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Development of a Virtual Disaster Simulator for Municipal Training in Japan

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Abstract. *This study introduces a comprehensive simulation model using agent-based modeling (ABM) to assist local governments in developing disaster training scenarios, focusing on earthquake-induced infrastructure damage, sediment disasters, and evacuation behavior. The model comprises three key components: a disaster simulator predicting infrastructure damage, a sediment disaster model replicating damage within warning zones, and an evacuation behavior model representing individual decision-making. Developed with the SOARS toolkit and visualized using Python and ArcGIS Pro, the model effectively captures disaster scenarios. Although infrastructure damage predictions were slightly lower than historical data, they were successfully incorporated into the scenarios. The sediment disaster model accurately reflected trends in the number of affected agents, like past events, and the evacuation model demonstrated consistent behavior patterns across simulations. Additionally, new insights emerged, such as cases where the number of evacuating agents exceeded shelter capacity. Municipalities can employ this model to enhance their disaster response capabilities and conduct more realistic and diverse disaster simulations, ultimately improving the effectiveness of their disaster preparedness training programs.*

Keywords. *Agent-based modeling, disaster simulation, evacuation behavior, SOARS toolkit, disaster tabletop drills*

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Introduction

Due to its geographical characteristics, natural disasters frequently occur in Japan, where earthquake activity is intense because the Japanese archipelago is located at the boundaries of multiple tectonic plates. There have been numerous major earthquakes in the past, including the Great Hanshin-Awaji Earthquake in 1995, the Great East Japan Earthquake in 2011, and the Kumamoto Earthquake in 2016. These earthquakes caused the collapse of buildings and roads, leading to significant physical damage. In some regions, earthquakes triggered sediment disasters, resulting not only in physical damage but also in human casualties, including people being buried under the debris. Sediment disasters refer to debris flows, landslides, and cliff collapses, all of which have significant destructive power and can sever roads. Sediment disasters are sudden events caused by natural disasters, making it difficult to predict when and where they will occur. Consequently, people might fail to evacuate in time and thus become trapped when a sediment disaster occurs. As a recent example, the Noto Peninsula earthquake in 2024 caused more than 450 sediment disasters, leading to numerous complete and partial house collapses, as well as many deaths and missing persons due to landslides [1].

Damage caused by earthquakes also affects infrastructure such as electricity, gas, water, and communication systems. Nojima et al. (1996) [2] summarized the damage to power and gas facilities in the Great Hanshin-Awaji Earthquake of 1995, with damage to many substations and power transmission lines resulting in power outages for up to 2.6 million buildings and gas supplies interrupted for over 850,000 buildings. In the Kumamoto Earthquake of 2016, power outages affected more than 470,000 buildings, although not to the same extent as the Hanshin-Awaji Earthquake [3]. Moreover, up to 445,000 buildings were without water supply, approximately 100,000 buildings suffered gas supply interruptions, and 350 communication base stations were shut down, affecting various institutions such as transportation and medical facilities. This demonstrates that the damage caused by earthquakes has a serious impact on infrastructure, highlighting the critical importance of disaster prevention measures.

When a critical situation arises due to natural disasters such as those mentioned above, the initial response of local governments especially municipalities with disaster prevention responsibilities is directly linked to the lives of residents [4]. It is essential for each municipality to promptly collect information on the damage and accurately disseminate it to minimize human casualties by ensuring the safety of disaster victims and improving the efficiency of rescue operations, thereby enabling swift evacuation instructions and support activities. Therefore, swift initial response is indispensable in every municipality.

However, there are significant differences in the disaster response capabilities of disaster-affected municipalities. Factors such as the number of municipal employees, disaster experience, and the frequency and content of disaster drills can result in varying degrees of damage and recovery speeds, even when facing the same disaster. In the Kumamoto Earthquake of 2016, the main municipal offices of some cities were damaged by the main shock, which rendered all necessary materials, telephones, and computers unusable during the initial disaster response period [5]. Additionally, during the Great East Japan Earthquake of 2011, although satellite communication lines were secured as a means of contact, they were not used regularly, leading to a lack of understanding of how to use them [6]. These situations resulted in inefficient sharing of victim information between the government and support organizations, leading to delays in safety confirmations and rescue operations that hindered recovery efforts and disaster countermeasures, ultimately exacerbating the damage. Therefore, it is essential to improve disaster response capabilities during the initial disaster period in all municipalities to ensure prompt recovery and effective rescue operations for residents.

Several methods exist to enhance disaster response capabilities, including drills and workshops. Disaster tabletop drills have recently gained attention [7], targeting specific stakeholders and aiming to understand response procedures and issues during disasters, facilitating smoother responses during actual disasters. Unlike lectures which involve passive information intake these drills require participants to actively engage and make decisions. During disasters, swift and accurate decision-making is required, necessitating the ability to process information accurately and identify critical information from a vast amount of data. Given that improving information processing capabilities is crucial to reducing decision-making errors during disasters and enabling efficient responses, disaster tabletop drills are indispensable [8].

