. Equation (7) shows the expression obtained by substituting the calculated proportional coefficient into equation (6).

$$d [m] = 0.1362h [m] \tag{7}$$

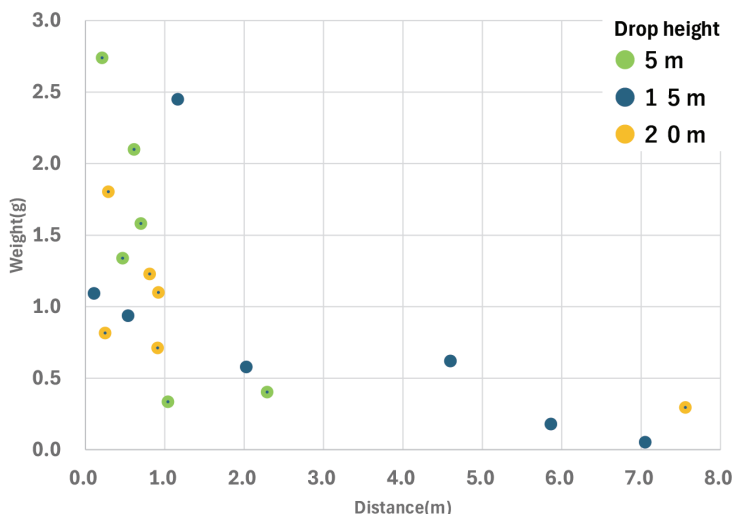


Figure 1 Relationship between fragment mass and dispersion distance

Table 1 Results of multiple regression analysis

Independent variable	Regression coefficient	p-value
Height [m]	0.1362	0.01***
Number of samples	19	

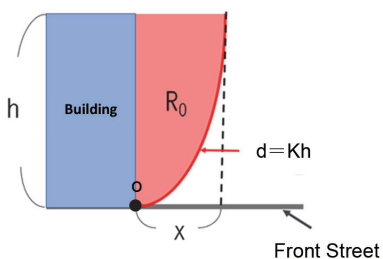


Figure 2 Schematic diagram of building-level risk

Figure 2 illustrates the relationship between the height of falling objects on a wall and their impact area. Since it is unknown at what height falling objects will occur during an earthquake, the impact in the vertical direction was accounted for by integrating the impact area expressed by equation (6). Point O is the most dangerous; it is a location where falling objects pose a risk regardless of the height from which they fall. By multiplying by the width b of the exterior wall facing the road, the hazard level $R(h, b)$ per building unit can be determined. The range of influence of falling objects from the wall surface can be calculated using equation (8).

$$R(h, b) = \frac{1}{2} K h^2 b \quad [\text{m}^3] \quad (8)$$

Building age was incorporated into the hazard assessment for buildings located along major roads with high hazard levels. Based on the “Estimated Damage in Tokyo from a Direct-Hit Earthquake in the Capital Area” [7], the estimated seismic intensity for Adachi Ward is 6.5, which was used to set the building age coefficient. Building age categories were divided into three groups, before 1981, 1982 to 1999, and 2000 or later, taking into account the year of the Building Standards Act amendment. The age coefficients corresponding to these categories were set at 0.9, 0.55, and 0.2, respectively, based on graphs showing the rates of total building collapse and large-scale damage (wooden structures, soft ground) due to shaking, as presented in the Report on Damage Projections for Tokyo from a Direct-Hit Earthquake in the Capital Area [7], published by the Tokyo Metropolitan Disaster Prevention Council. Furthermore, Zenrin residential maps from 1982, 2000, and 2025 were used to determine the age of the buildings. Equation (9) shows the definition. To calculate the age data, residential maps from different years (1982, 2000, and 2025) were compared, and the age was estimated by identifying the same buildings. The results were entered into ArcGIS Pro and organized as spatial data. The age data was acquired for the area near National Route 4.

$$T = \begin{cases} 0.9 (t \geq 1981) \\ 0.55 (1982 \leq t < 1999) \\ 0.2 (t < 2000) \end{cases} \quad (9)$$

$$R(h, b, t) = b t \frac{1}{2} K h^2 \quad [\text{m}^3] \quad (10)$$



Figure 3 Building risk level

Figure 3 shows that darker colors indicate higher levels of danger. As can be seen in figure 3, areas with high levels of danger are concentrated along major roads and near train stations.

