Evaluation of Improvement Projects in Densely Built-Up Area using a Large Earthquake Disaster Simulator: A case study in Kyojima Area, Tokyo

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ABSTRACT

This paper aims to (1) evaluate the disaster mitigation effects of improvement projects in a certain area and (2) provide a basis for strategic planning to promote further improvements. Specifically, we decompose local improvements in the analyzed area into multiple scenarios and examine their effects and issues. First, we describe the "large earthquake disaster simulator," which estimates property damage and human casualties in a large earthquake. Then, the Kyojima area of Sumida-*Ku*, Tokyo, is selected as the analyzed area. We decompose the improvement projects implemented during 2006 – 2016 and prepare six scenarios. Finally, a simulation analysis is conducted. We demonstrate that fire spread could be effectively blocked by (1) ensuring sufficient road width and (2) identifying the critical buildings in terms of fire spread mitigation and making them fireproof.

Keywords

urban planning, policy-making, large earthquake, disaster mitigation, improvement project, simulation.

INTRODUCTION

Background

To improve urban performance, such as safety and mobility, a wide variety of urban development projects have been promoted, including the construction of transportation networks and public facilities. However, these projects are not always proceeded as planned due to the difficulty in reaching a consensus among the numerous stakeholders involved. Therefore, it is essential to evaluate the projects after the implementation to (1) confirm whether the projects demonstrate the expected effects and (2) obtain valuable insights for the future project. In this paper, we take improvement projects for disaster mitigation in Tokyo, Japan, as an example for analysis.

Tokyo has many densely built-up wooden residential areas where urban renewal is stagnant. There are a high proportion of old houses and narrow streets and expected to be severely damaged if an earthquake directly hits the Tokyo metropolitan area (Tokyo Metropolitan Government, 2023a). It is urgent to improve the local environment and reduce disaster risk. To improve disaster resistance in densely built-up wooden residential areas, the Tokyo Metropolitan Government has designated the "Urban Development Plan for Disaster Resistance (Tokyo Metropolitan Government, 2023b)." It defines 28 districts (covering approx. 6,500 hectares) as "Development Districts." They also promote road widening projects to provide firebreak belts and the rebuilding/demolishing of vulnerable roadside buildings. However, approximately 35% of city planning roads in the development districts have remained unimproved (as of 2014). Although the fireproof area rate, which represents the district's inflammability, improved from 49% to 62% (as of 1996 and 2014), further efforts are needed to achieve the target

(70% in FY2025). This is because of the following reasons: (1) Residents' motivation to rebuild declined due to their aging; (2) It is difficult to reconstruct a building under current regulations due to its site conditions; (3) Due to complicated rights relations, it takes a long time to reach a consensus (Tokyo Fire Department, 2012). It is crucial to prioritize the projects and discuss how to proceed efficiently.

Many studies have analyzed improvement projects in densely built-up wooden residential areas. Park and Satoh (2013) clarified the characteristics of each improvement project in the wards of Tokyo by closely scrutinizing those previously implemented. Specifically, they categorized the projects in 32 districts into four project types. They then organized the characteristics of each project from five perspectives, such as "Timing of implementation" and "Project type." Although this study provided valuable knowledge for future improvement projects, it analyzed projects only from qualitative aspects. On the other hand, Igarashi and Murao (2007) evaluated the progress of improvement projects quantitatively. They confirmed the changes in the district's urban risk (building density, CVF, wooden house ratio, and the building collapse risk) over time, which was calculated with GIS data. However, they did not examine how those improvements affect disaster mitigation from a spatial viewpoint.

Estimating methods of the disaster mitigation effect due to improvements in the local environment, hereafter "local improvements," have also been proposed using a large earthquake disaster simulator. The simulator has been widely adopted in disaster risk reduction. Specifically, it provides a realistic environment to discuss disaster prevention among government agencies, landowners, and residents, based on estimated risk (Mota de Sá et al., 2016; Bonacho and Oliveira, 2018). In addition, it is also used to examine evacuation plans for residents (D'Orazio et al., 2014), maintain critical infrastructure (D'Agostino et al., 2019), and create recovery plans for essential lifelines such as water supply, power distribution, and transportation systems at the local government level (Deelstra and Bristow, 2020). Saitoh et al. (1999) and Kishimoto and Osaragi (2019) first evaluated disaster damage using a simulation model that describes property damages after a large earthquake. Then, they discussed the mitigation effects of local improvements based on aggregate values of local environments and disaster damages. On the other hand, Osaragi and Oki (2014) conducted a detailed simulation analysis using a simulator that considers the interaction between the local environment and the residents' movement. Although simulation analysis enables an evaluation of the mitigation effect in building/street units, it requires demanding preparation procedures for input data and a high computational cost. These studies analyzed the disaster mitigation effects of the improvement projects as one set. Therefore, their target was not to analyze the disaster mitigation effects of past urban development projects from multiple perspectives.

Research Objective

This study evaluates the disaster mitigation effects of improvement projects in densely built-up wooden residential areas and provides a basis for strategic planning to promote further improvements. Specifically, we conduct scenario analysis in the Kyojima area of Sumida-Ku, Tokyo. The structure of this paper is as follows. Chapter 2 describes our simulator, which estimates property damage (building collapse, street blockage, fire outbreak, and fire spread) and human casualties in a large earthquake. Then, Chapter 3 describes the analyzed area and the necessary data for the simulation. Chapter 4 explains the methodology of this study. Chapter 5 presents the simulation results, and we discuss the mitigation effects of improvement projects in Chapter 6.

PROPERTY DAMAGE AND HUMAN DAMAGE SIMULATION

Overview of the Simulation System

We evaluated the mitigation effect of local improvement quantitatively with a simulator consisting of two sub-models; the property damage model and the human damage model. In a simulator, we only considered the degree of property/human damage after a certain period (24 hours in this paper) had elapsed since an earthquake occurred.

We have developed the simulator independently as a program application, using Visual Studio as the development environment and C# as the programming language. The following are the steps of the scenario analysis using a simulator. First, we prepare input data for multiple scenarios according to the specified format (details on the data required for simulation will be described later). Next, set the simulation conditions such as seismic intensity, season, and time, and we estimated the spatial distribution of collapsed buildings, blocked streets, and fire spreads 24 hours after an earthquake using the property collapse model. This model consists of four existing models based on actual disaster data, such as the Great Hanshin-Awaji Earthquake. Each model is validated based on disaster data, and sufficient discussions on validation are presented in the original paper. Finally, considering the property damages previously estimated, we estimated the spatial distribution of human causalities using the human damage model. Since data on people's evacuation behavior after a large earthquake is limited, this study estimates human damage based only on the reachability of evacuation destinations under property damage and does not reflect phenomena such as crowd crush. In addition, the estimation results can be confirmed using a Windows Form application which is separately developed.

Property Damage Model

Various types of property damage models are available, ranging from those that estimate the damage at a regional level to those that predict damage at the individual building and street level. To verify the mitigation effects of specific building and street maintenance measures, we adopted a model that allows for damage estimation at the level of individual buildings and streets. Additionally, while several models can predict property damage by a building or street unit (Murao and Yamazaki, 1999; Murao and Yamazaki, 2000; Hayashi et al., 2000), we selected the appropriate model based on the attribute information of the available GIS data for this study. Hirokawa and Osaragi (2016) describe the property damage models in more detail.