Several types of disaster tabletop drills exist, but about 60% of municipalities express a preference for simulation-based types, recognizing the necessity of experiencing simulated disaster response. Simulation-based disaster tabletop drills involve conducting information transmission and decision-making in a coordinated manner among various departments under a hypothetical disaster scenario. These drills are highly useful for identifying inter-departmental collaboration issues and fostering relationships [9]. However, one drawback is the significant preparation effort involved as creating a simulation-based disaster tabletop drill requires scenarios that consider the type, location, scale, and damage of the disaster. Ensuring that the scenarios are realistic is crucial, as drills lacking realism do not lead to improvements in disaster response actions [10]. Realism in disaster tabletop drills means replicating how each stakeholder would act during a disaster, using detailed scenarios based on actual disaster sites, and reproducing actual work processes. For example, municipalities need to report to various agencies how many residents with specific attributes are gathering at which shelters and which areas are affected early in the disaster, as essential details to replicate. Additionally, training scenarios should include not only damage from earthquakes and sediment disasters but also infrastructure damage, requiring a variety of scenarios. Therefore, while the necessity of simulation-based disaster tabletop drills is high, the challenge of preparation remains significant.

Therefore, this study aims to create various training scenarios triggered by earthquakes by constructing a model to simulate damage situations. The model uses agent-based modeling (ABM), which simulates the actions and interactions of individuals to understand and predict complex overall movements. By utilizing technology to conduct disaster response drills in a virtual space, operational agencies and municipalities can repeatedly conduct diverse drills without being constrained by time or space limitations. Additionally, we aim to develop a more practical and effective tool for creating training scenarios by simulating lifeline disruptions and evacuation behaviors based on actual disaster procedures.

Research Methodology

In this study, we modeled the behavior of evacuees at a micro-level using ABM and described the simulation construction using the SOARS toolkit, a social simulation library implemented in Java [11]. SOARS represents the environment where agents exist as "spots." Multiple spots can exist within the model, allowing the representation of agents' geographical locations and their affiliations to social groups, such as households. In SOARS, “rules” describe the behavior of agents in the simulation. These rules can be scheduled at different conceptual stages of time within the simulation, known as "stages." For example, it is possible to design rules for information dissemination, decision-making, and movement by assigning them to corresponding stages, such as information dissemination, decision-making, and a movement stage.

This allows breaking down and describing complex sequences of agent behaviors using simple rules. Additionally, SOARS introduces the concept of "roles" to organize these rules, whereby an agent can hold multiple roles and switch between them as they behave. This feature enables the concise design and description of the complex social roles that agents might possess. In this study, we focused on the early stages of a disaster and conducted a seven-day simulation.

In this study, we used a large-scale household synthetic dataset created by Harada et al. (2018) [12] to conduct simulations that closely resemble reality. Synthetic population data is simulated data representing the population structure, including household members' ages, occupations, and other attributes within the target regions of Japan. This synthetic population is created by solving combinatorial problems using multiple statistical datasets while preserving individual privacy. Put simply, it is data that assigns a place of residence by matching statistical information such as the age and gender of people living in that municipality with statistical information such as household composition and occupation.

Therefore, synthetic population data is simulated individual data that is statistically correct without using any personal information. The synthetic population data includes both individual data and building data. The virtual individuals in the individual data have attributes such as an individual ID, age, and gender, while the building data includes the latitude and longitude of addresses within Japan. Table 1 shows the data used in this study. We used these data to generate 158,900 agents representing the population of Kushiro City and 5,273 evacuation sites throughout Hokkaido. The reason for including evacuation sites across the entire Hokkaido region is to account for scenarios where the nearest evacuation site is outside of Kushiro City. Figure 1 shows a visualization sample of the generated agents.

Table 1.
Data Used From Synthetic Population Data

Attribute	Explaianation
age	Age of agent
sex_id	0:male, 1:female
latitude	latitude of agent's house
longitude	logitude of agent's house
building_id	unique number of the building
mesh_code	Fifth mesh code

