Regional Analysis of Urban Development Based on an Evacuation Process in Earthquake Disaster Situations

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Abstract

Recently, there are many natural disasters accompanied by urban damage. The close analysis of local governments is required for the risk management, while relative examinations and data preparations need generally enormous times and efforts. On the other hand, local governments usually hold specific data for their daily implementation of administrative procedures. The data should be utilized for analyzing urban vulnerability to the disasters. There have however been few concepts or models for applying the data to the analysis. The purpose of this study is to suggest the concept and model for the analysis of the urban vulnerability. We apply the accumulated data to our model based on the concept with respect to earthquake evacuation behavior of residents. In addition, we adopt city planning roads as evaluation criteria, and we compare the results of analysis based on our model with those of conventional research for verification.

1. Introduction

Recently, there are many natural disasters accompanied by urban damage. The extensive damage from the earthquake and huge tsunami in the Tohoku Earthquake is widely known as a representative example. A large number of regions affected by the disaster are still in the process of being reconstructed even though about 2 years have passed by since the disaster happened.

For disaster prevention and mitigation, various measures in multiple fields are carried out nowadays. One of the approaches for urban planning and urban management is to analyze urban vulnerability to disasters for risk management. It is not merely incumbent on the government but also the responsibility of local governments since both general countermeasure and meticulous attention to detail are required.

The close analysis for the risk management requires examinations and data preparations while they generally need enormous times and efforts, which cause severe strain on the finances of local governments. On the other hand, local governments usually hold specific data for their daily implementation of administrative procedures. The data should be utilized for analyzing the urban vulnerability because of local government accountability. There have however been few concepts or models for applying the data to the analysis for the risk management.

The purpose of this study is to suggest the concept and model for the analysis of the urban vulnerability to natural disasters. Through the local government cooperation, we apply the accumulated data to our model based on the concept with respect to earthquake evacuation behavior of residents. In addition, we adopt city planning roads as evaluation criteria, and we compare the results of the analysis based on our model with those of conventional research for verifying the proposed method.

2. Materials and methods

2.1. Study area

In this study, the whole area of the Neyagawa city was adopted as the area of interest. This area is located in the Osaka prefecture in the western part of Japan. It covers about 5 km in an east-west direction and 5 km in a north-south direction. The Neyagawa city has a population of about 250 thousand. There are various types of districts in this area: densely built-up districts developed rapidly during a high economic growth period after

World War II, district planned areas, and districts developed through surveying and estimation of crop yields during the latter half of the 16th century.

2.2. Concept and model

2.2.1. Concept

The concept of our model consists of 3 points as follows:

1. To analyze a whole area of interest to compare between local districts for decision support.
2. To be based on residents behavior in disaster situations for the accountability of local governments.
3. To apply the data accumulated by general administrative procedure to the analysis.

2.2.2. Model

Fig. 1 shows the model we propose in this study. According to the concept, the population distribution of the study area is adopted as the spatial index for the comparison between local districts. Based on evacuation behavior of residents, a road blockade caused by building collapse given by earthquake is defined as the urban disaster in this study.

The evacuation behavior has been studied in various fields. Kady and Davis (2009) investigated the impact of route design on evacuation times for crawling movements in a building. They showed that both gender and BMI were major physical determinants of evacuation time of crawlers in an indirect route. Tang, et al. (2008) pointed out that the purpose of evacuation plan diagrams was for readers to comprehend and plan an evacuation route, and the understanding such diagrams influenced the times that they spent planning their escape route. Chiu, et al. (2008) analyzed the situation in which evacuees were given a set of system-optimal paths; the evacuees chose their evacuation routes, following a certain route-choice behavior. A behavior-robust feedback information routing strategy was also proposed to update the advised routes. Based on a survey for understanding the people's decision making process for evacuation routes, a prototype version of multi-agent simulation system was developed (Xu (2007), Lui, et al. (2008)).

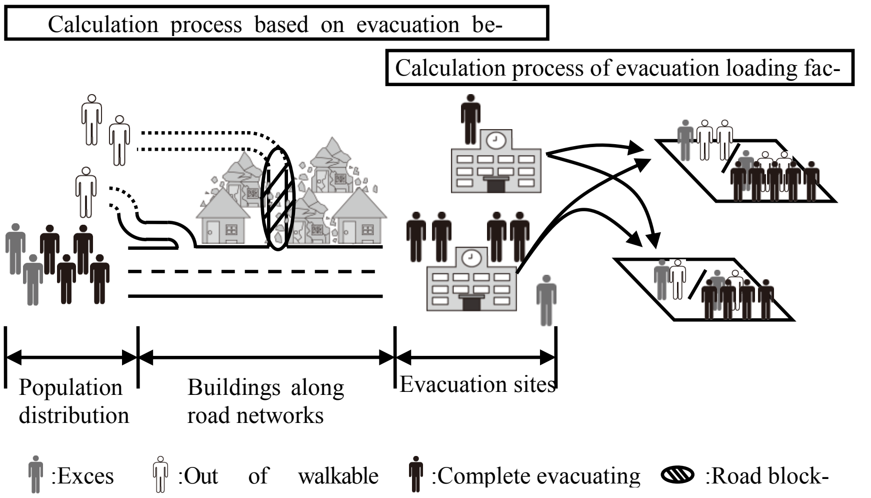


Fig. 1. Design of the model we propose. The model consists of two parts: “Calculation process based on evacuation behavior” and “Calculation process of an evacuation loading factor”.

