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Search Path Optimization Method Considering Building-Specific Probability of Victims Requiring Rescue and Time Dependent Decay of Survival Rates

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This study proposes a search path optimization method for post-earthquake rescue operations that considers both the spatial distribution of people requiring rescue and the time-dependent decline in survival rate. Conventional search planning often prioritizes the shortest travel distance, although such a route does not necessarily maximize the number of people rescued when damage is unevenly distributed. In this study, building-specific seismic motion is estimated first, and the expected number of people requiring rescue is calculated from building damage probability and occupancy information. For practical search operations, these values are aggregated at the block level, and a rescue score is defined by combining the expected number of people requiring rescue with the survival rate at the arrival time. Monte Carlo simulations were carried out for a virtual city consisting of eight districts while keeping the total expected number of people requiring rescue constant at 40. The results showed that the score-maximizing route increased the average expected number of rescues by 4.9 and improved the rescue rate from about 35% to 47% compared with the shortest path. These results demonstrate the effectiveness of incorporating victim distribution and survival-rate decay into rescue route planning.

Keywords: Real-time earthquake damage estimation, Building-specific ground-motion prediction, Survival-rate decay model, Search-path optimization, Extended Traveling Salesman Problem (TSP)

1. Introduction

In rescue operations following a major earthquake, it is essential to quickly locate and rescue victims amid numerous collapsed buildings and affected areas. In particular, since the survival rate of victims trapped inside collapsed buildings decreases over time, the speed of the initial response and the order of search operations have a significant impact on the number of people rescued. However, it is not easy to immediately determine which locations should be prioritized during an actual disaster, and on-site teams tend to focus on minimizing travel distance and response time. On the other hand, when survivors are concentrated in a specific location, prioritizing that area—even if it involves a slightly longer travel distance—may lead to more successful rescues.

Furthermore, while conventional earthquake damage estimation is often performed at the grid level—which is effective for grasping overall damage trends across a region—it is difficult to adequately account for variations in damage between individual buildings. Consequently, it has been challenging to determine search routes based on buildings where a large number of people in need of rescue are likely to be present.

Therefore, in this study, we use an earthquake damage estimation system developed by our team—capable of estimating damage on a building-by-building basis—to estimate the expected number of people in need of rescue for each building, and we propose a search route optimization method that takes into account the time-dependent decline in the survival rate of people in need of rescue.

Generally speaking, to maximize the number of people rescued within a limited timeframe, it is considered effective to prioritize searching buildings with a high expected number of people in need of rescue. This approach is appropriate in situations where buildings are relatively scattered, such as in suburban areas. However, in actual disaster response, factors such as the location of buildings and the extent of damage, as well as considerations of fairness and ethics in rescue operations, influence decision-making; therefore, it is not always possible to conduct efficient searches targeting only buildings where people in need of rescue are presumed to be present.

Furthermore, according to interviews with Self-Defense Forces personnel who participated in search operations during the Great Hanshin-Awaji Earthquake, the method employed in urban areas was to treat blocks separated by roads and other features as units and systematically search every building within each block. This indicates that it is necessary not only to utilize building-specific information as is but also to reorganize it into a format that can be implemented on-site.

Therefore, in this study, we investigated a method for optimizing search routes at the block level while utilizing damage estimates for individual buildings. To optimize search routes, we first calculate the expected number of people in need of rescue based on the damage estimates for each building. Next, we aggregate the expected numbers of people in need of rescue for each building to calculate the expected number for each block. Using this expected number of people in need of rescue per block and the decline in survival rates over time, we evaluate how many people can be expected to be rescued depending on the order in which each block is searched. We then calculate a rescue score for each patrol route at the block level to determine the most effective search route. Furthermore, to verify the effectiveness of the proposed method, we conducted search simulations and compared the results with the conventional approach of patrolling as quickly as possible.
First, in Chapter 2, we describe the earthquake damage estimation system we developed and present a method for calculating the expected number of people requiring rescue based on damage estimates for individual buildings. In Chapter 3, we calculate a rescue count score based on the expected number of people requiring rescue calculated in Chapter 2 and its temporal decay and present a "search path optimization method" designed to maximize the number of people rescued. In Chapter 4, we conduct search simulations using a virtual city, compare the shortest path with the path that maximizes the score, and demonstrate the effectiveness of the proposed method.