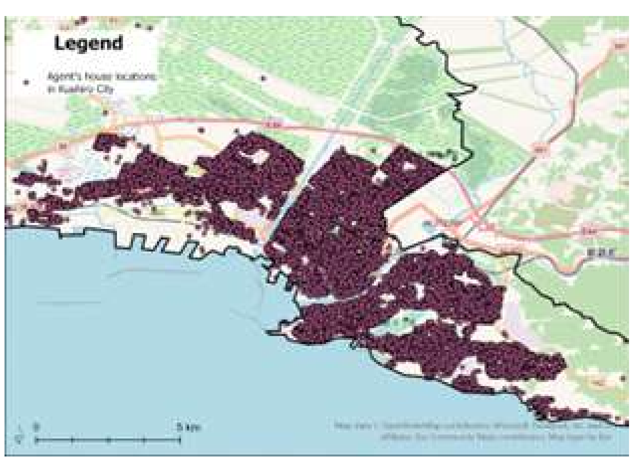

Figure 1.
Agents' house locations in Kushiro City

The simulation model used in this study comprises three components to recreate damage situations. Although the simulation model is applicable to the entire country of Japan, this paper focuses on the Tokachi-Oki earthquake which has frequently occurred in the past and recreates the damage situation in Kushiro City in Hokkaido Prefecture. The Tokachi-Oki earthquake has historically recorded multiple occurrences with seismic intensities of 5 or higher, and it is predicted that the death toll could exceed 8,000 people [13]. Located at the heart of the region, Kushiro City is a municipality in northern Japan with a population of approximately 155,000 residents, known for its natural beauty.

Disaster Simulator: A model that simulates the simulated damage situations of four infrastructures electricity, gas, water, and communication immediately after a disaster. It serves as one of the input values for the ABM.

Sediment Disaster Occurrence Model: A model that triggers sediment disasters in landslide warning areas and special landslide warning areas due to an earthquake.

Evacuation Behavior Model: A model that triggers evacuation to the nearest shelter based on the probability determined by the extent of housing damage and the availability of infrastructure.

A. Disaster Simulator

The disaster simulator follows the design philosophy of Urushibara et al. (2020) [14], Yanagisawa et al. [15], and Iwasaki et al. [16]. It receives seismic intensity distributions or inundation areas as input values, probabilistically inflicts damage on virtual infrastructure constructed within the simulator, and outputs the disruption status of each infrastructure as a CSV file that is assigned a small area code from the national census or a fifth mesh code. A mesh refers to a grid system overlaid on a map with assigned numbers, and a fifth mesh corresponds to a grid with each side measuring 250 meters.

The damage status of each infrastructure is visualized using a geographic information system (GIS). GIS is a general term for information systems that electronically process and analyze various attribute information linked to spatial locations, and it is expected to be useful for disaster damage prediction and evacuation planning [17]. The ArcGIS Pro 3.0.0 software was used in this study.

Subsequently, the method for calculating the damage to each infrastructure is explained. The probability of destruction for each infrastructure is calculated using a seismic fragility curve, representing the relationship between the strength of an earthquake and the damage level of structures [18]. In this study, the seismic fragility curve is expressed using a hyperbolic tangent function with parameters, and the probability of damage for each seismic intensity is determined. The calculations were performed using the Python 3.9 programming language, with the curve fitting undertaken using the curve fit function from the SciPy module. The seismic fragility curve was defined as equation (1) based on the paper by Iwasaki et al. [16]. Here, x refers to the seismic intensity information of the fifth mesh, and the magnitude of the seismic intensity is assigned. In other words, the larger the seismic intensity, the higher the probability of damage.

$$y = a \cdot \tanh(k \cdot (x - x_0)) + c. \qquad (1)$$

x : *Independent Variable*
x_0: *Translation Parameter = 6.934*
a : *Amplitude Parameter = 0.094*
k : *Slope Parameter = 0.720*
c : *Vertical Shift Parameter = 0.101*

Next, the destruction settings for each infrastructure are described. While equation (1) is used for all infrastructures, the spread of damage differs depending on the type of infrastructure. For electricity, following the design philosophy of Yanagisawa et al. [15], seismic intensity is used as the input value to determine the destruction of power plants and substations. At the same time, power grid data for each power company is loaded, and areas with power grids associated with the damaged power plants and substations are designated as blackout regions. This method enables establishing a blackout model that propagates damage to adjacent areas when power plants and substations lose functionality. For gas, following the design philosophy of Iwasaki et al. [16], seismic intensity of lower 5 or higher are considered, and destruction probabilities are used. For water supply, similar to electricity, destruction is evaluated using equation (1).

However, for water outage damage, the water supply area data published by the National Land Numerical Information dataset is used to compare the difference in water supply volume between normal and disaster conditions. The water supply volume in grids that have experienced a water outage is temporarily set to zero, and the average water supply volume of the neighboring grids (top, bottom, left, and right) is calculated for each grid. If the averaged value falls below 50% of the normal water supply volume, the grid is considered to have experienced a water outage. However, this threshold is based on empirical data. For gas, the supply area is defined as the municipalities where city gas suppliers provide city gas. The target municipalities are divided into third mesh units, and evaluation using equation (1) is performed. Subsequently, damage in the fifth mesh units is calculated for each small area. If more than half of the meshes in a small area are damaged, the area is considered to be damaged.

