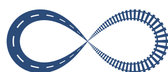

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IMPACT OF ROAD NETWORK CHANGES ON TRANSPORTATION ACCESSIBILITY BEFORE AND AFTER THE 2024 NOTO PENINSULA EARTHQUAKE

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Abstract

Large-scale earthquakes inflict extensive damage on road networks, significantly impairing transportation functions and emergency mobility, particularly in areas with limited alternative routes. This study aims to quantitatively assess the impact of changes in road network conditions – from pre-earthquake (normal) to post-earthquake (recovery phase) – on transportation accessibility and lifesaving potential, using the 2024 Noto Peninsula Earthquake as a case study. The target area was Suzu City, Ishikawa Prefecture. We constructed both the pre-earthquake normal road network and a post-earthquake network (recovery phase) reflecting road closures and traffic restrictions. Network analysis estimated the arrival time to the nearest available rendezvous point (RP) from the center of each 250 m population mesh, designated as the emergency demand location. Furthermore, the estimated arrival time was substituted into Cara's life-saving curve (Golden Hour Principle), survival rates were calculated using cardiac arrest as a representative case, and a spatial distribution of survival rates was created at the 250 m mesh level. Analysis revealed that post-earthquake increases in response times were observed across a wide area. Particularly in mountainous and peripheral regions with limited alternative routes, lingering road disruptions caused significant increases in response times. The spatial distribution of survival rates also showed an expansion of low-survival-rate areas post-earthquake. This decline in lifesaving potential resulted from increased response times due to road damage, traffic restrictions, and constraints on RP utilization. Based on the above, this study empirically compared road network changes from before the earthquake through the recovery phase and presented a framework for evaluating changes in accessibility linked to survival probability. This provides fundamental insights contributing to the effectiveness evaluation of road recovery measures during disasters, the development of recovery strategies independent of road hierarchy, and the maintenance of emergency medical accessibility, including the securing of alternative routes.

Keywords: transportation accessibility, network analysis, earthquake, emergency medical accessibility, doctor helicopter, rendezvous point, survival rate

1 Introduction

At 4:10 p.m. on January 1, 2024, an earthquake with a maximum seismic intensity of 7 struck the Noto region of Ishikawa Prefecture. On the Noto Peninsula in Ishikawa Prefecture, near the epicenter, numerous road closures and traffic restrictions occurred due to landslides, road surface damage, and bridge damage, resulting in a significant reduction in ground mobility.

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Even after the earthquake, some sections remained impassable, forcing drivers to take wide detours across the region, creating conditions that could easily lead to increased emergency transport times. Such a decline in transportation capacity affects the emergency medical care system and has the potential to cause serious disruptions, particularly in the treatment of time-sensitive injuries and illnesses. On the Noto Peninsula, coordination between ambulances and doctor helicopters is crucial as a means to supplement the limitations of ground transportation. A doctor helicopter is a dedicated helicopter equipped with the medical equipment and pharmaceuticals necessary for emergency care. It is staffed by doctors and nurses who respond to emergency scenes and can provide initial treatment en route to the hospital. While ambulance-only transport can delay the start of treatment until arrival at a medical facility, doctor helicopters can begin initial treatment near the scene. This is expected to improve survival rates for time-sensitive injuries and illnesses. On the other hand, helicopters cannot always land directly at the scene of an injury or illness. In urban areas and mountainous regions, landing sites are limited due to obstacles such as power lines, trees, and buildings; terrain conditions; nighttime and weather conditions; and safety considerations. Therefore, a rendezvous point (RP) is utilized as the location where the ambulance and doctor helicopter converge to transfer the patient and commence treatment. RPs are selected from relatively open spaces such as parks, school grounds, athletic fields, or parking lots. Generally, they must meet conditions including sufficient size and flatness, minimal obstacles in the takeoff/landing direction, accessibility for ambulances, and safety considerations for surrounding residents.