Figure 1 Process for estimating ground motion for each building based on seismometer data

2. Estimation of Seismic Motion and Damage Risk for Each Building

Figure 1 shows an example of seismic motion estimation for individual buildings using this system. As shown on the left side of Figure 1, the trend distribution shown in the center of the figure is estimated using seismic waves observed by a limited number of seismometers installed on the engineering ground surface. By applying the amplification factors at the surface layer of each building location to the estimated trend distribution, the ground-surface seismic motion shown on the right side of the figure is estimated.
To estimate damage for each building, a damage function is developed that takes into account building attributes such as structural type (wooden, reinforced concrete, etc.), age, and seismic assessment score (Ig value), and this function is used to estimate the damage risk for each building based on the seismic motion specific to that building. By multiplying the damage risk—such as the estimated probability of total or partial collapse—for each building by the number of occupants in that building, we calculate the expected number of people requiring rescue for each building. Consequently, buildings that are more vulnerable to damage and have a larger number of occupants will have a higher expected number of people requiring rescue. The expected number of people requiring rescue in each building is calculated based on the estimated number of people inside the building at the time of the earthquake and the probability of building damage. "People requiring rescue" refers to those who are trapped or buried under debris due to building collapse and cannot escape on their own, thus requiring rescue. In official earthquake damage estimates, the number of people unable to escape on their own is evaluated using the building total collapse rate and the indoor occupancy rate, with coefficient B used to represent the incidence rate of people unable to escape on their own.
Therefore, the expected number of people requiring rescue $E_0(i)$in building(i) is expressed by the following equation.

$$E_0(i) = N(i) \cdot p(i) \cdot B \tag{1}$$

Here, $N(i)$ represents the number of people present in building i at the time of the earthquake, p represents the probability of total collapse for building i, and B is a coefficient representing the proportion of people who will require rescue in the event of total collapse. This equation implies that the higher the number of people present in a building and the higher the probability of total collapse, the greater the expected number of people requiring rescue in that building.

3. Search Path Optimization Method

3.1 Problem Statement

In this study, we treat building patrol routes within the framework of the Traveling Salesman Problem (TSP) and calculate a score based on travel distance and the number of people rescued for each candidate route. First, we define the route with the shortest travel distance as the optimal route.

On the other hand, in search and rescue operations following a major earthquake, the survival rate of people in need of rescue decreases over time; therefore, simply having a shorter travel distance does not necessarily maximize the number of people rescued. Since the likelihood of rescue decreases the later the arrival time at each building, route evaluation must take into account not only travel distance but also the expected number of people in need of rescue at each building and the survival rate based on the arrival time.
Therefore, in this study, we define the "number of people rescued score" as the product of the expected number of people in need of rescue in each building and the survival rate at the time of arrival. We then define the route that maximizes the sum of these scores as the "route with the maximum score based on the expected number of people rescued" (hereinafter referred to as the "route with the maximum score"). The route optimization problem addressed in this study differs from conventional route optimization problems that minimize travel distance; instead, it is formulated as a route optimization problem that maximizes the number of people rescued, taking into account the time decay of the expected number of people requiring rescue. Formulation of the Path Optimization Problem.

3.2 Formulation of the Path Optimization Problem

Let$E_0(i)$denote the expected number of people in need of rescue in building i, $t(i)$ the time of arrival at building i, and $f\big(t(i)\big)$ the survival rate at that time. In this case, the expected number of people rescued from building i is given by the following equation, which is the product of the expected number of people in need of rescue and the survival rate.

$$E_0(i) \cdot f\big(t(i)\big) \tag{2}$$

We define the total of these values across all buildings to be searched as the total rescue count score $S_{(N)}$for the entire route.

$$S_{(N)} = \sum_{i=1}^{N} E_0(i) \ \cdot f\big(t(i)\big) \tag{3}$$

Here, N represents the number of buildings to be searched. This formula is an evaluation metric that simultaneously accounts for the spatial distribution of people in need of rescue across each building and the time-dependent decline in survival rates as arrival times elapse.
In this study, we define the path that maximizes this rescue count score $S_{(N)}$ as the score-maximizing path, and we formulate the path optimization problem from the perspective of maximizing the number of rescues rather than minimizing travel distance.