The optimal routing of evacuees in emergency situation has been generally discussed in various fields (Francis (1981), Smith (1988), Vargas-Villamil (2006), Lu, et al. (2006)). Ferranti, et al. (2008) devised distribution algorithms that allowed agents to dynamically discover and maintain short evacuation routes connecting emergency exits from a building. They proposed two evacuation route discovery mechanisms and integrated them with existing exploration algorithms. An approach for managing crowd evacuation from buildings was also suggested (Pizzileo, et al., 2010). Total egress time was reduced through driving individuals towards less congested exits and comparing between the predicted evacuation times from each exit. On a county or city scale, optimization of evacuation traffic on road networks has been discussed. Raub, et al. (1998) examined fifteen incidents involving crashed and disabled vehicles, and headways were measured and estimates of vehicles flow rates computed. Cova, et al. (2003) proposed a network flow model for identifying optimal lane-based evacuation routing plans in complex road network. The model included an intersection model because most traffic delays in regional evacuations occurred at intersections. An evacuation route control strategy based on real-time data for urban freeways was also propounded for speed up egress (So, et al., 2010). On the other hands, Yuan, et al. (2006) indicated the use of prespecified destinations for evacuees almost resulted in less-than-optimal evacuation efficiency because of uncertain road conditions including traffic congestion, road blockage, and other hazards associated with emergency.

The road network accumulated by the government is the framework of this study because most of evacuation routes consist of the roads. The feature of the model is not the solution of the shortest route to an evacuation site but the occupation of network buffers from evacuation sites. The model consists of two parts: “Calculation process based on evacuation behavior” and “Calculation process of an evacuation loading factor”.

In the first process, we determine the evacuation sites as key points, and we execute network buffering along road networks. Then, we calculate the numbers of people along the road network, recognized as “Out of walkable range from evacuation sites”, “Excess of an evacuation site capacity even though within the walkable range”, and “Complete evacuating”, respectively. In the second process, we feed back these numbers to every small district. Then, the ratio of “Out of walkable range” and “Excess of an evacuation site capacity” to local population every small district is calculated. This ratio is defined as an evacuation loading factor in this study. These calculations will be described fully in section 2.3.2.

2.3. Data preparation and methods

2.3.1. Data preparation

We used the Digital Map 2500 (Spatial Data Framework) and the Fundamental Geospatial Data issued by the Geospatial Information Authority of Japan. Center lines of roads, blocks, and outlines of buildings were prepared from these data sources. The Japan Engineering Geomorphologic Classification Map and the Digital Map 5m Grid (Elevation) were applied as geotechnical data (Wakamatsu, et al., 2004). House ledger was digitized for the extraction of building properties: structure, date of construction, and floor level. In cases where the analysis can be carried out in broad areas (e.g. multiple cities or the whole of a prefecture), much effort will be expended on digitizing the house ledger. The house ledger is however basic information for the management of a real estate tax. It will be previously digitized through the spread of GIS in local governments. Evacuation sites were geocoded from a disaster prevention map of the Neyagawa city through the CSV Address Matching Service provided by the Center for Spatial Information Science in Tokyo University, and point data of the evacuation sites were acquired. Population distribution held by blocks was derived from the 2005 Population Census in Japan. For the spatial analysis along with the road networks, the local population was allocated to each road center line surrounding the block relative to the line length as a spatial weight.

2.3.2. Methods applied in the model

Building collapse risk

Behavior of the building collapse generally depends on a location of an earthquake's epicenter, intensity of an earthquake motion, and a type of tremor. It is also needed to compare between districts independently of the earthquake attribute. The building collapse risk applied in this study has been defined by opinions of experts on earthquake disasters (e.g. the Great Hanshin-Awaji Earthquake Disaster). Table 1 shows the building collapse risk. Building properties (the structure and the date of construction) and geomorphological land class choose the building collapse risk for assignment of a relative weight to the building (Murao, et al., 2000).

Table 1. Building collapse risk applied in this study. Building properties (the structure and the date of construction) and geomorphological land class choose the building collapse risk for assignment of a relative weight to the building (Murao, et al., 2000).

Structure	Date of construction	Geomorphological land class					
		Hill	Alluvial fan low grounds	Gravelly terrace	Volcanic ash terrace	Delta low grounds (sand)	Delta low grounds (mud)
Wooden building	-1961	16.0	9.1	13.1	46.0	41.9	60.6
	1962-1971	8.6	3.9	6.5	36.9	32.4	53.6
	1972-1981	7.6	3.3	5.7	35.6	31.0	52.7
	1982-1991	2.2	0.8	1.5	14.6	12.1	25.6
	1992-	1.0	0.4	0.7	5.6	4.7	10.0
RC building	-1981	3.5	2.1	2.9	10.9	9.7	16.0
	1982-1991	0.9	0.4	0.7	4.2	3.5	7.1
	1992-	0.5	0.3	0.4	1.7	1.5	2.7
Steel construction	-1981	13.2	8.8	11.4	30.3	27.9	39.5
	1982-1991	1.9	0.9	1.5	9.5	8.0	15.8
	1992-	1.0	0.6	0.9	3.6	3.2	5.7
Light-weight steel construction	-1981	8.8	5.3	7.3	24.9	22.4	34.5
	1982-1991	2.7	1.9	2.4	6.2	5.7	8.4
	1992-	2.1	1.5	1.9	4.5	4.2	6.1

Calculation of road blockade risk

Road blockade risk is calculated from the building collapse risk. Likewise, relationship of locations between a road and buildings is required for the detection of a road blockade caused by building collapse. Laefer, et al. (2006) mentioned an influence of fallen trees on the safe and uninterrupted use of the road transportation system during storm events, and they proposed a methodology for automating the tree threat identification process by using airborne laser altimetry data and GIS. In this study, we calculate ranges of building rubble using buffer zones (see Fig. 2). The ranges of building rubble depended on the floor level are derived from building properties. All directions of building rubble are approximately generated because of uncertainty of earthquakes. Discrimination of road blockade is given by the comparison of locations between a road and the ranges of building rubble in a building-by-building basis.