The locations and nature of infrastructure damage can be represented using the damage data for the four aforementioned types of infrastructure. This enables creating scenarios in which infrastructure damage varies depending on the seismic intensity for each drill. By utilizing these data, it is expected that discussions aimed at improving disaster response capabilities will be prompted, such as how to coordinate with various agencies in the event that communication is unavailable.

B. Sediment Disaster Model

The occurrence of sediment disasters is modeled by creating data that can be loaded into SOARS using GIS. The locations where sediment disasters are likely to occur are determined using the sediment disaster warning area data from the Ministry of Land, Infrastructure, Transport and Tourism (MLIT; 2020 edition). A sediment disaster warning area is a designated zone recognized as having a potential risk to human life or health in the event of a sediment disaster, and the Sediment Disaster Warning Area dataset provides these zones as polygons. Using this data, sediment disasters are triggered probabilistically based on seismic intensity. The seismic intensity data used is the same as that used in the disaster simulator. The probability of sediment disasters is calculated based on data from the 2024 Noto Peninsula earthquake.

The Geospatial Information Authority of Japan has released polygon data (sediment disaster occurrence polygons) showing the locations of sediment disasters caused by this earthquake. In this study, we define the sediment disaster occurrence probability using data from the Suzu, Wajima, and Anamizu areas, where the seismic intensity was particularly strong. We quantify the occurrence probability using fifth mesh units, whereby the number of sediment disaster occurrence polygons overlapping with the fifth mesh units within the sediment disaster warning area polygons serves as the numerator, while the number of fifth mesh units overlapping with the sediment disaster warning area polygons in high seismic intensity regions serves as the denominator, yielding a sediment disaster occurrence probability of 16.8%. Based on this calculated value, sediment disasters are triggered along the sediment disaster warning area polygons.

C. Evacuation Behavior Model

The evacuation behavior model discusses the decision-making process for evacuation and the locations to which people evacuate. While numerous prior studies have explored evacuation decision-making, we base our approach on the work of Tsukamoto et al. [19], who conducted a survey influenced by these prior studies. They extracted factors that are likely to influence evacuation decisions from 21 papers and analyzed the results through a questionnaire survey. A notable feature of their survey is that it is not retrospective, which allows applying the results without being tied to a specific earthquake. From this paper, we identified four prominent evacuation factors water outage, power outage, building damage, and evacuation of surrounding people as the key factors in our study. These four factors are quantified by sex and age group using the aforementioned survey.

The probability calculation equation is defined as equation (2), with each evacuation factor as a variable, and weights shown in Table 2 assigned to each variable. For example, if P(x) is 60%, the agent will engage in evacuation behavior with a 60% probability. The weights are calculated using the rate of increase in evacuation intention when each situation occurs, based on the questionnaire conducted by Tsukamoto et al. The weight is determined by standardizing the rate of increase for each gender and age group, and setting the total value as 1. In addition, x is assigned the value of 1 if the item occurs and zero if it does not, and only the binary values are used.

$$P(x) = ax_1 + bx_2 + cx3 + dx_4. \qquad (2)$$
$$a + b + c + d \fallingdotseq 1$$

x : Occurrence of each variable (0 or 1)
a : Weight of building damage
b : Weight of water outrage
c : Weight of power outrage
d : Weight of neighbor's evacuation

The occurrence of each variable is described below. For water and power outages, the results from the disaster simulator are used. The disaster simulator assigns infrastructure damage to each fifth mesh, whereby if there is a simulated building within a damaged mesh, that building is assigned either a water outage, a power outage, or both. If assigned, the value of x is set to 1.

For building damage, the total destruction rate of buildings is determined based on data from the Cabinet Office [20]. When an earthquake occurs in the simulation, buildings are completely destroyed according to various probabilities. If a building is completely destroyed, it affects the evacuation probability of the agents living in that building, changing x_4 to 1. Table 3 shows the total destruction rates for various buildings. In Japan, the Building Standards Act was revised in 1981, making the seismic standards more stringent. As a result, compared to older buildings, newer buildings are less likely to collapse in the event of a major earthquake.

Table 2
Variable Weighting

Sex	Age	Building damage	Water outrage	Power outrage	Surrounding evacuation
Male	20s	0.601	0.336	-0.029	0.092
Male	30s	0.803	0.193	-0.097	0.1
Male	40s	0.865	0.185	-0.106	0.056
Male	50s	1.001	0.142	-0.199	0.055
Male	60s	0.728	0.253	-0.065	0.085
Female	20s	0.692	0.25	0	0.059
Female	30s	0.748	0.19	-0.017	0.08
Female	40s	0.775	0.215	-0.037	0.047
Female	50s	0.737	0.214	-0.077	0.126
Female	60s	0.717	0.256	0.009	0.018

Table 3
Building Structure And Collapse Rate

Japanese seismic intensity scale	Wooden (Before 1980)	Non wooden (Before 1980)	Wooden (Since 1981)	Non wooden (Since 1981)
6+	0.51	0.17	0.12	0.07
7	0.92	0.48	0.5	0.2

For evacuation related to the surrounding area, this is calculated using information on the household (household id) to which the agent belongs. If any member of the household to which the agent belongs engages in evacuation behavior, this variable x_4 is set to 1. In SOARS, a function allows agents to share information with other agents within the same spot. Using this function, the information that someone in the household has evacuated is passed to other agents living in the same location within the household.