Building Collapse Model

The probabilistic determination of building collapse was conducted by referencing fragility curves informed by actual property collapses during the 1995 Great Hanshin-Awaji Earthquake (Murao and Yamazaki, 1999; Murao and Yamazaki, 2000). This determination was accomplished by estimating probabilities using the Peak Ground Velocity (PGV), the structural material (wooden, reinforced concrete, or steel), and the construction age of the building. Subsequently, the state of each building (whether it had collapsed or not) was determined by comparing the probability of collapse with a randomly generated uniform number.

Street Blockage Model

We employed the model advocated by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) to assess the likelihood of street blockage (MLIT, 2003). In this model, the debris generation was posited to be contingent on the collapsed state of the buildings. Specifically, we estimated the probability, $P_b(W)$, that a street with a width of W [m] would be obstructed by debris resulting from collapsed buildings.

Fire Outbreak Model

The probability of a fire outbreak from each building was estimated based on building usage (19 categories) considering earthquake intensity, the season, the time of day, and the collapse status of a building (Tokyo Fire Department, 1997; Tokyo Fire Department, 2005).

Fire Spread Model

Using the fire spread model (Hirokawa and Osaragi, 2016), we estimated the final extent of fire spread based on the fire outbreak location. Specifically, building pairs with the possibility of catching fire were extracted based on the fire spread limit distance and the relative location to the neighboring building. The fire spread possibility was calculated for each building pair based on the fire-extinguishing and heat-receiving buildings' fire protection structures, location relationships, wind conditions (speed and direction), and others. Then, we constructed the fire spread network (Figure 1), which showed the fire spread relationship between the buildings, and estimated the final fire spread extent with the fire outbroke location.

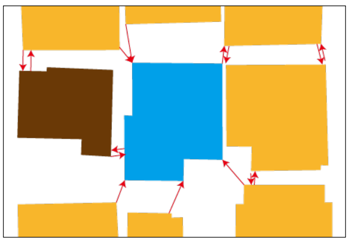

Figure 1. Fire spread network: Semi-fireproof, Wooden engineering for fire prevention, Wooden

Human Damage Model

The human damage model estimated the number of human casualties and people with difficulty in an evacuation after a certain period (24 hours in this paper) had elapsed since an earthquake occurred. In this model, taking into account the property damage distribution, evacuees searched for available routes to the evacuation destination.

Note that, to reduce the calculation cost, this model did not consider the dynamic change of fire spread or evacuation route, nor does it account for rescue and firefighting efforts. In the event of an earthquake, delays in emergency response efforts could exacerbate both the property and human damage. However, this model is not designed to account for the interplay between such activities. It has been demonstrated to produce relatively small differences in the estimates of casualties when compared to the model that considers firefighting and rescue activities (Oki et al., 2019).

People were classified into three major categories (Table 1). Those who were trapped in a collapsed building were classified as (3); otherwise, those who could find an evacuation route as (1), and who could not find a route as (2). Oki et al. (2019) describe the human damage model in more detail.

Table 1. Classification of evacuee

(1) People capable of evacuation; a person who can obtain the route to an evacuation site.	
(2) People stuck in a street	
(2-1)	**Casualty** by fire, who was stuck in a burnt-down area.
(2-2)	People with difficulty in evacuation who were stuck in a street outside a burnt-down area.
(3) People stuck in a collapsed building	
(3-1)	**Casualty** died instantly
(3-2)	People capable of escaping from a collapsed building by oneself
(3-3)	People who were (possibly) rescued by a person classified in category (1).
(3-4)	**Casualty**, who was in a burnt-down area.
(3-5)	**Casualty**, who was not in a burnt-down area but was seriously injured.
(3-6)	People with difficulty in evacuation, who were not categorized in (3-1) to (3-5).

DATA COLLECTION AND PREPARATION

Overview of Analyzed Area

We quantitatively evaluated the effects of improvement projects in the Kyojima area in Sumida-*Ku*, Tokyo. Although public institutions have been working to improve the vulnerability in this area, Tokyo Metropolitan Government (TMG) categorizes this area as one with the highest community risk level during a large earthquake (TMG, 2022). In other words, severe damage, such as a large-scale fire spread, is expected at the time of a large earthquake.

Several improvement projects have been implemented to reduce disaster risks in the area. Figure 2 shows the projects implemented during the ten years from 2006 to 2016, including the construction of community housing for former residents who lost their homes due to improvement projects, the development of city planning roads, and the removal/construction of buildings with subsidies, and, urban redevelopment projects (Table 2).

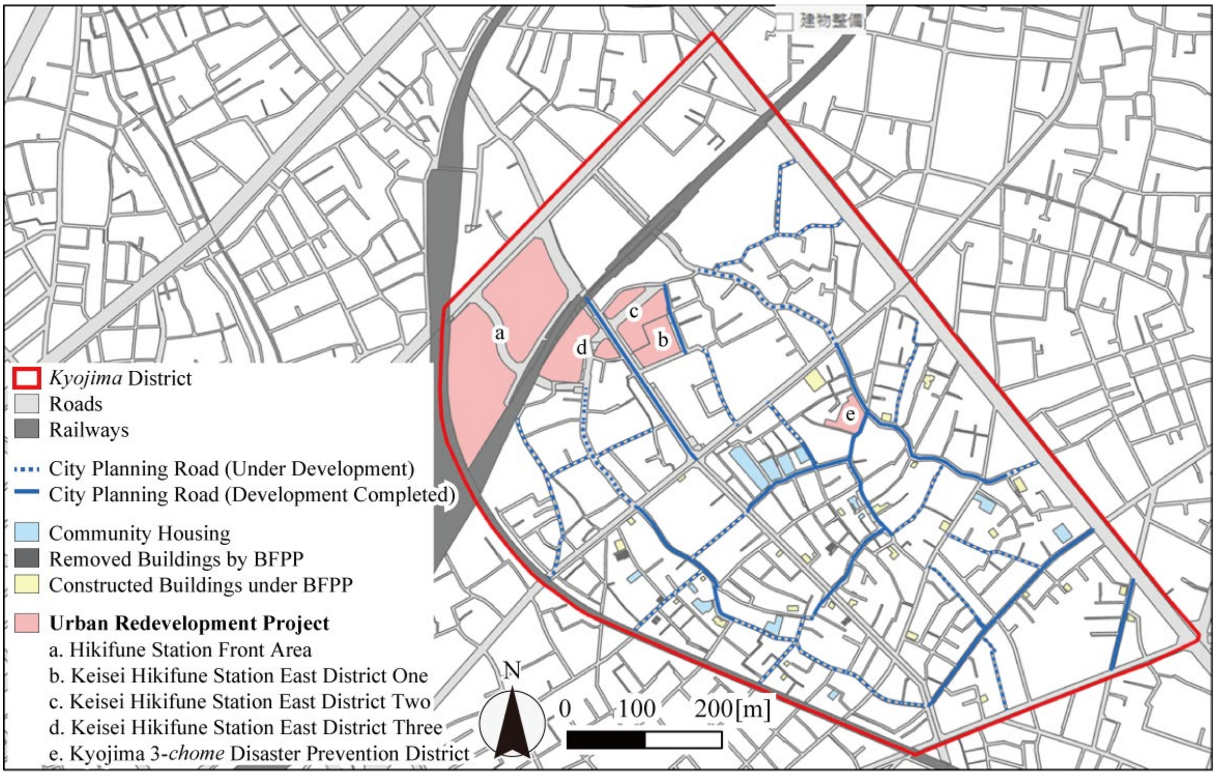

Figure 2. Main improvement projects in *the Kyojima* area.