The building collapse risk and the discrimination are then applied to GIS analysis to determine the risk of the road blockade. The road blockade risk on a road is derived from probability based on building collapse risk and the locational relationship between a road and rubble ranges. The probability space of the road blockade on a road basically consists of the combination of building collapse events: whether building collapse occurs or not at each building around a road. The relationship between a road and rubble ranges is also added to the probability space. The road blockade risk is calculated as the probability of occurrence of both building collapse events and the road overlaid by their rubble ranges.

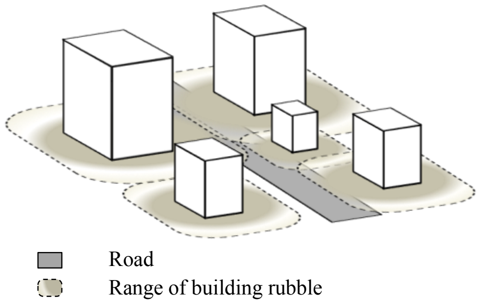


Fig. 2. Comparison of locations between a road and the ranges of building rubble on a building-by-building basis. The comparison leads to discrimination of road blockade when the building collapse occurs.

Making road blockade patterns

Making road blockade patterns, we apply the road blockade risk to the Monte Carlo simulation. In the simulation, the road blockade risk is adopted as the probability of occurrence of road blockade. The simulation is executed 100 times in this study, and the road blockade patterns are obtained as the results.

Calculation of the evacuation loading factors

In “Calculation process based on evacuation behavior” in Fig. 1, we determine the evacuation sites as key points, and we execute network buffering along road networks. For uniquely identifying road networks, a network voronoi division is also applied to the network buffering so that the coverage of the evacuation sites is clarified. The network voronoi division divides a network according to the shortest distance from the key points. The network voronoi division is then applied to the results of the simulation, and 100 results of the division are obtained. Fig 3 shows the features of the road networks in this study. The feature of isolated roads is displayed in Fig. 3. The no-divided roads through the network voronoi division are defined as the isolated road because it is assumed evacuation routes from the road to any evacuation site cannot be ensured by the road blockades. Throughout the 100 results, the frequency of the occurrence of the no-divided road is kept count on a road-by-road basis. There are various frequencies of the occurrence of the isolated road in Fg.3. Low frequencies are located widely in the eastern part of the test site, while high frequencies are distributed in some local areas. Highest frequency (colored with red in Fig. 3) seems to be densely distributed in specific areas. Most of the areas are densely built-up districts developed rapidly during the high economic growth period after World War II.

There seem to be various road network routes to the evacuation sites in the 100 results. We focus on the variations as the uncertainty of the urban structure. The shortest path method studied popularly generates the probability to reach all the evacuation sites generally. In this study, the fluctuations of local populations divided according to the road network variations on a basis of the road blockades are defined as the local features of the urban vulnerability.

We also define walkable distances from the evacuation sites, depending on the generations of the residents along the roads. Then, we calculate the number of people along the road network at the distances or more, recognized as “Out of walkable range from evacuation sites”. Within the dis-

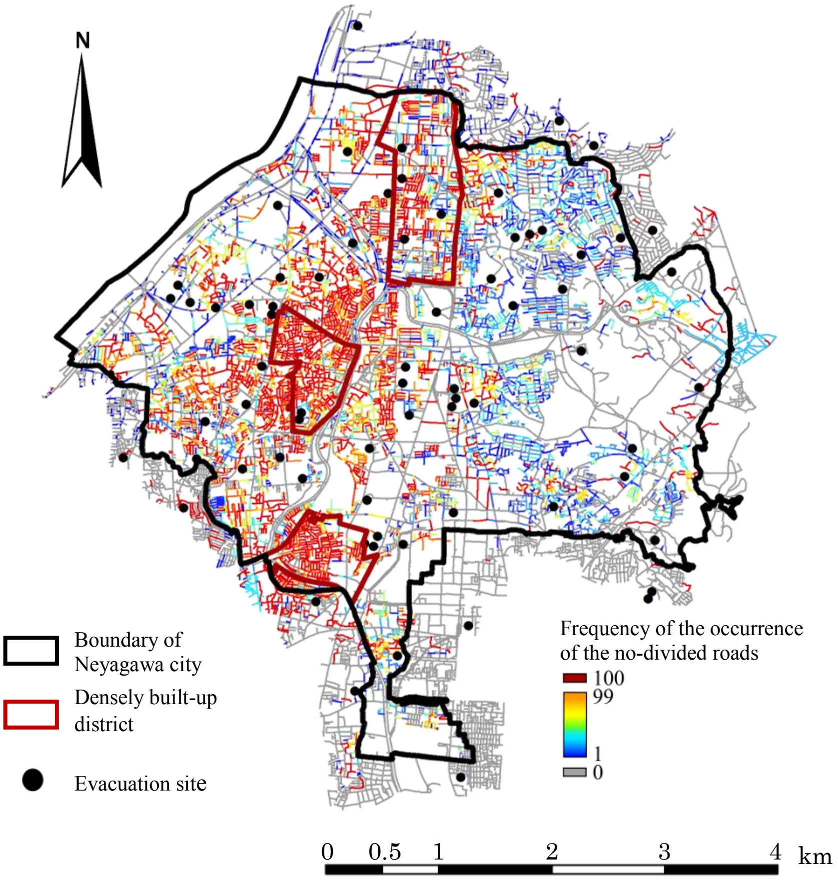


Fig. 3. Isolated roads calculated in this study. Throughout the 100 results, the frequency of the occurrence of the no-divided roads was kept count on a road-by-road basis.

tances, we compare the number of the people with the capacity of the evacuation site, and we obtain differences between them. We define the differences as “Excess of an evacuation site capacity even though within the walkable range”, where the number is more than the capacity. “Complete evacuating” is defined the number of people within the distances, where the number is less than or equal to the capacity.