Next, when an agent chooses to evacuate, the model determines where they will evacuate. In this model, the agent evacuates to the nearest shelter in terms of road distance from their building. To find the nearest shelter by road distance, we use the "Closest Facility" function, a network analysis tool in ArcGIS Pro that calculates the cost of traveling from a certain point (incident) to a target facility (facility) and outputs the nearest route. Using this function, we assigned the address of the building as the incident input and the shelters as the facility input, assigning each agent to the nearest shelter. However, in cases where the address of the building cannot connect to the road data, the agent is considered unable to evacuate, even if they wish to do so. Additionally, only walking as a mode of transportation is considered in this study.

In this study, the above model is used for simulation, whereby the disaster simulator is first activated to output information on infrastructure damage in units of fifth mesh. At the same time, the sediment disaster model determines the polygons that are likely to be affected. If an agent's residence is located in the polygon where the disaster occurred, the agent is considered dead and excluded from the simulation. Next, the total building damage is determined based on the effects of the earthquake shaking and the landslide. Up to this point, damage information is determined as an occurrence within the simulation. Subsequently, the agent makes an evacuation decision based on this damage information. If the agent decides to evacuate, they move to the nearest evacuation site and remain there. The agent repeats this evacuation behavior for 7 days.

Results and Discussion

D. Results of the Disaster Simulator (Maps and Table of Affected Population by Attribute)

Figure 2-5 show the status of infrastructure outages in the central urban area of Kushiro City. In each figure, the colored meshes (labeled as "true" in the legend) represent locations where infrastructure has been halted. Regarding power outages, when a single power plant or substation is destroyed, it affects the associated power grid, making it more likely for the damage to spread over a wide area. For water outages, the spread of outages is reflected around the center of the affected locations, although water outages do not occur as extensively as power outages. Although gas and communication outages occur collectively, the probabilities of occurrence vary due to random number generation. Table 4 shows the number of damaged buildings and affected people for each type of damage. The impact of power outages is the most significant, while the other types of damage do not have such a severe impact.

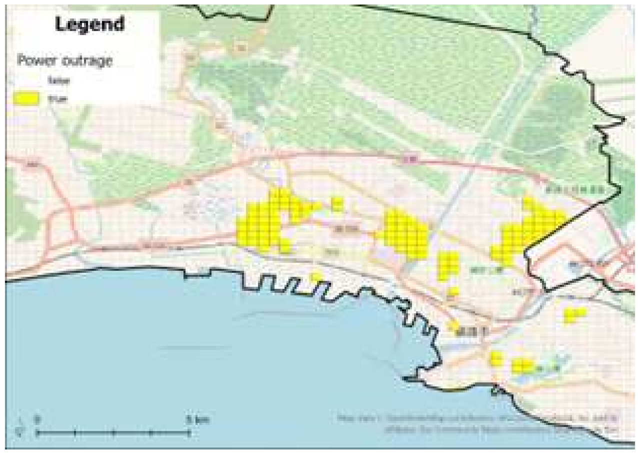

Figure 2
Areas Affected By Power Outages

Figure 3
Areas Affected By Water Outages

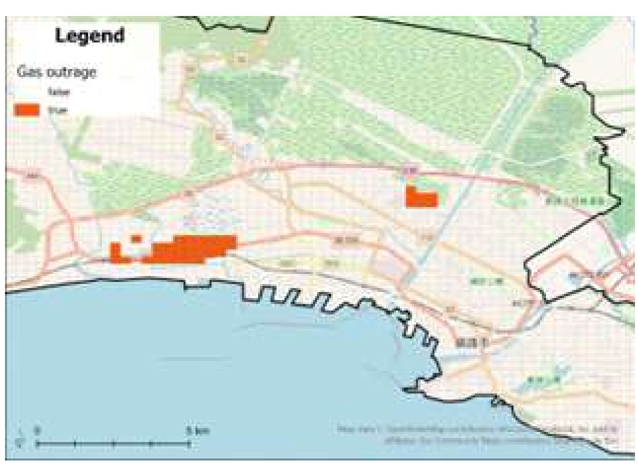

Figure 4
Areas Affected By Gas Outages

Figure 5
Areas Affected By Communication Outages

Table 4
Impact Of Damage In Kushiro City

Category	No. of house	No. of people
Power outrage	5,776	12,937
Water outrage	203	733
Gas outrage	960	1,936
Communication outrage	91	174