Figure 1 Workflow of ambulance–doctor helicopter rendezvous and patient handover at an RP

The operational flow involves an ambulance being dispatched from the scene of the injury or illness, transporting the patient to the RP, meeting the doctor helicopter at the RP to begin initial treatment, and then transporting the patient to the hospital. Therefore, the time taken to reach the RP from the emergency location is a key factor determining the start time of treatment and is a critical indicator that can affect the likelihood of survival. Particularly during disasters causing road closures or traffic restrictions, ground access to the RP becomes prone to delays and instability, making it central to quantifying the decline in emergency medical access. Furthermore, an analysis of changes in the medical helicopter operation system following a decrease in RPs, based on flight records from Ishikawa Prefecture, revealed no statistically significant difference in the operation system before and after the earthquake. Therefore, this study focuses on ground transport rather than air transport and aims to quantitatively evaluate changes in access to emergency medical care by analyzing the impact of changes in the road network caused by disasters on ambulance arrival times at RPs. In particular, during disasters, road closures and traffic restrictions may increase response times to the RP, making it important to quantitatively assess this impact. Following an earthquake, in addition to increased arrival times due to road closures and traffic restrictions, the RP itself may become unusable due to the establishment of temporary housing and other factors. When RP availability decreases, the number of merge points (RPs) available for ambulances to choose from becomes limited, potentially requiring detours or selection of distant RPs, further increasing arrival times. Therefore, to evaluate emergency medical access during disasters, it is necessary to consider not only changes in the road network but also changes in RP availability.

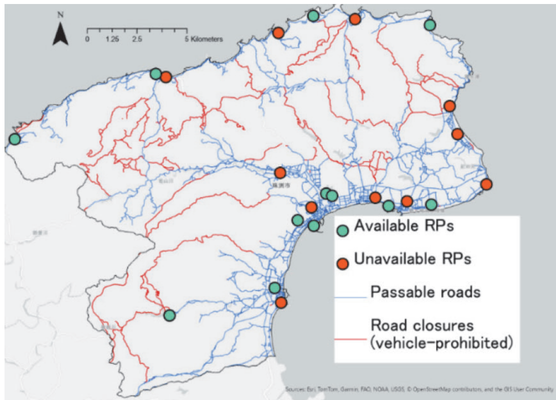

Figure 2 Road network status and RP availability (as of 10 Sep 2024).

Previous studies have evaluated the vulnerability and resilience of road networks during disasters through complex network metrics and reductions in accessibility. For example, Wei and Xu [1] demonstrated the importance of redundancy and alternative routes in road networks, while Martín et al. [2] conducted a comparative evaluation based on the decline in accessibility resulting from the loss of road segments. Meanwhile, in the field of HEMS, studies have been conducted on factors affecting base development [3], the optimization of base locations [4], the definition of service areas based on actual operations [5], and analysis of the spatial relationship between incident locations and prehospital mortality [6]. However, many of these studies have focused primarily on either evaluating road network performance, optimizing HEMS base locations, or examining the relationship between incident location and outcomes. There is a lack of research that simultaneously considers post-disaster road disruptions and changes in RP availability, links these factors to the survival curve via RP arrival times, and quantifies them as a spatial distribution of survival rates. This study focuses on this issue and evaluates the impact of road conditions and the reduction in RP availability following the Noto Peninsula Earthquake on medical helicopter operations and regional survival rates.

The objective of this study is to quantitatively evaluate the spatial distribution and reduction in survival rates before and after disaster. This is achieved by estimating the arrival time from emergency demand locations to the nearest available RP using network analysis, reflecting changes in road network conditions and RP availability around the time of the 2024 Noto Peninsula Earthquake. The estimated arrival times are then substituted into the Cara's life-saving curve to calculate survival rates. This approach visualizes the impact of road closures/traffic restrictions and RP utilization constraints on the potential for saving lives, providing fundamental insights to support considerations for road restoration and securing alternative RPs during disasters.