In “Calculation process of an evacuation loading factor” in Fig.1, we feed back these numbers to every small district on the basis of the segment ratio of road networks contained. Then, the ratio of “Out of walkable range” and “Excess of an evacuation site capacity” to local population every small district is calculated as the evacuation loading factor.

We obtain the evacuation loading factors from every result. Finally, the averages and standard deviations of the evacuation loading factors are derived as the variation of “Excess”, “Out of walkable range” containing local population along the isolated roads, and “Complete evacuating”.

The population applied in this study is night-time population. It is possible to apply any kinds of population (e.g. daytime population) to the model according to disaster-occurring time.

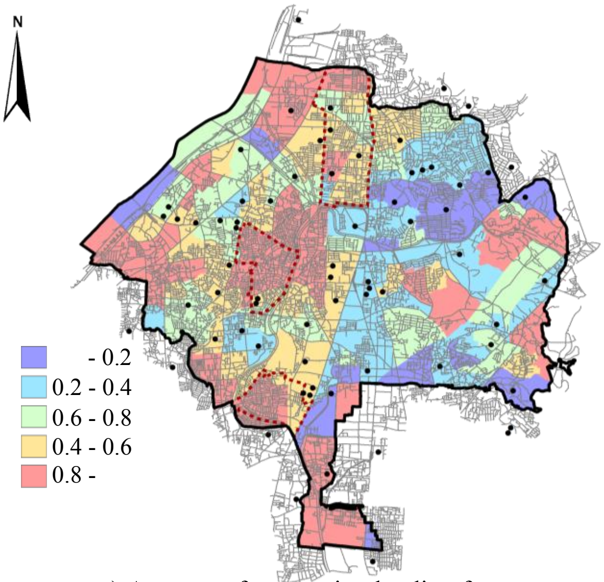
3. Results and discussion

3.1. Results of the analysis

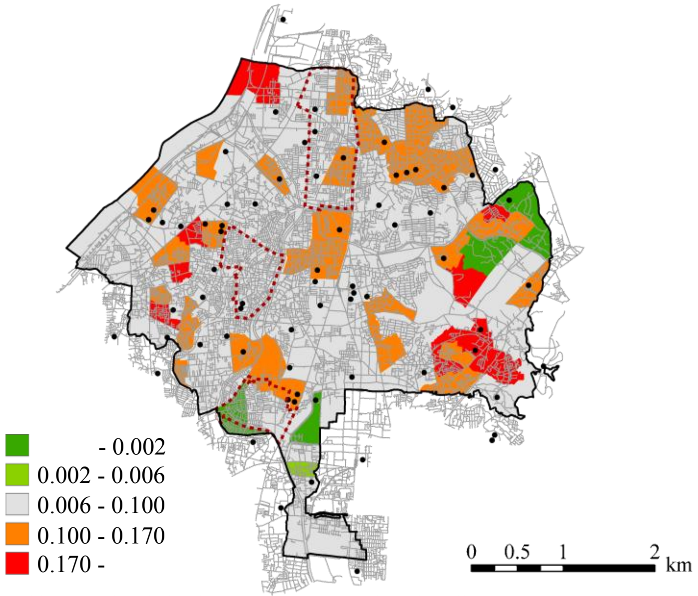
Fig. 4 shows the results of the application of the model. Figures 4a and 4b reveal the average and standard deviation of the evacuation loading factors, respectively. Gradations in color from blue to red denote the average of the evacuation loading factors in Fig. 4a, while gradations in color form green to red denote the standard deviations of the evacuation loading factors in Fig. 4b. There are large amounts of high average areas in the western part where the rapid development occurred after World War II. The distributions of the average of evacuation loading factors seem to have no correlation to those of the standard deviation of evacuation loading factors. Fig. 5 reveals a scatter diagram with respect to the relationship between the averages and the standard deviations. There are some districts distributed high standard deviation range and middle average range in Fig. 5. They seem to have a potential risk for evacuations along the road networks because of the road blockades and the locations and capacities of the evacuation sites.

3.2. Verification through the application of city planning roads

To verify the results of our model, we apply the surveying results of city planning roads in the test site. The city planning roads were generally decided to be constructed in the high economic growth period after World War II. Their width, alignment, and locations were idealized and well-designed. There used to be high development pressures around the past center of cities. There also are not enough sites for the construction of the roads now. Many plans have not been able to be put into execution because of the spread of the rapid private developments. Recently, urban de-



a) Average of evacuation loading factors



b) Standard deviation of evacuation loading factors

— Road ⁞ Densely built-up district ● Evacuation site

Fig. 4. Results of the application of the model: averages and standard deviations of evacuation loading factors.