E. *Results of the Sediment Disaster Model*

Figure 6 shows the locations where agents residing in Kushiro City were affected by sediment disasters. When a sediment disaster occurs, agents living in buildings located within the warning areas are considered to be affected. The orange areas represent the warning zones, and the yellow points indicate the locations where agents were caught in the sediment disaster. In this simulation, 54 out of 158,900 agents in Kushiro City were affected by sediment disasters. Additionally, Figure 7 shows the damage to buildings caused directly by the earthquake. The pins indicate locations of building collapses due to the earthquake, with a total of 53 buildings collapsing in Kushiro City.

Figure 6
Sediment Disaster Areas And Their Victims

Figure 7
Location Of Damaged Buildings

F. Results of the Evacuation Behavior Model

Figure 8 shows the daily transition of evacuees following the earthquake. This box plot represents the results of 30 simulations using the model. At the time of the earthquake, approximately 35,000 people evacuated, while around 45,000 agents had evacuated by the following day. The number of evacuees gradually increased thereafter, with more than 50,000 agents eventually evacuating. There was little variation in the number of evacuees each day, resulting in a consistent number of evacuees. Figure 9 shows the final number of evacuees at each evacuation facility. The size of the circles represents the number of evacuees, with larger circles indicating a higher number of evacuees. In the commercial area where shelters are concentrated (the lower central area in the image), the circles are smaller and more dispersed due to the smaller number of residential buildings. On the other hand, in the residential area (the upper central area of the image), some circles are larger and more clustered. Table 5 shows the attributes of evacuees at each shelter. The age of evacuees is displayed in ten-year increments, and the number of male and female evacuees is also provided. The capacity factor represents the ratio of the number of evacuees relative to the capacity of each shelter. There is a noticeable variance in the number of evacuees relative to capacity across shelters. Figure 10 presents a box plot of the number of evacuees at each shelter from the 30 simulations of the model. While there is a variation of several hundred people at some shelters, the overall number of evacuees is consistent, which enables developing strategies for shelters where many people tend to gather. Figure 11 shows the time that it takes for evacuees to reach the shelters, showing that 90% of evacuees reach a shelter within a 10-minute walk. However, some evacuees take more than 15 minutes to reach a shelter, indicating the considerable distance to the shelter in such cases.

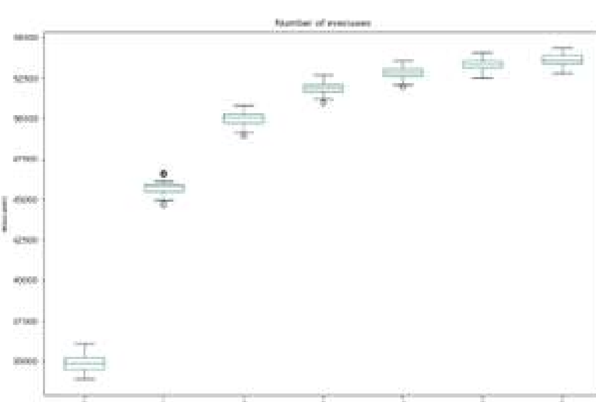

Figure 8
Changes In Evacuees

Figure 9
Distribution Of Evacuees

Table 5
Information On Evacuees At Each Shelter

under 10	10s	20s	30s	40s	50s	60s	over 70	male	female	total	capacity	capacity factor	latitude	longitude
0	0	0	7	0	35	11	0	25	28	53	20	2.65	43.097989	144.120055
0	0	0	6	0	7	0	0	0	13	13	79	0.16	43.144413	144.14505
0	0	0	0	0	6	0	0	0	6	6	26	0.23	43.155255	144.151149
0	0	0	0	0	20	0	7	7	20	27	97	0.28	43.174118	144.222869
0	0	0	5	0	39	7	0	28	23	51	22	2.32	43.222635	144.114762

Figure 10
Box-And-Whisker Diagram Of The Number Of Evacuees By Shelter

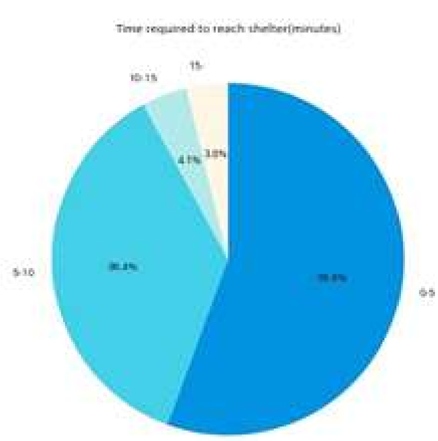

Figure 11
Time Required To Reach Shelter

Discussion

In this study, we used ABM to simulate a virtual earthquake, calculating the number of evacuees at each shelter and the impact of infrastructure and building damage. While several papers have focused on damage estimation due to natural disasters using ABM, no prior studies have provided a generic model offering the damage and evacuation information that municipalities need during the initial stages of a disaster. For example, MAS et al. (2012) [21] constructed a tsunami model and evacuation model for the Great East Japan Earthquake using ABM in NetLogo, demonstrating the usefulness of ABM.

