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|----------------------|--------------------|
| 巻號                  | 6                  |
| 号数                  | 1                  |
| 発行年月日            | 2018-01-15         |
| URL                   | http://doi.org/10.24517/00053237 |
| Creative Commons      | https://creativecommons.org/licenses/by-nc-nd/3.0/deed.ja |
| 提供                 | 長沢大学総合学術リポジトリ |

doi: 10.14246/irspsd.6.1_18
An Evacuation Simulator for Exploring Mutual Assistance Activities in Neighborhood Communities for Earthquake Disaster Mitigation

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Received: Oct 11, 2016; Accepted: June 19, 2017

Key words: Disaster Mitigation, Earthquake, Mutual assistance, Multi-agent Simulation, Community-based Activities

Abstract: Japan is at great risk of being struck by huge earthquakes. When a strong earthquake occurs, various other disasters such as fire, collapsing buildings, and road blockages simultaneously occur as a result. In such a situation, it is difficult to ensure that the local emergency activities by, for example, the public fire company and community volunteers, are sufficient. Considering this issue, mutual assistance among residents, such as firefighting, evacuating victims, and helping those in need of assistance to designated safety sites, is extremely important. This paper proposes the development of an evacuation activities simulator, considering the capability of mutual assistance under various earthquake disasters to support exploration of community-based activities. In particular, the simulator calculates the time that local resident agents take to evacuate to the designated safety site, and the number of agents that can and cannot evacuate. Users can change the ratio of those who cannot evacuate to the designated safety site based on whether they are without some support or with persons who support them. Therefore, users can compare the simulation results of various outcomes. Through the experimental demonstration the following findings were obtained. Confirming the simulation results, users can understand that human suffering is reduced by mutual assistance activities. In addition, users can distinguish when the capability of mutual assistance is high or low, and when the capability of mutual assistance is changed according to the time of day due to the presence of the commuting population. Therefore, users can explore the countermeasures used to reduce human suffering when the capability of mutual assistance is low.

1. INTRODUCTION

1.1 Back ground and objective

Japan is at great risk of damage from very large earthquakes. To minimize the damage caused by earthquakes, the improvement of safety in built-up areas is an urgent issue. Although the improvement of physically built-up environments is important, improving disaster response techniques by community associations is significant for the safety of those built-up
areas. To improve the capability for disaster response, enhancing self-help, mutual assistance, and public help for disaster mitigation is important.

However, an issue of concern is the increasing elderly population, who cannot evacuate without assistance from others. Another concern is that of the disastrous activities that result from earthquakes. Due to these issues, it can be difficult to ensure efficient emergency responses. Thus, mutual assistance between local residents is extremely important. To improve the capability of mutual assistance among neighborhood communities, it is necessary to develop techniques to evaluate the mutual assistance capabilities of neighborhood communities for disaster mitigation, visually display the results, and support further exploration of this topic based on the results.

This paper utilizes a simulator of evacuation activities, and this simulator is developed by using a multi-agent based model. Through the simulator, this paper considers the capability of mutual assistance under various earthquake disasters in order to explore the contents of community-based activities. As resident agents take action through mutual assistance to respond to various emergencies, the simulator calculates the time that resident agents evacuate to the designated safety site, the number of agents that can evacuate, and the number of agents that cannot evacuate.

1.2 Study method

First, to understand the issues surrounding the mutual assistance of neighborhood communities in disaster mitigation activities and the required techniques to address those issues, a survey was distributed to local government staff. Second, the detailed capability of mutual assistance was explored and evaluated to better comprehend the degree of mutual assistance capabilities and to identify areas displaying high or low capabilities of residents. Third, to explore the contents of community-based activities considering mutual assistance, a large earthquake (higher than magnitude 6 on the Richter scale) was simulated. Finally, to verify the usability of the developed simulator, experimental usage was conducted. The results of some simulations reflected scenarios in which residents performed activities related to mutual assistance, as well as cases in which they did not perform those activities. The results also showed scenarios in which mutual assistance changed according to the time of day due to the commuting population.