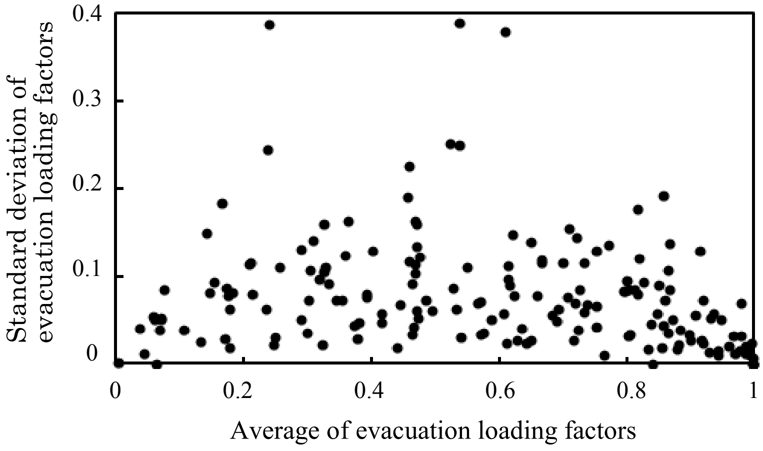


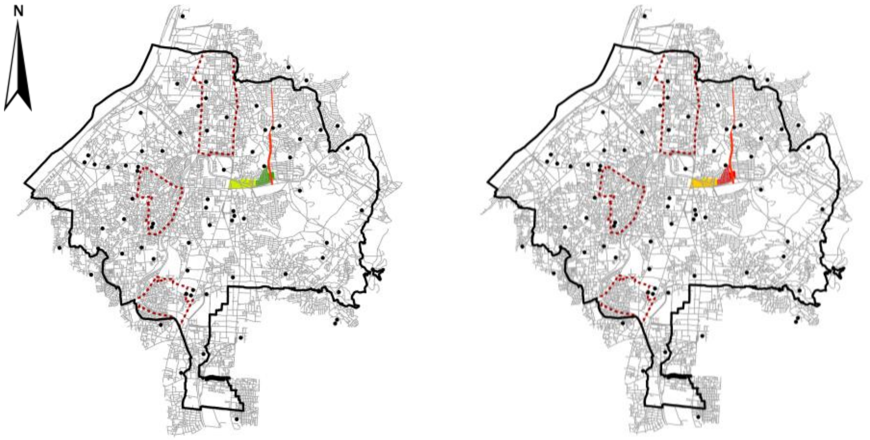
Fig. 5. Scatter diagram of the average and standard deviation of evacuation loading factors every small district.

velopment in Japan enters into a period of maturity. We also move into the age of an aging population due to a low birth rate. It is needed to have a rethink on the city planning roads from multiple view points: economic contributions, disaster prevention and mitigation, environmental issues, transportation system, and other facility issues. On the other hand, we had huge damages from the earthquake and tsunami lately. The role of the city planning roads in preserving and mitigating disasters has been gaining renewed attention.

3.2.1. Results of the application of city planning roads

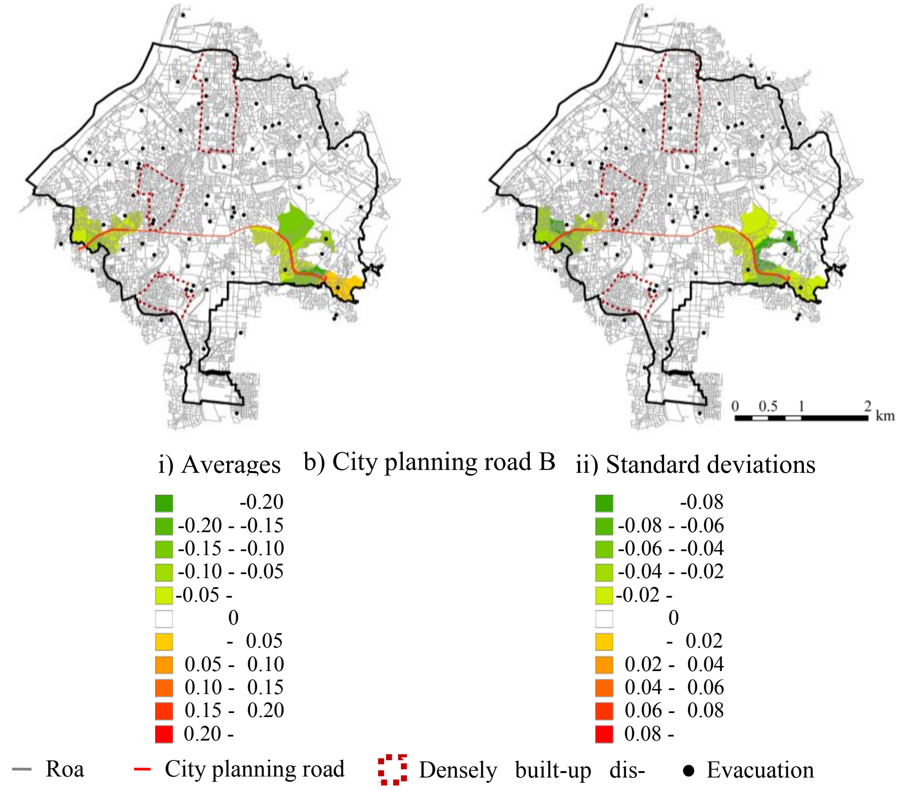
We apply the data of city planning roads to the model. We previously made the data of each city planning road through digitizing city planning map and allocating population to nearest roads as a road property. To clarify the effectiveness of the application with regard to the disaster prevention and mitigation, the differences between the current result and each result of the application are derived from the comparison between evacuation loading factors: the averages and standard deviations.