Table 2. Information on urban redevelopment projects implemented in the analyzed area (TMG, 2023c)

	Project Name and Main Management Agency	Approved Date	Completion year	Area [ha]	Project Cost [JPY]
a	Hikifune Station Front Area by Urban Renaissance Agency	Nov. 2001	2010	2.8	43.2 billion
b	Keisei Hikifune Station East District One by Urban Redevelopment Association	Jan. 2003	2007	0.4	6 billion
c	Keisei Hikifune Station East District Two by Urban Redevelopment Association	Dec. 2006	2012	0.5	9.7 billion
d	Keisei Hikifune Station East District Three by Urban Redevelopment Association	Nov. 2009	2015	0.7	12.1 billion
e	Kyojima 3-chome Disaster Prevention District by Urban Renaissance Agency	Nov. 2009	2013	0.2	1.5 billion

Note: Urban Redevelopment Association is a corporation composed of all landowners within the implementation area of the urban redevelopment project and is responsible for implementing the project.

Data Collection and Utilization in the Simulation

Table 3 shows the list of data used in this analysis. There are multiple available GIS data for buildings and streets in Tokyo. In this paper, we utilized data that satisfy the necessary conditions for estimating property damage, which (1) has an exact shape as much as possible, and (2) possesses detailed attribute information.

The building layers of the land use surveys by TMG, Zmap-TOWN II by Zenrin, and the National Land Numerical Information 5000 by the Geospatial Information Authority of Japan are available for building data. We use the land use survey, which contains detailed attribute information. These data include attribute information such as the number of floors, building area, and building use, while it does not include those on the structural material or construction age. This data is updated every five years. GIS data before and after the projects are necessary to analyze the effects of improvement projects. Therefore, we used the latest data (as of 2016; Figure 3) and ten years earlier (as of 2016; Figure 4).

There are some available data for street network data, including Open Street Map and the Digital Road Map Database (DRM-DB). In this study, however, we used data from Tokyo Fire Department, which includes detailed information on minor roads. Due to the difference in the data creation year among data, we modified the street map and width information referring to the land use layer of the land use survey as of 2006 and 2016.

Table 3. Simulation data source

	Data	Creation Year	Data Provider
1	The land use survey (Land use layer and building layer)	2006, 2016	TMG
2	Street network	2014	Tokyo Fire Department

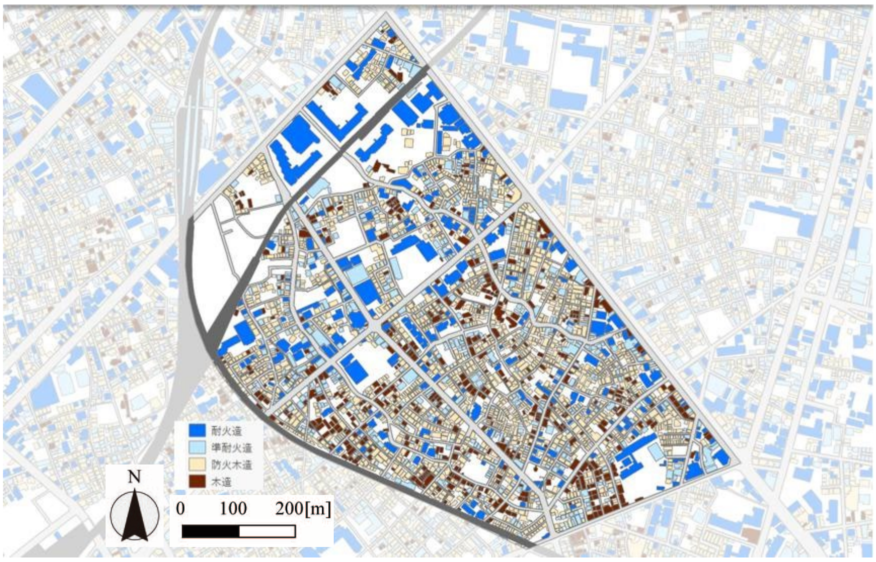

Figure 3. Building data as of 2006 shown by building structure (Total number of buildings: 3,016)**:** ■ Fireproof, □ Semi-fireproof, □ Wooden engineering for fire prevention, ■ Wooden

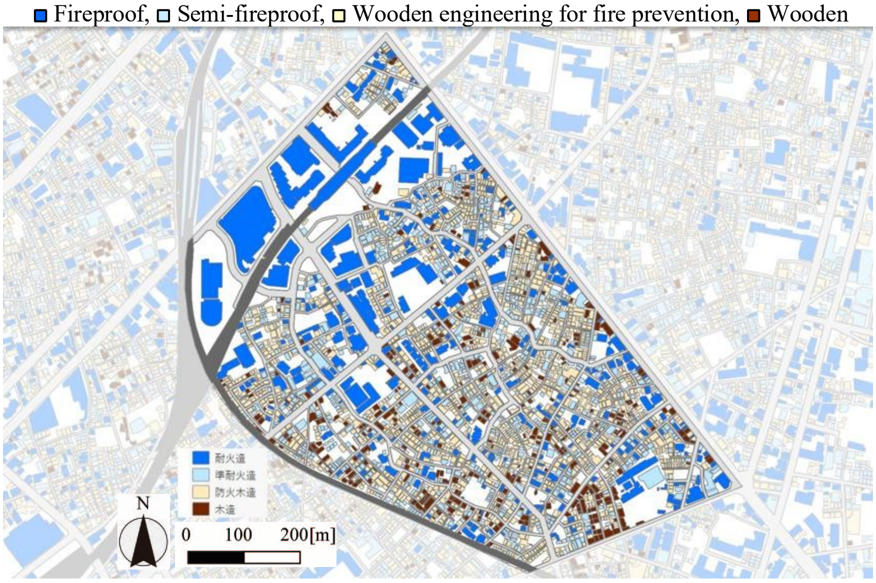

Figure 4. Building data as of 2016 shown by building structure (Total number of buildings: 2,848): ■ Fireproof, □ Semi-fireproof, □ Wooden engineering for fire prevention, ■ Wooden

Building Attribute Estimation

Table 4 summarizes the attribute information for the building and street data, which were necessary to execute the simulation. In this section, we estimated the attributes that are not available in the original data, namely "Structural material," "Construction age," and "Number of people inside" (Table 5 and Table 6). Hereafter, buildings classified by fire resistance type (fireproof, semi-fireproof, wooden engineering for fire prevention, and wooden) are referred to as "by fire resistance structures," and those classified by structural material (Wooden, Reinforced Concrete, or Steel) are referred to as "by Structural material."