1.3 Related study

Very few previous studies have used an evaluation method to explore mutual assistance for disaster mitigation. Akiyama and Ogawa (2013) suggested an evaluation method to quantitatively estimate mutual assistance as the initial response ability during large earthquake disasters. However, the estimated values utilize mesh data to analyze large-scale attributes such as the urban scale. Another related study approach is model development, which simulates human behaviors such as evacuation responses to natural disaster. One of the most popular methods is using the multi-agent system (MAS). Uhrmacher and Weyns (2009) described how MAS has been used to understand the interaction among and between agents as well as their dynamic environment. For example, D’Orazio et al. (2014) proposed an innovative approach to earthquake evacuation, presenting an agent-based
model to describe phases and rules of motion for pedestrians. Wagner and Agrawal (2014) presented a prototype of a computer simulation and decision support system that uses agent-based modeling to simulate crowd evacuation in the presence of a fire disaster, and provides testing of multiple disaster scenarios at virtually no cost. Takabatake et al. (2017) developed an agent-based tsunami evacuation model which considers the different behaviour of local residents and visitors, which can estimate the evacuation time, number of individuals reaching each evacuation area, the location of bottlenecks and the number of casualties. Wang et al. (2016) presents a multimodal evacuation simulation for a near-field tsunami through an agent-based modeling framework to investigate how the varying decision time impacts the mortality rate, how the choice of different modes of transportation (i.e., walking and automobile) and how existence of vertical evacuation gates impacts the estimation of casualties.

This current study is unique because it attempts the development of a simulation of evacuation activities that considers the capability of mutual assistance under various earthquake disaster scenarios. Further, this paper promotes exploring the contents of community-based activities.

2. SURVEY

To comprehend the issues related to neighborhood communities’ mutual assistance in disaster mitigation activities as well as the required techniques to solve those issues, a survey distributed to local government staff was conducted. The following opinions were obtained as a result of the survey.

- If there were a map to understand the capability of mutual assistance by building units, residents would more easily understand the capability of their living area. In addition, a map may promote residents’ awareness and the discussion of community-based activities for disaster mitigation.

- It is ideal that residents understand that the capability of mutual assistance is changed according to the time of day due to the commuting population.

- Local governments want to discuss urban improvement and support contents to promote the capability of mutual assistance, using methods such as those mentioned above.

Based on these responses, we think that the following two points are important for the required techniques to support issues related to mutual assistance for disaster mitigation.

1) Information in map-form to enable understanding of the capability of mutual assistance by neighborhood community; and

2) Information to promote the discussion of community-based activities for disaster mitigation considering mutual assistance activities.

To provide this necessary information, we developed a tool to calculate the capability of mutual assistance by neighborhood community, using GIS techniques and a simulator to simulate evacuation behaviors in response to earthquake disasters, including collapsing buildings, road blockages, and fire spreads. Further, to express the human suffering resulting from these simulations, a multi-agent model was required, and a support technique to address the concerns mentioned above was developed.
3. MAP DEVELOPMENT SHOWING THE CAPABILITY OF MUTUAL ASSISTANCE

3.1 Evaluation method

To evaluate the capability of mutual assistance by neighborhood communities, the evaluation method suggested by Akiyama and Ogawa (2013) was utilized. First, the expected value for the rescue of each person was calculated by using Table 1. The expected value for rescue is the numerical value showing the ability to rescue the victims (e.g., pulling a survivor from a wreckage) in accordance with gender, age and strength. This table was organized based on the actual rescue activities in the Great Hanshin-Awaji Earthquake in 1995 in Japan. For example, the expected value of a 40-year-old man is calculated by the following formula:

\[
\text{strength} (0.93) \times \text{executing rate} (0.298) \times \text{activity rate} (0.72) = 0.1995
\]

Strength: This value is calculated in accordance with age and gender based on the strength value of a man in his teens through to his twenties being set at 1.

Executing rate: This value is set in accordance with the condition of actual rescue activities in the Great Hanshin-Awaji Earthquake.