3.3 Extension to a search method based on individual sections

When it is possible to take into detailed account the locations of people in need of rescue and the varying degrees of damage across buildings, determining the search order on a building-by-building basis may result in the rescue of more people in need of rescue. In particular, since the earthquake damage estimation system used in this study allows for damage estimation on a building-by-building basis and enables the assignment of expected values for people in need of rescue to each building, it is ideally desirable to optimize the search order on a building-by-building basis.
However, optimizing the search order on a building-by-building basis for an entire city leads to an explosive increase in the number of possible combinations as the number of buildings increases, resulting in an extremely high computational load. Furthermore, according to interviews with Self-Defense Forces personnel regarding the Great Hanshin-Awaji Earthquake, the method adopted in urban areas was to treat blocks divided by roads and other features as units and search the buildings within them sequentially. This indicates that in actual disasters, it is necessary to reformulate the problem into units that can be executed on-site. Therefore, in this study, we aggregate the expected number of people in need of rescue and the search time estimated at the building level to the block level, and extend the model to a block-level search model. The expected number of people in need of rescue for each block is defined as the sum of the expected values for the buildings within that block, and the search time is given as the sum of the search times for each building. All buildings within a block are searched sequentially upon arrival.
Based on this block model, we optimize the order of movement between blocks. Upon arriving at a block, the search team searches the buildings within it consecutively and moves to the next block upon completion. Therefore, the rescue effectiveness of each block depends not only on the expected number of people in need of rescue but also on the travel time to reach that block and the cumulative search time from previous blocks.
Based on the above, this study reformulates the problem as a zone-based path optimization problem that maintains building-level detail while considering computational feasibility and practical operability.
Furthermore, let B(k) denote the set of buildings in block k; the expected number of people requiring rescue in block k, $E_0(k)$, is defined by the following equation.

$$E_0(k) = \sum_{i \in B(k)} E_0(i) \tag{4}$$

Table 1: Simulation Constraints	
Item	Settings
Distance between plots	Distance between lot center points
Movement Speed	Walking speed: 4 km/h
Building search time	15 minutes per building
Delay in the initial search response	Three hours after the earthquake
Restrictions on Search Operations	10 hours of searching, 14 hours of rest

Furthermore, the rescue count score for each compartment is expressed by the following equation, using the survival rate at the time of arrival in the compartment, in the same manner as the formulation for each building.

$$S(K) = \sum_{k=1}^{K} E_0(k) \cdot f\big(t(k)\big) \tag{5}$$

4. Search Simulation

4.1 Simulation Conditions

In this study, we conducted a Monte Carlo simulation focusing on the distribution of people in need of rescue in a virtual city.

The virtual city under study consists of eight districts. Search teams were assumed to depart from a predetermined starting point and patrol each district sequentially. The distance between districts was determined by the distance between their respective centers, and the movement speed was set at 4 km/h, assuming travel on foot. It was assumed that searching each building took 15 minutes, and an initial response delay of 3 hours was applied between the occurrence of the earthquake and the actual start of the search. Furthermore, considering that continuous searching is difficult in actual rescue operations, a duty schedule consisting of 10 hours of searching and 14 hours of rest per day was established.

With the above conditions kept constant, the only variable in each simulation was the distribution of people in need of rescue across each zone. With this setup, the comparison between the shortest route and the route with the highest score is evaluated not merely in terms of relative movement efficiency, but from the perspective of how well it accounts for the spatial distribution of people in need of rescue and the decline in survival rates associated with delays in arrival times. Therefore, the differences between the two routes obtained in this simulation can be interpreted not as differences in the severity of the disaster, but as differences in route selection that take into account variations in the distribution of people in need of rescue and changes in the likelihood of survival over time

4.2 How to Set the Expected Number of People in Need of Rescue by Zone

In this study, we normalized the data so that the total number of people requiring rescue in a single Monte Carlo simulation remained constant (40 people); after standardizing the overall scale, we varied only the spatial distribution of the people requiring rescue.