Estimation of structural material and construction age

We estimated each building's structural material (Wooden, Reinforced Concrete, or Steel) and construction age (five categories for wooden and three for other structures). Specifically, we first integrated the available information from multiple sources (data 1~ data 4, Table 4). Then, for missing information, GIS data and satellite images were used to visually confirm the structural material and the construction age (data 5 and data 6, Table 4). Although determining those attributes can be challenging in some cases, it is only used when estimating collapsed buildings. Therefore, the impact on the simulation results should be minimal.

Table 4. Resources used for estimating structural material and construction age

	Data	Creation Year	Reference
1	The land use survey	2006, 2011, and 2016	Tokyo Metropolitan Government (2023d)
2	Earthquake structure map	2006, 2011, and 2016	*Sumida-Ku* (2017)
3	Fixed asset register	2017	*Sumida-Ku*
4	LIFULL HOME'S	Oct 2021	LIFULL Co., Ltd. (2021)
5	Google Earth *satellite Images*	Dec. 2006 and Apr. 2019	Google (2023)
6	*Satellite Images*	2006, 2016	Geospatial Information Authority of Japan (2023)

Estimation of the number of people in the building

The number of people in a building was estimated using Mobile Spatial Statis-tics (MSS) by NTT DoCoMo (as of 6:00 pm on Tuesday, 20 Oct. 2015), which is demographics estimated from the location information of mobile phone users in urban areas. Here, the number of people in a 500-m grid obtained from mobile spatial statistics was allocated to each building according to time of day, building use, and floor area (Osaragi and Kudo, 2019). When a building was demolished or reconstructed within a grid cell of MSS data, the total population of a cell was constant under this estimation method, while the number of persons assigned to each building changed. Moreover, since the target area spanned multiple 500-meter cells, note that the total population in the area remained unstable between 2006 and 2016.

Estimation of the rebuilding status

Table 7 shows the rebuilding status from 2006 to 2016. The rebuilding status was judged based on the following procedure. First, we used GIS software to compare the building polygons at the exact location at each time point. Buildings with the same outline were judged as "No change," buildings that did not exist at the previous time point but appeared later were judged as "Newly constructed." Buildings that existed at the previous time point but were not confirmed at the latter time point were regarded as "Demolished." For buildings that could not be classified in any of the above categories, the rebuilding status was determined by checking the condition of those roofs and exteriors using satellite images (data 5 and 6, Table 4) and Google Map Street View. Under this classification method, buildings newly constructed after 2016 were also judged as "Newly constructed as of 2016." Although we were unable to find relevant data for cross-validation of the data, the rebuilding status should be reasonably accurate since we visually confirmed the outline shape and exterior of each building each time using GIS data and satellite images.

Table 5. Correspondence between attribute information necessary for simulation execution and that contained in the original data: Those included in the original data are indicated by "✓."

		2.4(1) Building Collapse	**2.4(2)** Street Blockage	**2.4(3)** Fire Outbreak	**2.4(4)** Fire Spread	**2.5** Human Damage
Building	Num. of floors		✓		✓	
	Building usage			✓		
	Fire resistance structure				✓	
	Structural material	✓				
	Construction age	✓				
	Num. of people inside					✓
Street	Street width		✓			

Table 6. Attribute information included in the original data: Those included in the original data are indicated by "✓," and those not are indicated by "□."

		The land use survey	Street network data
Building	Number of floors	✓	
	Building usage	✓	
	Fire resistance structure	✓	
	Structural material	□	
	Construction age	□	
	Number of people inside	□	
Street	Street width		✓

Table 7. The rebuilding status from 2006 to 2016: Each number indicates the number of buildings.

2006	2006~2016		2016
3,016	No change:	2,373	2,848
	Demolished:	643	
	Newly constructed:	475	

SCENARIO ANALYSIS: DISASTER MITIGATION EFFECTS OF IMPROVEMENT PROJECTS

Preparing scenarios by decomposing local improvements

We conduct scenario analysis to understand the disaster mitigation effects of improvement projects. Specifically, we decomposed the improvement projects shown in Figure 2 from multiple viewpoints. Then, we organized the building construction/demolition and road widening into three categories; (1) Area development projects, (2) Development of city planning roads, and (3) Promotion projects of the city's incombustibility. Moreover, we organized six scenarios, including urban conditions of 2006 and 2016 (Table 8). By comparing the simulation results of scenarios, it became possible to understand the disaster mitigation effects of improvement projects from multiple perspectives.

Table 8. List of Simulation Scenarios

Name	Explanation
Scenario 1	Urban conditions as of 2006 (**Figure 3**)
Scenario 2	Urban conditions considering area development projects during 2006-2016 (**Figure 5**).
Scenario 3	Urban conditions considering the improvement of city planning roads during 2006-2016 (**Figure 6**)
Scenario 4	Urban conditions considering improvement projects during 2006-2016
Scenario 5	Urban conditions as of 2016 (**Figure 4**)
Scenario 6	Urban conditions when the improvement of all city planning roads is completed (**Figure 7**)

1. Scenario 1 examined the urban conditions as of 2006 (Figure 3).
2. Scenario 2 examined the mitigation effects of the area development projects from 2006 to 2016 (Figure 5). Specifically, we focused on "the Kyojima 3-*chome* Disaster Prevention District Improvement Project" and "the Keisei Hikifune Station Urban Redevelopment Project," as well as urban changes through other subsidized projects. This scenario also included reconstructions of neighboring buildings, which were considered to have been caused by a chain reaction from the relevant area development projects.
3. Scenario 3 examined the mitigation effects of improving city planning roads from 2006 to 2016, which mainly aimed at widening (Figure 6). Reconstruction of roadside buildings, considered a chain of improvements that occurred following the improvement of roads, was also included in this scenario.
4. Scenario 4 examined the mitigation effects of all improvement projects from 2006 to 2016. In addition to Scenarios 2 and 3, this scenario also examined the mitigation effects of "Promotion projects of the city's incombustibility" by Urban Renaissance Agency (Hereafter, UR), one of the semi-governmental organizations in Japan. This is the project that residents can make use of the UR's possessing land when they reconstruct their building within the area.
5. Scenario 5 examined the mitigation effects of local improvements over ten years, including improvement projects conducted from 2006 to 2016 and urban changes unrelated to any project (Figure 4). Specifically, it analyzed all changes during the ten years; the urban conditions as of 2016.
6. Scenario 6 examined the urban condition after the completion of city planning roads currently underdeveloped (Figure 7). Specifically, in addition to Scenario 5, we assumed that buildings along those roads would be rebuilt.

Note that each scenario was created based on the map information as of 2006. Specifically, to verify the effect of the improvements, the urban conditions in 2006 were overwritten with updated information on streets and buildings in each scenario.