However, their study is limited to faithfully reproducing the Great East Japan Earthquake, and the model cannot be used for training by municipalities across Japan. Similarly, Nakanishi et al. (2020) used ABM to model the evacuation behavior of residents during a flood in Takamatsu City in Kagawa Prefecture [22], confirmed that it is viable to use ABM in this study to indicate the evacuation behavior of residents. Moreover, the aforementioned study summarized the position of existing disaster simulators and ABM, affirming their utility. While their study offers valuable insights such as evacuation models and road network creation, it does not include an earthquake component in the model. Thus, there is no existing study that offers a generic evacuation model using ABM focused on earthquakes in Japan.

Given these points, the novelty of the virtual disaster response simulator in this study lies in its focus on municipal training, providing essential information such as evacuation and building damage data that municipalities seek during the initial stages of a disaster. Another strength is the model's applicability to any municipality in Japan, as it can be implemented wherever seismic intensity data is available. We hope that this system will be widely used by municipalities as a resource for tabletop simulation-based drills.

Next, we discuss the accuracy of each simulator and model. The data related to the 2003 Tokachi-Oki earthquake is publicly available from the Ministry of Internal Affairs and Communications, including the number of buildings affected by various infrastructure damages [23]. Regarding power outages, 379,440 buildings across Hokkaido were affected. Even when considering the municipalities that issued evacuation advisories, approximately 15,000 buildings were affected, indicating that the power outage extended across the entire prefecture. In contrast, our model produced 5,776 affected buildings in Kushiro City, or around 6% of the city's total. For water outages, 15,799 buildings across Hokkaido were affected in 2003, again pointing to prefecture-wide disruption, whereas our current run shows fewer incidents (no historical data were available for gas and telephone services). While infrastructure resilience might have improved over the past two decades, the present model seems to underestimate damage compared with the historical record. However, importantly, the model is stochastic, whereby running the simulation multiple times can generate cases in which critical substations are completely destroyed, thereby triggering prefecture-level blackouts.

The example shown here merely happens to be a milder realization in that distribution. Given that the blackout algorithm scales directly with substation failure, exercise planners can dial scenario severity up or down selecting milder or harsher damage assumptions to match training objectives. Thus, although accurate results remain desirable, the chief aim of this study is to serve municipal training by supplying a spectrum of plausible scenarios. Experiencing such varied situations is expected to enhance disaster resilience among municipal staff, providing practical value even when precise replication of past events is not the primary focus [24].

Regarding the results of the sediment disaster model, no information on the occurrence of sediment disasters was found in the past data. However, given that sediment disaster warning areas have been designated, it is plausible that a major earthquake could trigger a sediment disaster. In the current simulation, 54 agents were caught in the sediment disaster. During the Noto Peninsula earthquake, there were 456 cases of sediment disasters, resulting in 27 casualties [25]. Therefore, although the number of casualties in the simulation is somewhat higher, the results seem to reasonably replicate the actual figures without significant deviation. Regarding building damage caused by the earthquake, the 2003 Tokachi-Oki earthquake resulted in the complete destruction of 116 buildings [26].

While the damage in the simulation is slightly less, the model successfully replicates building collapses without significant deviation from the actual figures. In addition, in this model, the sediment disasters occur only in the sediment disaster warning area. Originally, further sediment disasters would occur deeper in the mountains, although this is not taken into account because the sediment disaster warning area only covers areas where serious damage to residents and buildings will occur. In the future, different occurrence algorithms will be needed for sediment disaster locations to take road information into account.