First, a uniform random number u_g is generated for each zone g. These random numbers represent the relative concentration of casualties among zones, but at this stage, their sum does not match 40 people. Therefore, the expected number of people requiring rescueE_g for each zone was defined by the following equation.

$$E_g = 40 \cdot \frac{u_g}{\sum_{h=1}^{8} u_h} \tag{6}$$

Through this scaling operation, each district is assigned an expected number of people requiring rescue that includes a decimal point, while the total number of people requiring rescue remains constant at 40. This makes it possible to vary the distribution of casualties among districts with each simulation, while keeping the overall scale of casualties in the virtual city constant.

This allocation method allows for the continuous generation of scenarios ranging from cases where victims are concentrated in specific districts to cases where they are distributed relatively evenly, making it possible to evaluate differences in rescue effectiveness resulting from variations in search routes independently of the total scale of damage. In the search simulation, the expected number of people in need of rescue assigned to each zone was divided by the number of buildings within that zone to distribute the figure evenly among the buildings in the zone. This approach maintained the differences in the distribution of people in need of rescue between zones while assuming a uniform distribution among the buildings within each zone.

4.3 Performance metrics

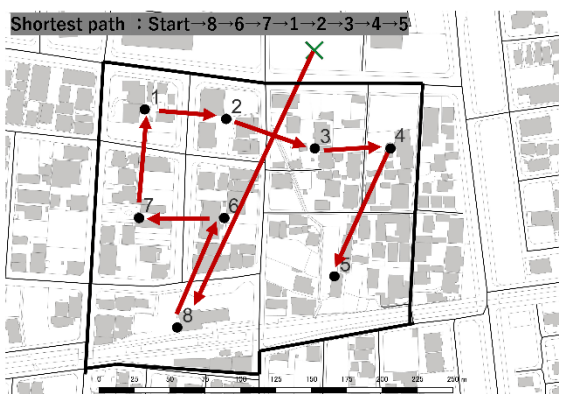
For each generated trial, we calculated the shortest path and the path with the highest score and evaluated the number of people rescued and the rescue rate. The number of people rescued is the sum of the expected number of rescues for all zones, calculated by multiplying the expected number of people in need of rescue in each zone by the survival rate corresponding to the arrival time. This allows us to compare which route can rescue more people in need of rescue.
Since the total number of people in need of rescue is fixed at 40, using the rescue rate allows for a comparison of the relative effectiveness of each route in a manner independent of the overall scale.
In this study, we conducted a Monte Carlo simulation by generating the distribution of people in need of rescue for each grid cell 10,000 times. Since results based on a single distribution may be strongly influenced by random biases or unusual configurations, performing a large number of trials allows us to statistically average out the variability in the distribution of people in need of rescue, enabling us to evaluate the difference between the shortest path and the path with the highest score as a stable metric.
The reason for setting the number of trials to 10,000 is that we confirmed that evaluation metrics such as the average number of people rescued and the rescue rate converged sufficiently, and that increasing the number of trials further resulted in minimal variation in the results. This approach balances computational complexity with the stability of the evaluation.

4.4 Simulation scenarios

In this study, to understand the impact of the spatial distribution of 40 victims on search results, we compared scenarios where victims were randomly dispersed throughout the target area with scenarios where they were concentrated in specific sections.
When victims are randomly distributed, the expected number of victims in each section and each building is generally balanced. Consequently, even if the search order is changed, the arrival times at specific locations are unlikely to vary significantly. For this reason, the performance difference between the shortest path based on distance minimization and the score-maximizing path that maximizes the expected number of rescues tends to be relatively small.

4.5 Simulation results

We present the results of 10,000 Monte Carlo simulations conducted based on the conditions outlined in the previous section. Figure 2(a) shows the route with the shortest distance based on the simulation results, while Figure 2(b) shows the route that maximizes the number of people rescued across the 10,000 simulations.
For each trial, we calculated the shortest path and the path with the highest score and evaluated the expected number of people rescued and the rescue rate for each. Below, we first present the difference in average rescue effectiveness, followed by a discussion of the variability and differences in distribution across trials. The average rescue score across all trials showed that the expected number of people rescued via the shortest route was approximately 14.4. In contrast, the route with the maximum score resulted in approximately 19.0 people being rescued, confirming an increase of about 35% in the number of people rescued compared to the shortest route. These results show that even when the total number of people in need of rescue is fixed at 40, selecting the path with the maximum score rather than the shortest path increases the average number of people rescued by 4.9. While the shortest path is rational from the perspective of search efficiency because it minimizes travel distance, there are cases where it takes longer to reach areas with a high concentration of people in need of rescue. As a result, delays in arrival times lower the survival rate, leading to a significant decrease in the number of people rescued. On the other hand, while the maximum-score route may involve a slight increase in travel distance, it prioritizes visiting zones with a higher expected number of people in need of rescue, thereby mitigating losses due to time decay. This difference is reflected in the increase in the average expected number of people rescued.
Next, we conducted an evaluation using the rescue rate as an indicator that does not depend on the total number of people requiring rescue. The rescue rate is defined as the expected number of rescues divided by the total number of