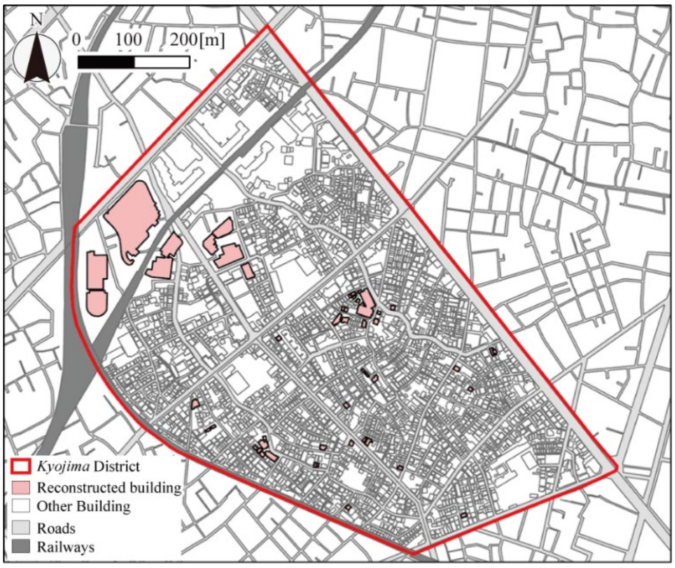

Figure 5. Spatial distribution of buildings reconstructed due to area development projects during 2006-2016 (Scenario 2)

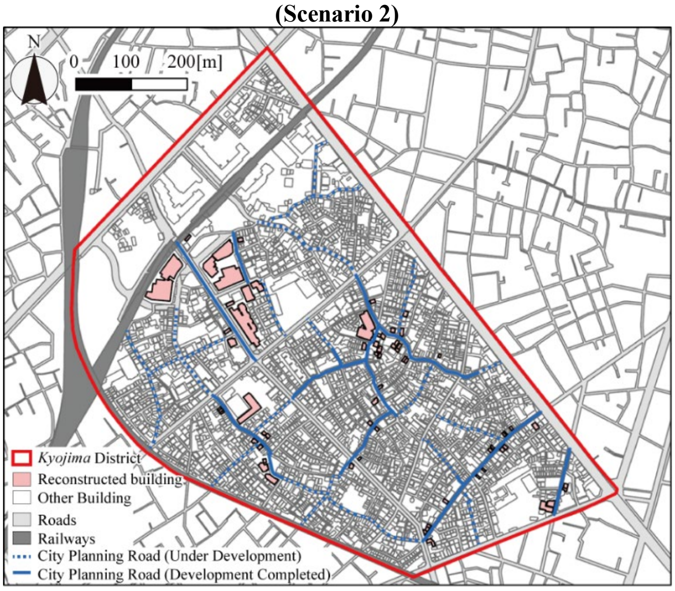

Figure 6. Spatial distribution of buildings reconstructed due to the improvement of city planning roads during 2006-2016 (Scenario 3)

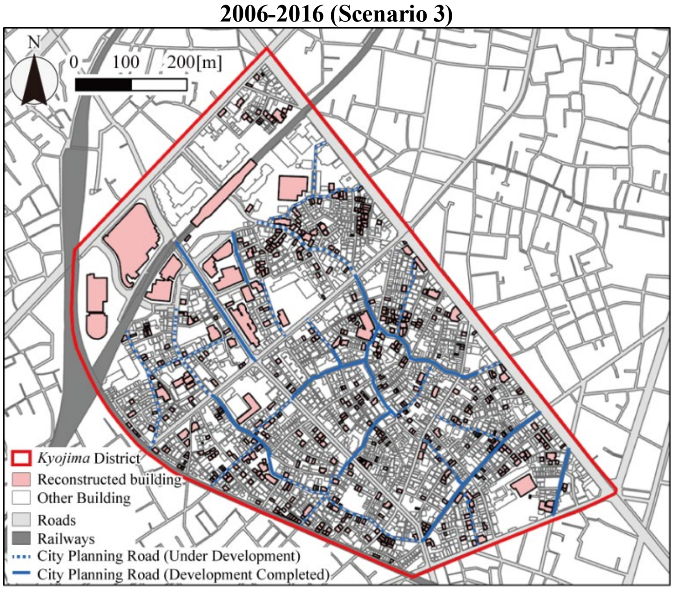

Figure 7. Spatial distribution of buildings under urban conditions when improvements of city planning roads are completed (Scenario 6)

Simulation Assumption

To estimate property and human damages, we performed a simulation under six scenarios (Table 8). We assumed the earthquake occurrence time to be 6:00 pm on a weekday in winter. There is a higher possibility of severe damage caused by the fire spread under this condition because (1) many people are preparing dinner at that time, (2) many heating devices are in use, and (3) the air is dry in winter in Tokyo. The fire outbreak (Section 2.2 (3)) and the distribution of people (Section 3.2 (3)) were also estimated under this assumption. The peak ground velocity (*PGV*) was fixed as 66 cm/s (not assuming any specific earthquake), and the wind condition was set as "North wind, 8.0 m/s," regarding the damage estimate by the TMG (2022b).

In this paper, we assumed that each person was in a building at the time of an earthquake. The analyzed area has a high potential for catastrophic damage throughout the region at the time of a large earthquake. Therefore, it is considered that evacuating outside the area is necessary rather than to shelters within the area. For this reason, we took that their evacuation was completed when they reached (or obtained any route to) the area's boundary.

Since property damage was determined probabilistically with a uniform random number, we prepared 100 cases of property damage for each scenario to consider the effects of the variance of property damage. Namely, the simulation was executed 600 times (=6 scenarios × 100 cases of property damage). Property damages were estimated independently among scenarios. In other words, the distribution of its occurrence varied from scenario to scenario, even for the same case number. Furthermore, the distribution of casualties associated with property damage differed among scenarios. For this reason, it was difficult to compare results on a building or street basis.

The fire outbreak probability from a building is minuscule (about 1/3000) compared to the building collapse probability or the street blockage probability. Therefore, the characteristics of extreme value distribution are likely to appear in fire outbreak determination using uniform random numbers. In other words, the result is expected to be counterintuitive, such as "the number of fire outbreaks increases despite the increase in the number of fireproof buildings." To compare the results of multiple scenarios, the following procedure was used to fix the number and location of fire outbreaks among scenarios. First, using the existing model (Section 2.1), we estimated the number of fire outbreaks for Scenario 1. Next, we randomly selected as many buildings from the building set common to all scenarios and set them as the fire location. Here, we assumed that each building had a constant probability of being selected regardless of the building use or the collapsed situation. By the above operations, fires outbroke from the same building in scenarios 1 to 6 for the same case number. We applied the above operations for all 100 cases. Note that the number and location of fire outbreaks differed in all 100 cases. For example, four fires outbroke in some cases, while none in others.

DISASTER MITIGATION EFFECT OF EACH SCENARIO

Table 9 shows the simulation results for each scenario, and Figure 8 to Figure 11 shows the relationship between the number of demolished buildings and each indicator (all values are averages of 100 simulation results). These figures show that the efforts of local improvements had steadily enhanced the disaster prevention performance of densely built-up residential areas. As the number of demolished buildings increased, as the newer buildings substituted the older ones, the disaster mitigation effects gradually increased. In the following sections, we compared the simulation results for each scenario to understand the mitigation effects from multiple perspectives.