Figures 6, 7, 8, 9, and 10 show the differences between the current result and each result of the application. We adopt 10 city planning roads: from city planning road A to city planning road J. In these figures, each city planning road is colored with red. The gradations in color in the green hue mean decreasing the averages and standard deviations of evacuation loading factors through applying a city planning road, while the gradations in



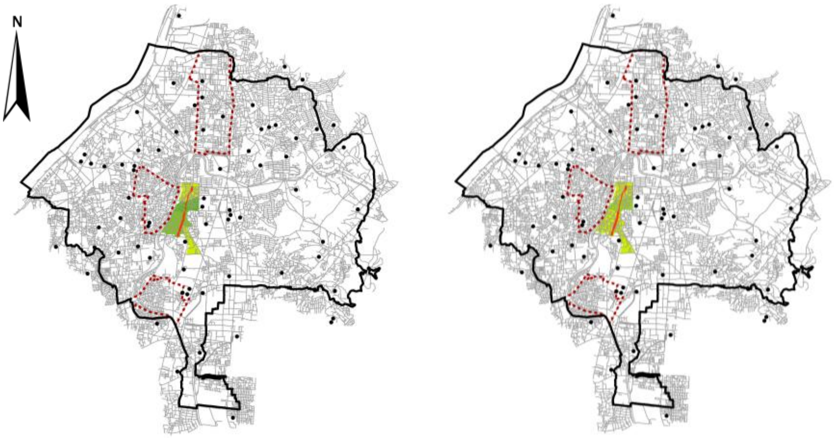
i) Averages ii) Standard deviations

a) City planning road A



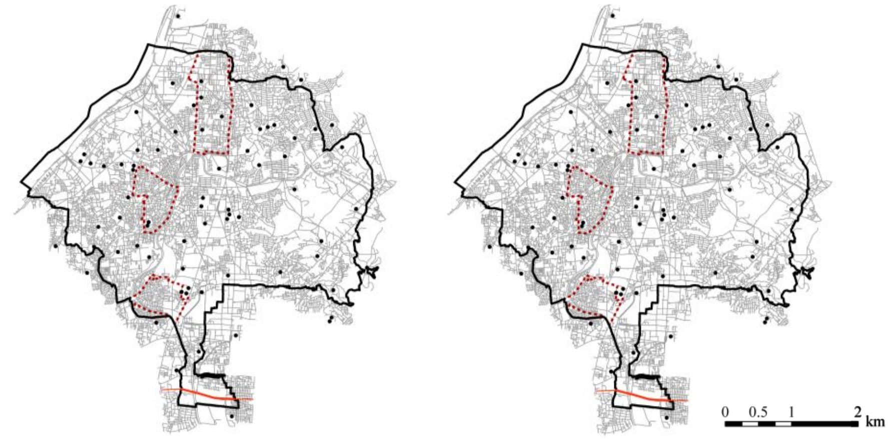
i) Averages b) City planning road B ii) Standard deviations

Fig. 6 . Discriminated results of the averages and standard deviations between the current status and the assumed development of city planning roads A and B.



i) Averages ii) Standard deviations

a) City planning road C



i) Averages ii) Standard deviations

b) City planning road D

🟩 -0.20
🟩 -0.20 - -0.15
🟩 -0.15 - -0.10
🟩 -0.10 - -0.05
🟨 -0.05 -
☐ 0
🟨 - 0.05
🟧 0.05 - 0.10
🟧 0.10 - 0.15
🟥 0.15 - 0.20
🟥 0.20 -

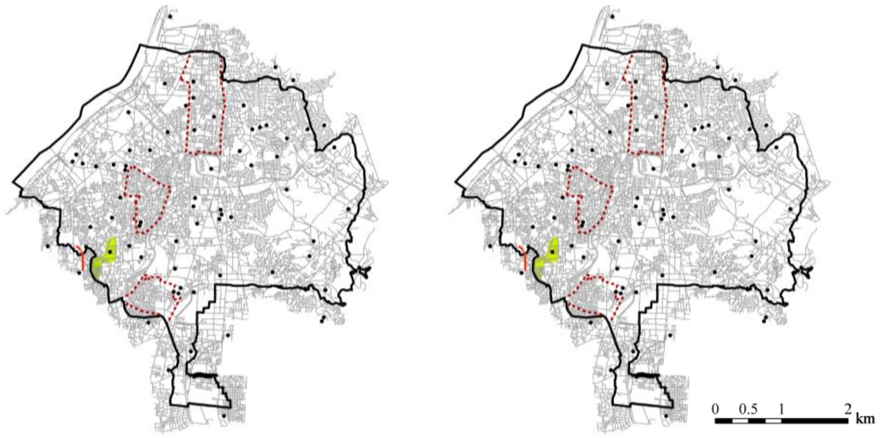
🟩 -0.08
🟩 -0.08 - -0.06
🟩 -0.06 - -0.04
🟩 -0.04 - -0.02
🟨 -0.02 -
☐ 0
🟨 - 0.02
🟧 0.02 - 0.04
🟧 0.04 - 0.06
🟥 0.06 - 0.08
🟥 0.08 -

— Road — City planning road ⁞ Densely built-up district ● Evacuation site

Fig. 7. Discriminated results of the averages and standard deviations between the current status and the assumed development of city planning roads C and D.

i) Averages ii) Standard deviations

a) City planning road E



i) Averages ii) Standard deviations

b) City planning road F

🟩 -0.20
🟩 -0.20 - -0.15
🟩 -0.15 - -0.10
🟩 -0.10 - -0.05
🟩 -0.05 -
⬜ 0
🟨 - 0.05
🟧 0.05 - 0.10
🟧 0.10 - 0.15
🟥 0.15 - 0.20
🟥 0.20 -