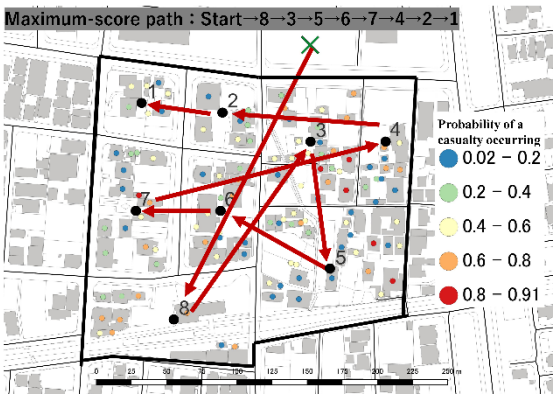


Figure 2 **(a) Shortest path** **(b)Maximum score path**

people in need of rescue (40). The results showed that while the rescue rate for the shortest path was approximately 35%, it was approximately 47% for the path with the maximum score, confirming the superiority of the proposed method from the perspective of rescue rate. By using the rescue rate, it is possible to compare relative rescue effectiveness even across trials with different distributions of people in need of rescue. In particular, in trials where victims were concentrated in specific zones, the difference between the shortest path and the maximum-score path tended to widen. On the other hand, when victims were distributed relatively evenly across zones, the difference in rescue rates between the two paths became smaller. These results indicate that path optimization accounting for time decay is more effective in situations where the difference in the expected number of victims is greater.

5. Conclusion

In this study, based on an earthquake damage estimation system capable of estimating the probability of casualties and the expected number of people requiring rescue for each building, we proposed a route optimization method that incorporates the realistic constraint that the survival rate of people requiring rescue decreases over time into the search plan. In particular, we used the shortest-distance search route, which is commonly adopted in the field—as a baseline and quantitatively evaluated the impact of different search orders on rescue effectiveness by comparing it with a route that maximizes rescue scores while accounting for the time-dependent decline in survival rates based on arrival times. Results from Monte Carlo simulations using a virtual city confirmed that, even under conditions where the total number of people requiring rescue was kept constant, the score-maximizing route consistently improved the expected number of people rescued and the rescue rate compared to the shortest route.

Future challenges include the need to extend the method to search heuristics and approximate algorithms, as exhaustive search becomes impractical when the number of zones or the city's scale increases. Furthermore, while this paper used a simplified model to estimate the expected number of people requiring rescue per zone, incorporating more detailed estimates based on building attributes and seismic motion analysis results is expected to further enhance the method's applicability to real-world cities.

References

Keizo H, Yan S, Yoshinori O, Natsuki S, Kazutoshi N, Michiyo S, Yasuhiro M: Fundamental Study on the Development of a Building-by-Building Earthquake Damage Estimation System Using the Extended Kriging Method, Annual Report of the Institute for Environmental Management, No. 21, pp. 24–30, December 2022

Michiyo S, Yukari Mi, Yasuhiro M: Practical Application of Building-by-Building Earthquake Hazard Estimation Using the Kriging Method, Technical Reports of the Architectural Institute of Japan, Vol. 22, No. 51, pp. 447–452, June 2016

Ryosuke U: Study on Probabilistic Damage Functions Using Natural Period-Dependent Spectral Intensity as Seismic Intensity, February 2020

Ryosuke S, Hiroshi M, Yukari M, and Hideki I: "A Study on Damage Functions Using Spectral Intensity Dependent on Natural Period as an Earthquake Motion Intensity Index," Proceedings of the Architectural Institute of Japan, Volume B-2, p. 553, 2018