Table 9. Urban conditions, property damage, and human casualties in each scenario

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Basic information about the urban conditions							
1	Num. of buildings	3016	2877	2926	2892	2848	2848
2	Num. of demolished buildings	0	188	157	225	643	702
3	Num. of newly constructed Buildings	0	49	67	101	475	534
4	Fireproof buildings ratio [%][1]	40.97	47.87	44.51	48.70	56.34	57.74
5	Street width (average value) [m][2]	5.77	5.77	5.86	5.86	6.02	6.29
6	Num. of people[3]	7433	8446	7800	8472	8598	8591
Property damage and human casualties							
7	Building collapse rate [%][4]	11.60	11.46	11.41	11.16	10.98	10.61
8	Street blockage rate [%][5]	18.53	17.92	17.85	17.77	14.93	14.43
9	Num. of fire outbreaks	0.94	0.94	0.94	0.94	0.94	0.94
10	Burnt building rate [%][6]	13.29	11.93	12.09	11.95	8.56	7.75
11	Num. of casualties	129.16	110.15	117.32	116.31	74.44	60.59

1 The ratio of fireproof buildings to the total number of buildings.

2 The weighted average value of street width.

3 The number of people in the district differs among scenarios. Please refer to the "Estimation of the number of people in the building" section for a detailed description.

4 The ratio of collapsed buildings to the total number of buildings.

5 The ratio of blocked streets to the total number of streets.

6 The ratio of burnt buildings to the total number of buildings.

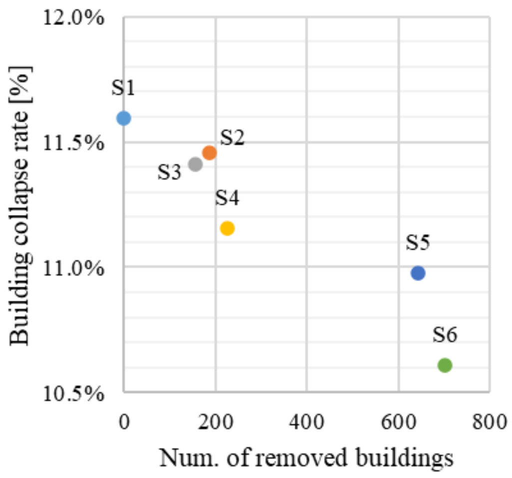

Figure 8. Num. of demolished buildings and Building collapse rate

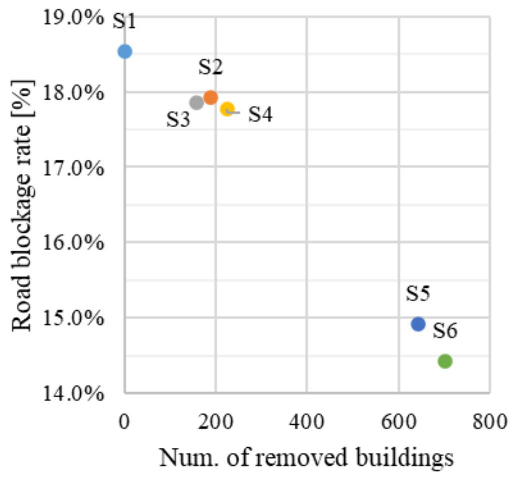

Figure 9. Num. of demolished buildings and street blockage rate

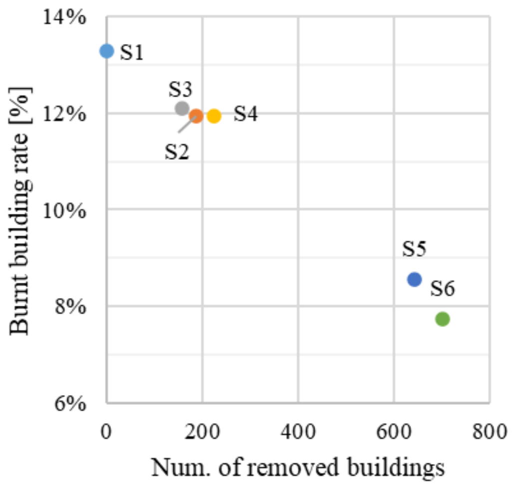

Figure 10. Num. of demolished buildings and burnt building rate

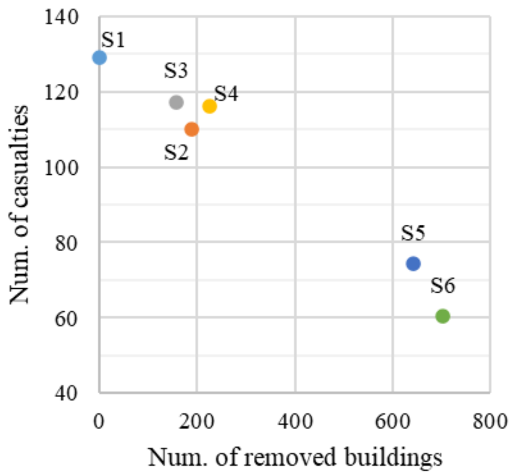

Figure 11. Num. of demolished buildings and Num. of casualties

Scenario 1: Estimation results of urban conditions as of 2006

The simulation result shows that 13.29% of the buildings in the area were burnt down, and 129.16 fatalities occurred in Scenario 1 (Table 9). In the worst case of damage, four buildings caught fire, and most of the buildings in the area were burnt (Figure 12).

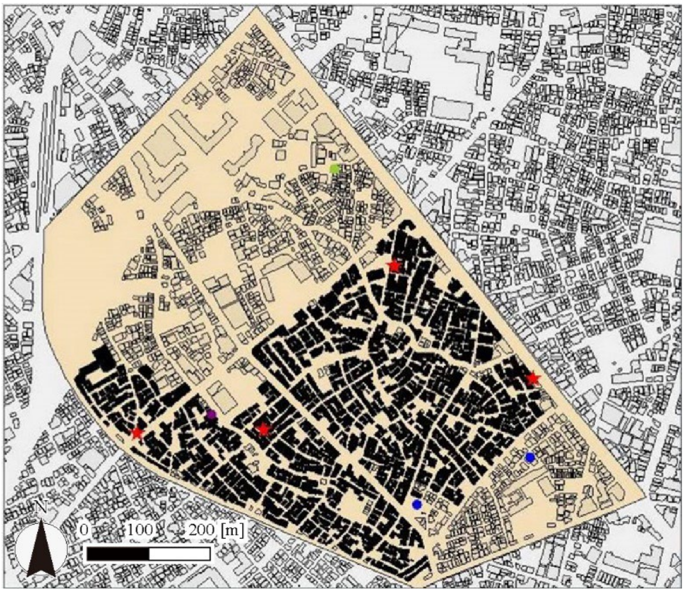

Figure 12. Distribution of fire outbreaks and burnt buildings in worst-case property damage in S1:
★ Fire outbreak, ■ Burnt down buildings, ● Casualty by fire who was stuck in a street, ● Casualty by fire who was stuck in a collapsed building, ●Casualty in a collapsed building who was seriously injured, ● Casualty died instantly

Scenario 2: Estimation results of urban conditions considering area development projects during 2006-201

The simulation shows that the burnt building rate decreased from 13.29% (Scenario 1) to 11.93% (-1.36 percentage points: Table 9).