2.2 Hazard Level per road link

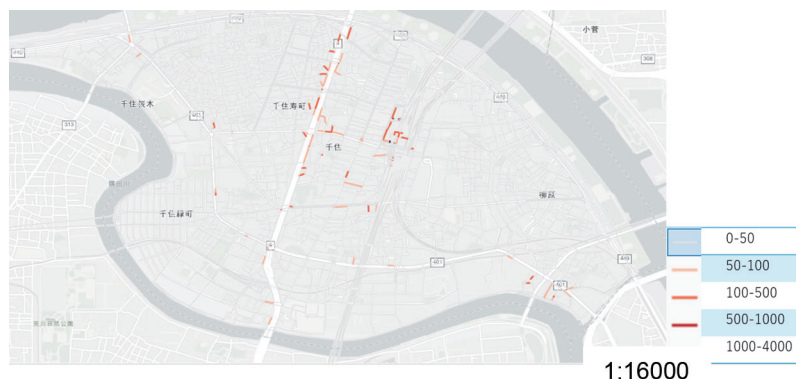


Figure 4 Risk level by road link

Table 2 Results of multiple regression analysis

Density [person/m ²]	Status	Risk multiplier
0.308	Free walking	1
0.431	Somewhat crowded	1.2
0.718	Contact initiated	1.5
1.076	Flow restriction	2
2.513	Jostling	3.5
3	Danger Zone	6

For each building (i), the hazard levels of buildings adjacent to each road link were aggregated and defined as the hazard level of the corresponding road link.

$$R_{ao} = \sum_i R_i(h, b, t) = \sum_i b_i t_i \frac{1}{2} K h_i^2 \quad [m^3] \quad (11)$$

Figure 4 indicates that darker colors represent higher levels of danger. When comparing this map of building-specific risk levels to figure 4, it becomes clear that locations where building risk is high also correspond to dangerous road sections. To evaluate hazard levels reflecting road congestion conditions, equation (12) was defined by incorporating road width, road length, and the number of evacuees into the hazard assessment for each road.

$$R_a = R_{ao} \left\{ 1 + \alpha \times \left(\frac{Q}{WL} \right)^\beta \right\} \quad [m^3] \quad (12)$$

Where is:

R_{a0} - initial hazard level of the road when no people are present

Q - number of evacuees

W - road width

L - road length

For parameter setting, the concept of Pedestrian level of service (LoS) proposed by John J. Fruin was adopted as an indicator of pedestrian congestion conditions. LoS is classified based on pedestrian density, and previous studies have shown that high-density conditions lead to pedestrian interference and reduced safety. The specific threshold values for the density classifications were determined based on previous research literature. The parameters were determined from table 2. Equation (13) shows the expression obtained by substituting the parameters into (12).

$$R_a = R_{a0} \left\{ 1 + 0.81742 \times \left(\frac{Q}{WL} \right)^{1.6076} \right\} \quad (13)$$

Figure 5 shows the risk levels for each road as the density is increased. Blue indicates the risk level for each building, while red indicates the risk level for each road. In both cases, darker colors indicate higher risk. Since the red color for the roads becomes darker with each level, it is visually apparent that the number of dangerous roads is increasing.

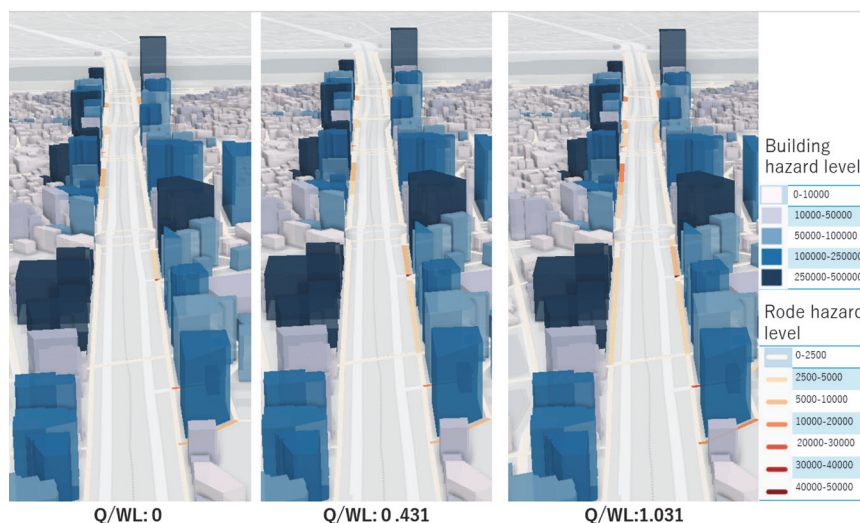


Figure 5 Differences in road hazard levels when density (Q/WL) is set

3 Conclusion

In this study, a method was developed to evaluate hazardous buildings and sidewalks using a 3D urban model based on building height, the weight of falling objects, and the width of building facades facing sidewalks. In addition, incorporating building age into the analysis enabled a more accurate assessment of hazard levels. By introducing the density parameter (Q/WL), it was demonstrated that hazard levels increase as road congestion intensifies. These findings suggest that the proposed method may serve as a useful indicator for safer evacuation behavior during large-scale earthquakes. Future work will apply user equilibrium assignments to calculate evacuation routes that reduce congestion imbalance. In addition, evacuation simulations will be conducted using the proposed routes to compare shortest routes with safer evacuation routes.

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9

RAILWAY CONDITION ASSESSMENT AND AI-DRIVEN MAINTENANCE