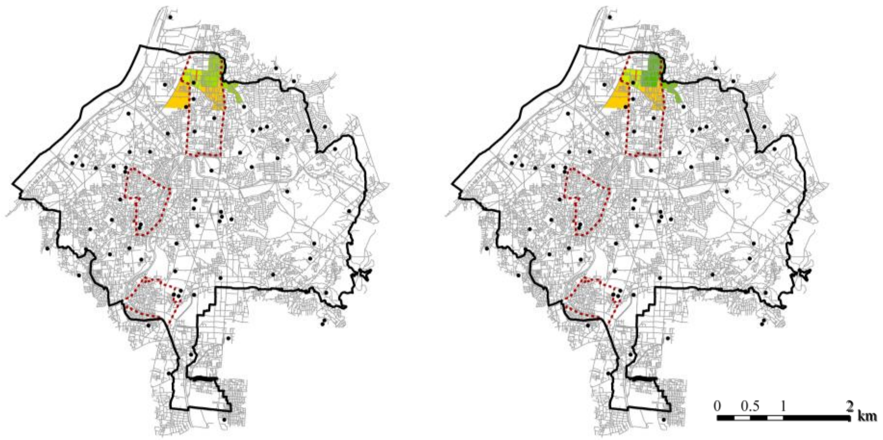
🟩 -0.08
🟩 -0.08 - -0.06
🟩 -0.06 - -0.04
🟩 -0.04 - -0.02
🟩 -0.02 -
⬜ 0
🟨 - 0.02
🟧 0.02 - 0.04
🟧 0.04 - 0.06
🟥 0.06 - 0.08
🟥 0.08 -

— Road — City planning road ⬚ Densely built-up district ● Evacuation site

Fig. 8. Discriminated results of the averages and standard deviations between the current status and the assumed development of city planning roads E and F

i) Averages ii) Standard deviations

a) City planning road G



i) Averages ii) Standard deviations

b) City planning road H

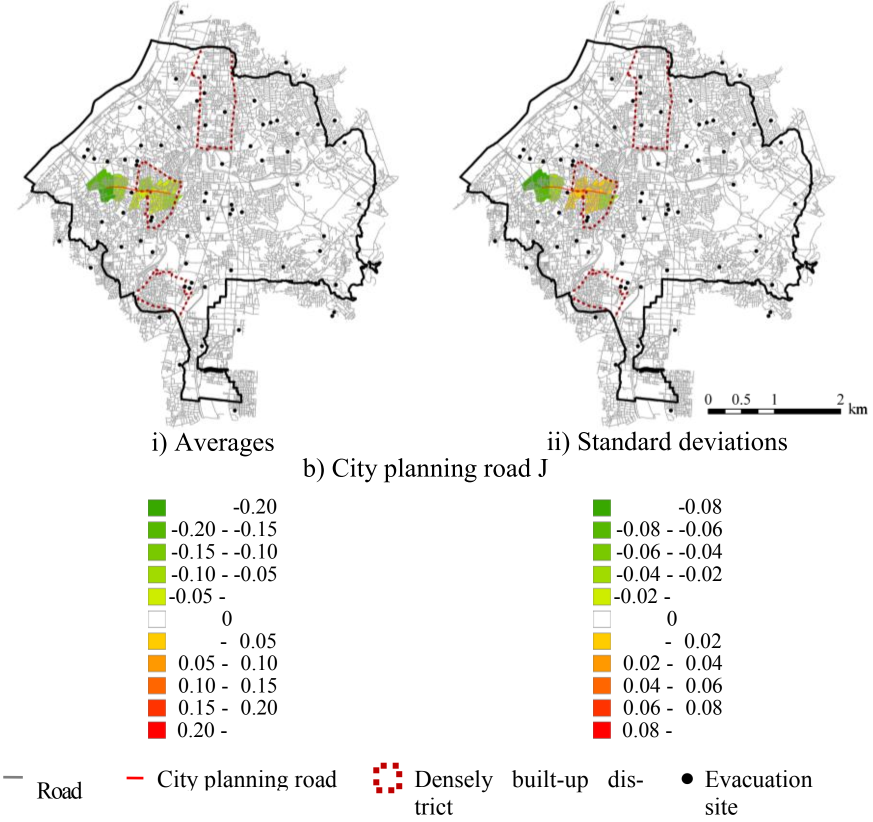
🟩 -0.20	🟩 -0.08
🟩 -0.20 - -0.15	🟩 -0.08 - -0.06
🟩 -0.15 - -0.10	🟩 -0.06 - -0.04
🟩 -0.10 - -0.05	🟩 -0.04 - -0.02
🟨 -0.05 -	🟨 -0.02 -
☐ 0	☐ 0
🟨 - 0.05	🟨 - 0.02
🟧 0.05 - 0.10	🟧 0.02 - 0.04
🟧 0.10 - 0.15	🟧 0.04 - 0.06
🟥 0.15 - 0.20	🟥 0.06 - 0.08
🟥 0.20 -	🟥 0.08 -

— Road — City planning road ⁚ Densely built-up district ● Evacuation site

Fig. 9. Discriminated results of the averages and standard deviations between the current status and the assumed development of city planning roads G and H.

i) Averages ii) Standard deviations

a) City planning road I



i) Averages ii) Standard deviations

b) City planning road J

Fig. 10. Discriminated results of the averages and standard deviations between the current status and the assumed development of city planning roads I and J.

color in the red hue mean increasing the averages and standard deviations according to assumed development of a city planning road. In other words, the green hue and red hue denote positive and negative implications for the function of disaster prevention and mitigation, respectively.

Figures 7a and 8b reveal green hue in both the averages and standard deviations of the evacuation loading factors. Through comparing these figures with Fig. 4, some of the small districts colored with green hue show high average and high standard deviation of the evacuation loading factors in the current results. The city planning roads C and F seem to be expected to contribute to the disaster prevention and mitigation.