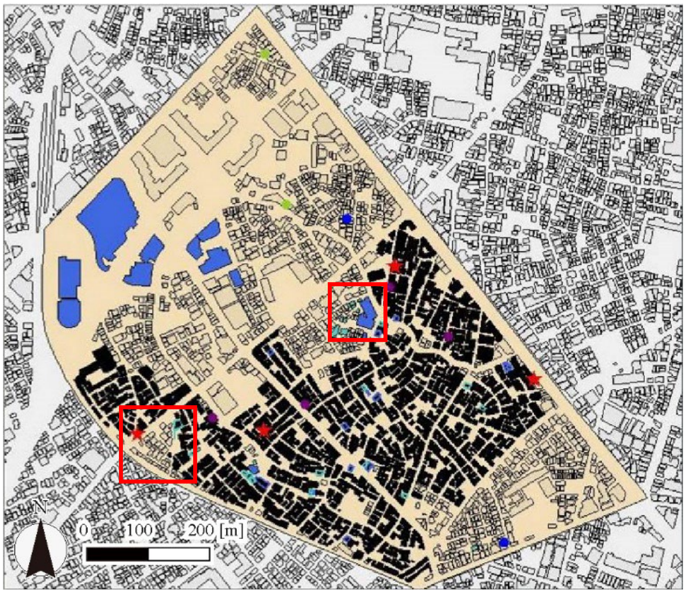

Figure 13. Distribution of fire outbreaks and burnt buildings in worst-case property damage in Scenario 2:
★ Fire outbreak, ■ Burnt down buildings, □ Newly constructed buildings, ● Casualty by fire who was stuck in a street, ● Casualty by fire who was stuck in a collapsed building, ●Casualty in a collapsed building who was seriously injured, ● Casualty died instantly

Scenario 3: Estimation results of urban conditions considering the improvement of city planning roads during 2006-2016

Figure 14 shows the spatial distribution of burnt-down buildings in the case with the most significant effects to prevent fire spread damage. Fig. 14 shows that the city planning road blocked the fire spread (Figures 12 and 14, indicated by a red line).

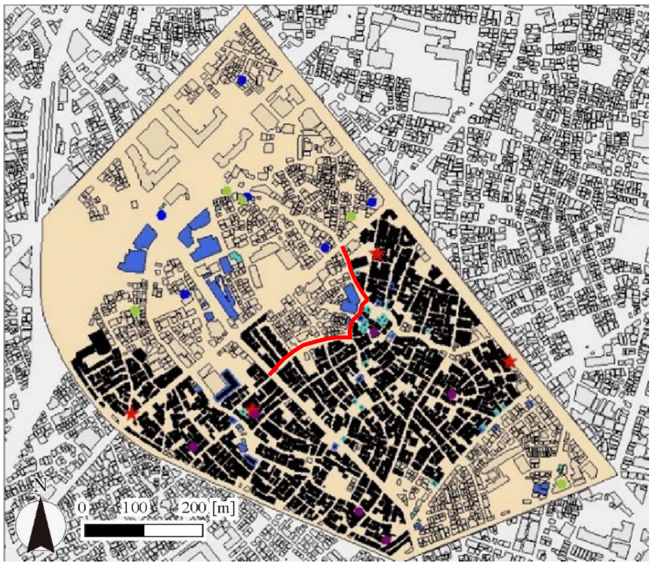

Figure 14. Distribution of fire outbreaks and burnt buildings in worst-case property damage in Scenario 3: ★ Fire outbreak, ■ Burnt down buildings, □ Newly constructed buildings, ● Casualty by fire who was stuck in a street, ● Casualty by fire who was stuck in a collapsed building, ●Casualty in a collapsed building who was seriously injured, ● Casualty died instantly

Scenario 4: Estimation results of urban conditions considering improvement projects during 2006-2016

In Scenario 4, the spatial distribution of burnt buildings showed that it was generally consistent with scenarios 2 and 3. The burnt-down building ratio was slightly lower than scenario 2 (-0.02 percentage points), although the total burnt-down building area had been reduced. The number of casualties was slightly worse than those in Scenario 2 (Table 9).

Scenario 5: Estimation results of urban conditions as of 2016

Each indicator was improved significantly when comparing the simulation results with those of Scenario 1: The building collapse rate decreased from 11.60% to 10.98% (-0.62 percentage points), the street blockage rate decreased from 18.53% to 14.93% (-3.6 percentage points), and the burnt building rate decreased from 13.29% to 8.56% (-4.73 points).

Scenario 6: Estimation results of urban conditions when improvements of city planning roads are complete

Figure 15 shows that the fire spread stopped on the newly developed road (Figures 14 and 15, indicated by a red line). The building collapse rate decreased from 10.98% to 10.61% (-0.37 percentage points), the street blockage rate from 14.93% to 14.43% (-0.50 percentage points), and the burnt building rate from 8.56% to 7.75% (-0.81 percentage points: Table 9). However, the property and human damage remained unresolved in the inner areas surrounded by city planning roads (Figure 15).

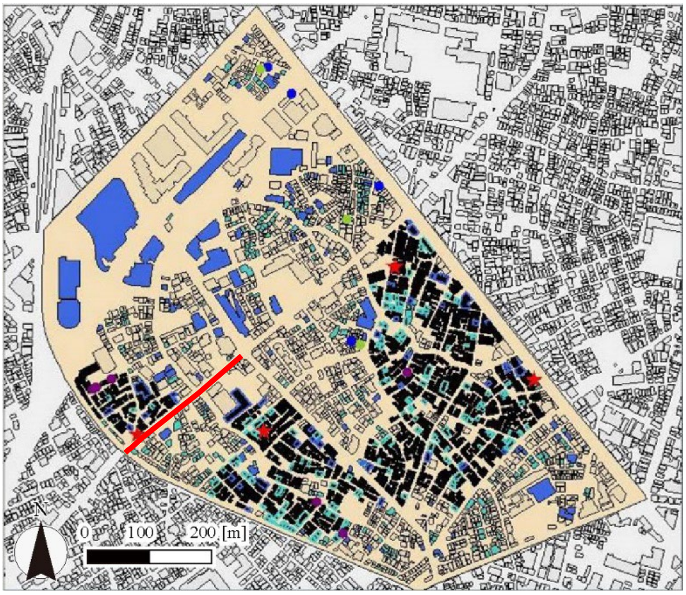

Figure 15. Distribution of fire outbreaks and burnt buildings in worst-case property damage in Scenario 6:
★ Fire outbreak, ■ Burnt down buildings, □ Newly constructed buildings, ● Casualty by fire who was stuck in a street, ● Casualty by fire who was stuck in a collapsed building, ●Casualty in a collapsed building who was seriously injured, ● Casualty died instantly

Discussion

In Scenario 1, we confirmed that the Kyojima area had a severe hazard risk in the event of a large earthquake regarding property damage and human casualties.