Finally, we discuss the results of the evacuation behavior model. After running 30 simulations with this model, we can interpret that there is not much variation in the number of evacuees. Across all runs, approximately 30% of residents chose to evacuate, reflecting a reasonable proportion in light of empirical data. For comparison, during the 2016 Kumamoto Earthquake, municipalities that experienced a JMA seismic intensity of 7 reported evacuation rates between 20% and 40%, placing our simulated value near the midpoint of what has actually been observed. According to the survey conducted by Tsukamoto et al., although various factors influence individual evacuation decisions, factors related to living infrastructure such as the collapse of buildings and the availability of electricity have a significant impact [19]. On the other hand, since the simulation targets areas with significant damage, building collapses and power outages are more likely to occur. As a result, even after multiple simulations, a large number of agents were inclined to evacuate, which might explain the observed trend. However, as Nakanishi et al. highlighted, it is also important to consider spatial constraints such as road damage [22]. Information on which roads are usable and which are not should be communicated not only to evacuees but also to organizations involved in support and rescue operations. Other considerations regarding evacuation should also be made for those who cannot evacuate, including people who need welfare assistance, such as those who need dialysis or pregnant women. In addition, those who own a car might spend their evacuation in their car. Based on this situation, a detailed evacuation algorithm is needed, as each stakeholder will behave differently regarding evacuation. This is an important issue for future work in this area.

Conclusion

In this study, we developed a basic simulation using ABM that considers infrastructure and building damage, as well as evacuation behavior due to earthquakes, as part of an effort to assist in creating scenarios for municipal tabletop simulation drills. The simulation is divided into a disaster simulator that generates infrastructure damage, a sediment disaster model that triggers landslides, and an evacuation behavior model that represents evacuation behavior. This simulation was implemented using the SOARS social simulation library and Python, with visualization carried out using ArcGIS Pro and Python. In terms of infrastructure damage, the number of incidents generated in the simulation was lower compared to past data, highlighting room for improvement in the disaster simulator model. However, since the purpose of this study is to assist in creating scenarios for municipal drills, the focus is placed on extracting information from the model about the damage and evacuation situations during a disaster, and applying it in drills.

The evacuation behavior model focuses on the initial phase of the disaster, with 30 simulations conducted over a seven-day period to visualize the progression of evacuees. The results showed little variation in the number of evacuees, with a consistent proportion of people heading to shelters. On the other hand, there was significant variation in the capacity of shelters, raising concerns that some shelters might become overcrowded.

However, as Tsukamoto et al. [19] caution, evacuation determinants derived from pre-event questionnaires offer only a coarse approximation. Consequently, even if our model captures the overall scale of evacuees, there are intrinsic limits to validating its precision. Because evacuation intent is highly sensitive to regional socio-economic and cultural contexts, conclusions drawn from one earthquake cannot be transferred wholesale to other locales or future events.

Overall, the simulation results suggest that the system developed can provide the information that municipalities need during the initial stages of a disaster and prove useful for tabletop simulation drills. Because municipal staff still strongly rely on expert judgment and spend considerable time manually compiling damage scenarios [27], the system can further support them by delivering pre-aggregated outputs such as municipality-level casualty and evacuee counts, as well as geospatial layers pinpointing potential landslide sites. Access to these datasets enables planners to decide for example which shelters warrant priority attention and where resources should be staged before an exercise begins. In this way, the system offers a practical means of supplying realistic, data-driven damage assumptions that strengthen disaster response training and ultimately municipal resilience.

In the next stage of development, we will focus on both accuracy and scope. First, the model parameters will be recalibrated against a wider catalogue of historical earthquakes to ensure that simulated losses more closely mirror observed damage. The 2024 Noto Peninsula earthquake has already produced valuable empirical insights, with Mashio et al. [28] tracking post-event population movements using Mobile Spatial Statistics and extracting the key drivers of evacuation behavior. By embedding these data-driven factors directly into the decision-making logic of our agent-based model, we can ground each agent's choices in real-world evidence and deliver scenarios that municipal staff recognize as credible.

Second, we will broaden the hazard portfolio to include heavy rain, fluvial floods, tsunamis, and road serviceability. This multi-hazard capability will enable municipalities to rehearse compound-disaster situations that are becoming increasingly common.

Third, drawing on the network-centric risk analysis framework of Dueñas-Osorio et al.(2007) [29] and Ouyangand Dueñas-Osorio(2011) [30], we will reproduce lifeline interdependencies with greater spatial and functional fidelity. A richer representation of power, water, and transportation grids will enable the model to capture cascading outages and sharpen loss estimates. In parallel, we will explore shelter-resource allocation strategies and dynamic warning protocols. When primary facilities exceed capacity, the simulator should advise officers on rerouting evacuees and repositioning supplies, basing these rules on surveys and post-event interviews. Evacuation modules will also be expanded to accommodate emergency buses, ambulances, and road-surface damage. By assessing how route blockages reshape the true "shortest" path, planners can stress-test contingency plans under realistic mobility constraints.

Finally, an iterative cycle of tabletop drills and practitioner feedback will be established. Insights gathered from municipal officers will flow back into the model, progressively refining both its behavioral rules and its user interface. Taken together, these improvements will produce a more robust, evidence-based training platform that strengthens local disaster resilience.

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All authors contributed equally as the main contributors of this paper. All authors read and approved the final paper.

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Competing Interest
The authors declare that they have no conflicts of interest to report regarding the present study.

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