Activity rate: This value is the ratio showing residents can perform rescue activities considering the degree of daily activities.

The expected value $R_{rj}$ of building $j$ is calculated as the total of the residents’ expected value at building $j$. However, in this paper, elementary school students and junior high school students have no capability for rescue. Second, the expected value is weighted by distance because of the assumption that residents take some time to discover (recognize) the person who cannot evacuate without some assistance in accordance with the distance. Therefore, the range limit in which residents can discover a person who cannot evacuate the building $i$ is set at 100m. The resident’s expected value is decreased with the increasing distance from building $i$. The weighted value $dwi$ of building $j$, having $dj$ [m] distance from building $i$, is calculated by formula (1), below. The evaluation unit of the mutual assistance capability is the building unit, based on the assumption that it is easy for residents to understand the capability.

\[
dw_j = \frac{1.502}{\log(1 + dj) + 1} \quad (0 \leq dj \leq 100) \quad (1)
\]

The capability of mutual assistance $= \frac{\sum R_{rj} \times dw_j}{5} \quad (2)$

| Table 1. The expected value in accordance with age and gender |
|-----------------|--------------|---------------|---------------|---------------|---------------|---------------|
| Age | Men’s strength | Women’s strength | Executing rate | Men’s activity rate | Women’s activity rate | Men’s expected value | Women’s expected value |
|-----|----------------|-----------------|---------------|---------------------|-----------------------|----------------------|-----------------------|
| 10  | 1              | 0.85            | 0.228         | 0.76                | 0.24                  | 0.1733               | 0.0465                |
| 20  | 1              | 0.76            | 0.228         | 0.76                | 0.24                  | 0.1733               | 0.0416                |
| 30  | 0.96           | 0.76            | 0.229         | 0.72                | 0.28                  | 0.1583               | 0.0487                |
| 40  | 0.93           | 0.73            | 0.298         | 0.72                | 0.28                  | 0.1995               | 0.0609                |
| 50  | 0.9            | 0.72            | 0.228         | 0.63                | 0.37                  | 0.1293               | 0.0607                |
| 60  | 0.84           | 0.7             | 0.191         | 0.74                | 0.26                  | 0.1187               | 0.0348                |
| 70+ | 0.78           | 0.65            | 0.129         | 0.75                | 0.25                  | 0.0755               | 0.021                 |
3.2 Creating a mutual assistance map

To evaluate the capability of mutual assistance by using the evaluation method, detailed population data such as the family structure within each building and the age and gender of each resident was necessary. To obtain such detailed data, cooperation from local government and residents was also necessary. To experimentally develop a mutual assistance map, a virtual space was created.

The concept of the virtual space is as follows. Each building had one household. Young generations and elderly persons were uniformly distributed in the entire space. Residents’ living space was changed according to the time of day in order to represent the commuting population. Thus, evaluating the capability of mutual assistance was conducted for each case. When calculating the capability of mutual assistance of the building at the edge of the virtual space, the buildings located outside of the virtual space were not considered. The mutual assistance value of commercial facilities was set at 0 because mutual assistance activities by commercial facility users were not anticipated as the local residents’ activities were. The age structure of the whole virtual space was set based on the result of the national population census by the Ministry of Internal Affairs and Communications (MIAC) (2011). There were five types of households (one-person household, married-couple household, and two-generation households with one, two, or three unmarried children). The ratio of two-generation households with over four children is under 10 percent. In this study, therefore, the limit of unmarried children in each two-generation household was set at three.

3.3 Evaluation of the capability of mutual assistance

The capability of mutual assistance was calculated following three cases considering commuting times: 1) the morning hours, 2) afternoon, and 3) early evening. In the morning hours, all household members are in each of their buildings. In the afternoon, almost all residents in the virtual space are stay-at-home wives and elderly persons, with almost all students and workers being outside of the virtual space (commuting). The commuting rate of each age was set based on the result of national population census data. In the early evening, almost all students are back home, and almost all residents in the virtual space are stay-at-home wives, students and elderly persons.