In scenario 2, we confirmed that reconstructed buildings changed the shape of the fire spread network (Figure 1) and, as a result, it reduced fire spread damage in a specific area (Figures 12 and 13). As Abe et al. (2004) pointed out, it is possible to effectively prevent fire spread by identifying the critical points of fire spread damage.

In scenario 3, we confirm that a certain city planning road blocked the fire spread, though the fire spread across the other uncompleted urban planning road. Generally, the improvement of city planning roads is crucial because (1) it prevents street blockages and secures evacuation routes, and (2) it creates a firebreak belt and prevents fire spread. However, while it has a great mitigation effect, it takes a long time to complete its improvement because of the large number of landowners involved. Previous research has emphasized the positive effects of road development, assuming that the infrastructure is already complete (Fujimoto and Kumagai, 1989). However, this result indicates limited mitigation effects during the intermediate stages. For promoting the project, it is necessary to devise ways to improve its effectiveness with the awareness of fire spread blockage.

These findings indicate that small-scale development projects focusing on constructing buildings with high mitigation potential, implemented individually, may have greater mitigation effects in the short term than large-scale urban development projects in the analyzed area.

In Scenario 4, we expected to capture the synergistic effects of the area development project (Scenario 2) and the improvement of city planning roads (Scenario 3). However, the result was less significant than expected. It was because (1) scenarios 2 and 3 shared some demolished or newly-built buildings, and urban planning roads are in the intermediate stages. The burnt-down building ratio was slightly lower than in scenario 2, and this was due to the difference in the denominator (total floor area of all buildings in each scenario).

In scenario 5, we can understand the disaster mitigation effects of all the changes in urban environments that have occurred over the past ten years by comparing the simulation results with those of Scenario 1 (Table 9). Scenario 5 showed a more significant mitigation effect in street blockage rate and the number of casualties per building than in scenario 4. This was because reconstructions unrelated to any project eliminated localized street blockages and secured evacuation routes for certain evacuees. Previous studies (Oki and Osaragi, 2016; Kishimoto and Osaragi, 2019) have pointed out the importance of securing narrow streets as evacuation routes, and some government agencies (Adachi City 2022) promote it as one of the valuable measures to reduce casualties in dense wooden housing areas.

In Scenario 6, the property and human damage remained unresolved in the inner areas surrounded by city planning roads (Figure 15). Since many buildings in these areas do not have adequate street access, it is difficult to reconstruct them independently under current city planning act. Therefore, it is necessary to reconstruct them in conjunction with surrounding houses; however, it is difficult to reach a consensus because of the large number of landowners involved. In other words, it is difficult to reduce the damage through conventional improvement approaches (Katsunuma and Takeya, 2021). More strategic approaches are needed to improve the urban vulnerabilities in those areas.

Also, the number of casualties was slightly worse in Scenario 4 than those in Scenario 2 because there was a case in which many evacuees could not complete evacuation due to the collapsed buildings and blocked streets in scenario 4. Although the effect of random numbers should have been smoothed out under sufficient simulation trials, it is presumed that more than 100 trials are needed (i.e., the impact of random numbers is significant). Therefore, increasing the number of simulation trials is necessary to avoid this confusion. On the other hand, since the estimation results of property damage (e.g., building collapses or fire outbreaks) were not fixed among the scenarios, it was still difficult to understand the mitigation effect in subsequent scenarios 2 through 6. It would be easier to understand the effect by fixing the results based on Scenario 1 (the urban situation as of 2006). Further consideration is necessary in this regard.

SUMMARY AND CONCLUSIONS

In this paper, we quantitatively evaluated the improvement projects in the densely built-up wooden residential area using the "large earthquake disaster simulator." Specifically, we discussed disaster mitigation effects and characteristics of improvement projects by decomposing them from multiple viewpoints. The following are the results obtained in each chapter.

Chapter 2 described the various models that compose the simulator in detail. It was possible to estimate property damage (building collapse, street blockage, fire spread) and human casualties in the event of a large earthquake by executing the simulator.

In Chapter 3, we described the Kyojima area of Sumida-*Ku*, Tokyo, the analyzed area in this paper. Many aged wooden buildings are densely built in this area, and severe damage, such as a large-scale fire spread, is expected after a large earthquake. Moreover, we described the necessary data for the simulation in this chapter.

Chapter 4 explained the methodology of this study. Specifically, we prepared six scenarios by decomposing the improvement projects implemented during 2006 - 2016 to evaluate how the local improvements from 2006 to 2016 improved the area's disaster prevention performance.

Chapter 5 presented the simulation results of the disaster mitigation effects of six scenarios. We first confirmed that the Kyojima area, as of 2006, had a severe disaster risk in a large earthquake. Then, we established the disaster mitigation effects of the improvement projects. We demonstrated that fire spread could be effectively blocked by (1) ensuring sufficient road width and (2) identifying the critical buildings in terms of fire spread mitigation and making them fireproof. Finally, we examined the disaster risk when the improvements of all city planning roads were completed. The property and human damage remained unresolved in the inner areas surrounded by city planning roads.

In Chapter 6, we discussed the mitigation effects of improvement projects and demonstrated the following contributions to the field of disaster mitigation.

1. We confirm that the spread of fire occurred across uncompleted urban planning roads, highlighting the limited effectiveness of mitigation measures during intermediate stages.
2. The study reveals that urban changes unrelated to any project can also yield a certain level of mitigation effect.
3. These findings indicate that small-scale development projects focusing on constructing buildings with high mitigation potential, implemented individually, may have greater mitigation effects in the short term than large-scale urban development projects in the analyzed area.

The insights gained from this study can provide valuable implications for disaster management authorities, private sectors, residents, and other relevant stakeholders. Specifically, disaster management authorities can utilize the knowledge of the mitigation effects of each project in future policy-making. In particular, the significant impact of rebuilding/demolishing a few vulnerable buildings unrelated to any development project will be crucial in policy decisions. These insights can motivate private sectors to develop those areas by understanding that the disaster prevention performance in densely built-up residential areas is improving yearly and that their development can contribute to disaster risk mitigation. Residents, including stakeholders, can enhance their disaster prevention awareness by recognizing the mitigation effects of each project, especially by understanding that rebuilding a single building can provide sufficient effects for the entire community.

With the proposed method, it is possible to discuss the effects and issues of multiple proposals for future improvement projects and support the strategies planning process. Several issues require attention in future studies. First, it was difficult to compare the mitigation effect among scenarios since the random number used in the estimation of property damage was not fixed. Further consideration is necessary in this regard. Second, it is essential to evaluate the disaster mitigation effect of intangible measures such as rescue and firefighting activities to raise residents' disaster awareness and confirm the importance of self-help and mutual help. Moreover, we did not incorporate cost factors in this study. Future studies could consider including cost factors to provide more comprehensive information for policymakers. Finally, developing a tool that allows easy processing and editing of the current simulator's input data is needed.

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