In Figures 6a and 8a, city planning roads A and E show the reduction of the averages even though they also display the rise in the standard deviations. Especially, city planning road E is located in the densely built up area. The road blockades occur frequently in this area on the simulation result (see Fig.3). Then, these results suggest that there is still the risk of evacuation confusing for the disaster after the development of the city planning road. It seems to be needed to have a total plan for redevelopment of this area.

Fig. 9b reveals there are both the decreases and the increases of the averages and the standard deviations in same small districts around city planning road H. The results are divided into the positive and negative implications on the basis of the location of city planning road H. In the southern districts colored with red hue, we confirmed the increase of “Excess”, while “Out of range” decreased in the northern districts colored with green hue, according to assumed development of a city planning road in the model. It is apparent that our model suggests simultaneously the positive and negative implications for the disaster prevention and mitigation on a district-by-district basis.

There is no implication for the disaster prevention and mitigation around city planning roads D and G in Figures 7b and 9a because there are few evacuation sites in these areas.

3.2.2. Comparison of results between our model and surveying for rethink

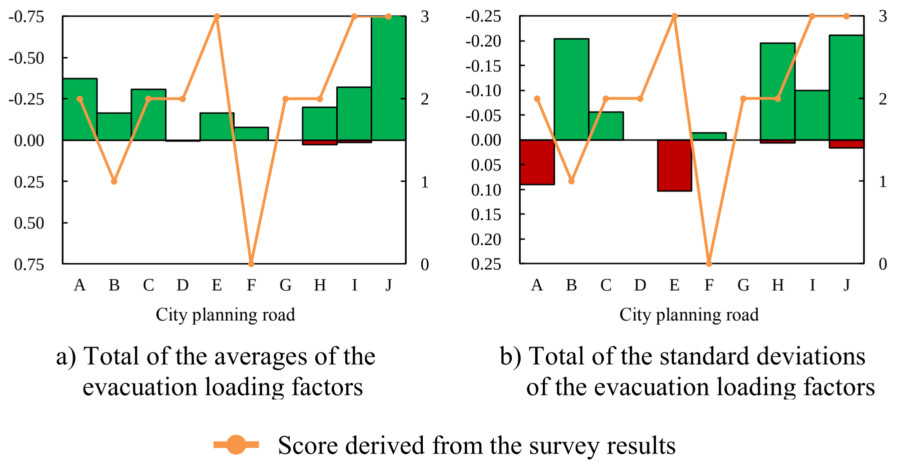
In this test site, the rethink project for the city planning roads is carried out by the local governments: the Neyagawa city and the Osaka prefecture. They surveyed the effectiveness of the development of each city planning road from multiple view points: economic contributions, disaster prevention and mitigation, environmental issues, transportation system, and other facility issues. We adopt the result of the surveying with respect to the disaster prevention and mitigation as a reference for comparing the result of our model.

The survey was carried out based on the calculation of the area of 15 m radius along each city planning road, defined as a disaster prevention area. The disaster prevention area is expected to prevent fire spreading. Then they divided the city planning roads into 4 classes on a basis of their areas: more than 5 ha, from 1 ha to 5 ha, less than 1 ha, and otherwise. The 4 classes were granted the scores of 3, 2, 1, and 0, respectively. The score of more than 2 means a positive implication to the function for disaster prevention and mitigation.

Fig. 11 shows the results of the survey and the application of the model. We sum respectively positive and negative implications from each result derived from the application of our model, i.e. Figures 6 to 10.

In Fig. 11a, matching ratio between the averages and the score with respect to the positive implications shows 0.6 in these 10 city planning roads. In city planning roads A and E, the standard deviations display the negative implications i.e. the increase, though the averages and the score shows positive. It would suggest the effectiveness of the application of the model as a multiple analysis.

In city planning road F, the score shows 0 because of the length of the road is too short in the test site, Neyagawa city. The averages and the standard deviations of the evacuation loading factors however indicate



a) Total of the averages of the evacuation loading factors

b) Total of the standard deviations of the evacuation loading factors

Fig. 11. Discriminated results and the score derived from the survey result for the assumed development of city planning roads. The left vertical axes mean total of the averages and standard deviations of the evacuation loading factors, while the right axes means the score derived from the survey results.

positive implications approximately. The city planning road F seems to play a role in disaster prevention and mitigation, especially with respect to road network connections over the boundary of the cities in spite of its length.

City planning road B reveals both positive implications in the model and negative implications in the survey results. The road B is mostly planned for widening, and its disaster prevention area is narrower than those of the other roads added newly. The score therefore shows low. On the other hand, the total of averages and standard deviations mean that city planning road B seems to hold the function for access to the evacuation sites and the population distributions in its background.

4. Conclusions

In this study, we proposed the concept and model to analyze the urban vulnerability to natural disasters. The concept was based on the features of local governments: utilization of the data accumulated by general administrative procedure. The approach of this study would be in consonance with data-driven decision making in performance management in government (Kamensky, 2011). The model consists of two parts: “Calculation process based on evacuation behavior” and “Calculation process of an evacuation loading factor”. We adopted the population distribution as the spatial index, and we applied general GIS processes and a simulation method to the model. The evacuation loading factor was newly defined as the spatial feature of urban vulnerability in the model using relative risk (e.g. building collapse risk) for disasters. Through the application of the model, it seemed apparent that the combination of the average and standard deviation of the evacuation loading factors indicated the local features with respect to urban vulnerability from multiple views based on the background: population distributions, the capacity and location of evacuation site, and road network complexity. We verified the effectiveness of the model through the comparison of the implications of the city planning roads between the results of the model and the current survey results. Consequently, the application of the model seemed to provide for suggestive results relative to disaster prevention and mitigation for comparing between local districts.

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