Figure 1 shows the evaluation results. By using this map, users can distinguish the areas with low capability of mutual assistance by neighborhood community, as well as the change of capability in accordance with the time change. Thus, by using this map, residents may better understand the capability for initial response to earthquake disasters, the issues surrounding mutual assistance activities, and the necessity of mutual assistance.
4. **MODEL DEVELOPMENT**

4.1 **Model structure in virtual space**

The model was set to simulate a large earthquake (intensity higher than magnitude 6 on the Richter scale). Collapsing buildings, road blockages, and fire spreads were generated. Residents are evacuated to the designated evacuation site. Six attributes as the components of a simplified virtual urban area (urban area, roads, fire origins, fire extinguishers, rubble and the designated evacuation site) and resident agents were generated. The virtual urban space consisted of 3m by 3m grid cells.

4.2 **Resident agents**

One resident agent represented one person. Each agent was given an age, gender and expected value as the initial setting for beginning the simulation. The age structure, household distribution and expected value were set according to the mutual assistance map.

*Figure 1.* Maps showing the capability of mutual assistance for each time period.
4.3 Road blockage model

For the road blockage model, the model proposed by Gohnai (2007) was incorporated. After setting the probability of building collapse for each building based on structure, floor number and year of construction, collapsed buildings were generated by using random numbers. When the rubble was spread on a road with a width under 0.6m, resident agents could not go through the road.

4.4 Fire spread model

The model proposed by Ohgai, Gohnai, and Watanabe (2007) was incorporated as the fire spread model. Fire origins were set by using random numbers. Users could set the wind velocity and wind direction. According to the conditions, a fire spread simulation was conducted.

4.5 Behaviour of resident agents

The resident agents performed the following seven actions.

4.5.1 Evacuation

Each resident agent evacuated from each building to the designated evacuation site. In this model, middle-class children above elementary-school age (8 and older) could evacuate alone. Children less than 8 years old evacuated with his/her parent.

4.5.2 Firefighting at initial period of fire

When there was a fire origin within 100m from a resident agent, the resident agent battled the fire with fire extinguishers. After firefighting, the resident agent reinitiated evacuation.

4.5.3 Waiting for rescue

A resident agent who was buried under a collapsed building would wait for help. A resident agent who was in a burning building had no support from other resident agents because in the real world it is difficult for residents to rescue someone who delays escape from a fire.

4.5.4 Rescue victims

When resident agents discovered a victim in need of help within 100m from him/her during evacuation, he/she took part in the rescue activity. However, a resident agent with an agent older than 65 years old or a child less than 8 years old (early elementary school years) was given priority in evacuation. When the total expected value of resident agents participating in rescue activities exceeded 1, they could rescue a victim. When the total expected value was not greater than 1 after a lapse of 5 minutes from earthquake generation, the resident agent gave up rescue and restarted evacuation.
4.5.5 Those in need of evacuation support

According to the Ministry of Health Labour and Welfare (MHLW) (2014), 5\% of the agents aged from 65 to 74 years old and 34\% of the agents over 74 years old were set as agents who were in need of evacuation assistance.

4.5.6 Those supporting evacuation

When resident agents discovered a resident in need of evacuation support within 100m of the evacuation site, he/she provided evacuation support. However, a resident agent with an agent older than 65 years old or a child less than 8 years old (early elementary school years) was given priority.

4.5.7 Awaiting public support

In the following three situations, resident agents could evacuate even when performing mutual assistance activities. Therefore, when residents are in the following situations, they would wait on support from public institutions, such as the local fire or rescue teams:

1) A resident agent in a burning building;
2) A resident agent who cannot be rescued by another in situations where the total expected value is not greater than 1 (see Section 3.1);
3) A resident agent who cannot reach the designated evacuation site due to road blockage.

4.6 Simulation flow

Figure 2, below, shows the simulation flow. First, the virtual space was generated, and then resident agents were generated under certain conditions. Second, a large earthquake higher than magnitude 6 was generated, followed by the simulation of a road blockage caused by simulated collapsed buildings and fire spread. Third, resident agents judged their actions (evacuation, firefighting, rescue and support for evacuation). In this phase, initial firefighting by residents was simulated up to ten minutes after the fire simulation was initiated. Fourth, resident agents went to the destination he/she chose from the aforementioned options. In the case of firefighting, resident agents went to the fire origin with an extinguisher. In the case of supporting evacuation, resident agents went to the individual in need of evacuation assistance. In the case of rescue, resident agents went to assist a victim. In the case of evacuation, resident agents went to the designated evacuation site. Fifth, after finishing each mutual assistance activity, resident agents restarted the evacuation process. Finally, resident agents reached the evacuation site.
4.7 Change of simulation conditions

As this simulator observes community-based activities for disaster mitigation, a function to change some of the simulation conditions was added. Figure 3, below, shows the pane to change the following conditions:

1) Fire origin: The users of this simulator can set the number of fire origins in the virtual urban space.
2) Wind velocity and direction: The users can set the wind velocity from 0 m/s to 9 m/s, and set the wind direction from eight directions.
3) Waiting time: The users can set the time from earthquake generation to starting evacuation.

Figure 3. The pane to change simulation conditions.
4) The ratio of resident agents who need some help for evacuation: The users can set the ratio of resident agents who need some evacuation assistance in the 65-year-old to 74-year-old range and the range of over 75 years old.

5) The ratio of residents who perform mutual assistance activities: The users can set the ratio of residents who perform mutual assistance activities.

6) The age limit of residents who perform mutual assistance activities: The users can set a limit that designates whether residents over 65 years old can perform mutual assistance activities or not.

7) Setting the point of fire origin: The users can set the point of fire origin freely.

5. EXPERIMENTAL USE OF DEVELOPED SIMULATOR

5.1 Perspective of evaluation

In the experimental use of the developed simulator, the following three scenarios were set: 1) The presence or absence of mutual assistance activities during evacuation; 2) The altering of the ratio of resident agents in need of evacuation assistance (this suggests the promotion of the declining birth rate and a growing population of elderly people in the future); 3) The capability of mutual assistance was changed according to the time of day caused by the commuting population.

The simulation results reflecting each scenario were evaluated following three points:
1) The time that all residents who could evacuate reached the designated evacuation site.
2) The number of residents who could reach the evacuation site.
3) The number of residents who could reach the evacuation site. This number refers to the number of residents who were waiting for help from a fire or rescue team in a collapsed or burning building, or who were on a blocked road.

The simulations reflecting each scenario were conducted ten times. After that, the average values were calculated and compared. The time it took to pull a survivor from a wreckage was not considered. The basic setting of values for simulating an evacuation are shown in Table 1. The simulation results are shown in Figure 3 and Table 3.

5.2 The presence or absence of mutual assistance activities during evacuation

Comparing the results of the scenarios, the evacuation time of all residents who could reach the evacuation site was longer when mutual assistance activities were considered than when they were not. However, the 20 resident agents who needed evacuation assistance (about 2% of the number of all residents in the virtual space) could reach the evacuation site when mutual assistance activities were considered. Following these results, users (local residents) can easily understand the effects of the mutual assistance activities. In addition, users can understand where to locate residents who cannot evacuate, as well as the disasters that cause entrapment.
such as collapsed buildings, road blockages, fire spreads, and a lack of neighborhood support. From these effects, users can better comprehend areas in need of improvement such as urban infrastructure or lacking mutual assistance activities. Furthermore, these results seem to promote the discussion of community-based, mutual assistance activities.

Table 3. The numerical value of simulation results

|                  | Without mutual assistance | With mutual assistance |
|------------------|---------------------------|------------------------|
| Time [s]         | 574                       | 657                    |
| Number of those reached | 651                       | 675                    |
| Number of those who could not evacuate | 199                       | 175                    |

|                  | Over 75 years old | Over 65 years old | Morning | Afternoon | Early evening |
|------------------|------------------|------------------|---------|-----------|---------------|
| Time [s]         | 621              | 635              | 657     | 607       | 630           |
| Number of those reached | 662              | 631              | 675     | 231       | 396           |
| Number of those who could not evacuate | 188              | 219              | 175     | 66        | 108           |

5.3 Changing the ratio of resident agents who needed evacuation assistance

Comparing the results of the residents over 75 years old who could not evacuate with the results of the residents over 65 years old who could not evacuate, the former showed 31 more residents (about 4% of the number of all residents in the virtual space) who could reach the evacuation site by mutual assistance activities than the latter. An increase in the number of residents who could not evacuate shows that rescuing all neighborhood residents who cannot evacuate by mutual assistance activities is impossible. In the future, when a declining birth rate and a growing population of elderly people are promoted, some countermeasures will be needed. In addition, this result reveals the risk to districts with a high ratio of elderly people such as local city and rural areas. Therefore, users can understand the necessity for promoting mutual assistance activities. Further, it seems that the discussion for exploring some countermeasures of community-based activities is promoted through this simulation.

5.4 Changing the timeframe

As mentioned in Section 3.3, in the morning hours, all household members are in their respective buildings. In the afternoon, almost all residents in the virtual space are stay-at-home wives and elderly persons, and almost all students and workers are outside of the virtual space (commuting), with the total population being 297 residents. In the early evening hours, almost all students are back home, almost all residents in the virtual space are stay-at-home wives, students and elderly persons, and the total population is 504 residents. Comparing the results of the morning, afternoon and early evening hour simulations, in the afternoon, mutual assistance activities become fewer because students and workers who could contribute to the promotion of mutual assistance activities are commuting. Therefore, the ratio of the residents who could not reach the evacuation site was higher in the afternoon than in the morning hours.
In the case of the early evening, the residents who could contribute to the promotion of mutual assistance activities increased because students had returned back home. Therefore, the ratio of the residents who could not reach the evacuation site was lower in the early evening than in the afternoon. In this way, the capability of mutual assistance activities by neighborhood was changed in accordance with the timeframe. Users can thus

*Figure 4.* Simulation results
understand the need for countermeasures such as the promotion of mutual assistance activities for timeframes when the capability is low.

6. CONCLUSION

In this paper, simulation of evacuation activities considering mutual assistance under various earthquake disaster scenarios was developed and conducted to support exploring the contents of community-based activities by using a multi-agent based model. To verify the usability of the developed simulator to support the discussion for exploring community-based activities and mutual assistance, experimental usage was conducted. The results of some simulations reflected scenarios such as whether the residents performed activities related to mutual assistance or not, and cases wherein mutual assistance was changed according to the time of day due to the presence or absence of the commuting population.

The following results were obtained from this study:

1. Through confirming the simulation results of the case wherein mutual assistance activities by residents were not performed, users can understand the number of people that cannot evacuate to the designated safety site and the areas where there are many people that cannot evacuate.

2. Through confirming the simulation results of the case wherein mutual assistance activities by residents were widely performed, users can understand that human suffering is reduced by mutual assistance activities even when evacuation times are longer. In addition, users can distinguish between neighborhoods with high and low mutual assistance capabilities. Further, users can more fully comprehend the importance of mutual assistance. Therefore, users can explore the countermeasures to ensure there are sufficient mutual assistance activities for areas where mutual assistance capability is low.

3. Users can understand that the capability of mutual assistance is changed according to the time of day caused by the commuting population. Therefore, users can explore countermeasures to reduce human suffering in the cases where the capability of mutual assistance is low.

Users can simulate cases where the ratio of those unable to evacuate the designated safety site without some support will be increased due to population aging in the future. Therefore, users can explore both short- and long-term countermeasures to ensure sufficient mutual assistance activities.

The developed simulator provides users with information for exploring countermeasures to ensure sufficient mutual assistance activities. Therefore, the simulator is useful to explore different community-based activities considering mutual assistance activities. Improvement of the simulation model is required to reproduce more accurate mutual assistance activities, and some demonstrations in a full-scale model district is required to verify the usability of the developed tool.

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