This study estimates the arrival time from emergency demand locations to the nearest available RP using pre- and post-earthquake road network conditions and RP information, then converts this to survival rates. This chapter outlines the data used and the preprocessing steps. The road network was constructed from the centerlines of the Digital Road Map (DRM). Travel costs utilized the daytime non-congested driving times assigned to road links. The normal-state network included all links assumed passable. The post-earthquake network reflected closed or restricted sections, treating affected links as impassable to vehicles, thereby representing post-disaster reachability and travel times. The target area is Suzu City, Ishikawa Prefecture. The comparison conditions are the normal-state network prior to the earthquake and the recovery-stage network reflecting road closures and traffic restrictions after the earthquake. The post-earthquake network reflects the road restriction status as of September 10, 2024, prior to the heavy rain disaster.

2 Analysis

2.1 Change in travel time to the nearest RP

Road networks were constructed for both pre-earthquake (normal conditions) and post-earthquake (emergency recovery phase) scenarios. Network analysis was used to estimate the shortest-time routes from emergency demand points (250 m population mesh centers) to RP locations. For each demand point k, the nearest RP was defined as the RP within the set of available RPs $\mathcal{R}$ that minimized the arrival time. The arrival time t_k to the nearest RP was calculated using the following equation.

$$t_k = \min_{j \in R} t_{kj} \tag{1}$$

There were 603 grid points for which arrival times could be calculated both before and after the earthquake, while there were 13 points for which the arrival time difference could not be calculated. Examining the distribution of the arrival time difference Δt, the median was 1.03 minutes and the maximum was 14.6 minutes, confirming a tendency for arrival times to increase after the earthquake. Note that among the arrival time differences, those with an absolute value of 1 second or less were judged to represent a negligible difference and were treated as no change. The results of the time differences are shown in table 1 below.

Table 1 Travel-time change summary (Δt) to the nearest available RP

Valid meshes	603
Unreachable locations	13
Median Δt	1.03 min
Maximum Δt	14.6 min
Time Increase locations	410
No change	185
Time decreased locations	8

2.2 Change in survival probability

The survival rate based on the Cara's life-saving curve was calculated using the estimated arrival time t_k (minutes) from the estimated emergency demand location k to the nearest available RP. In this study, cardiac arrest (i = 1) was adopted as a representative case of high severity, using the coefficient b_1 =1. 6029. The survival rate $R(t)$ is given by the following equation.

$$R(t) = 1 - \left\{ \frac{1}{1 + exp(4.80861 - b_i t)} \right\} \tag{2}$$

Note that the condition-specific constants b_i are as follows: "Cardiac arrest (i = 1):1.6029", "Respiratory arrest (i = 2):0.4809", "Massive hemorrhage (i = 3): 0.1603".

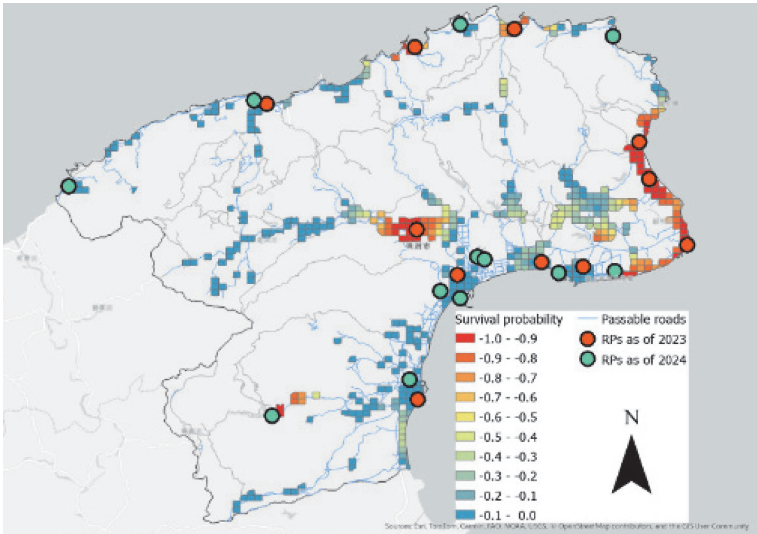

Figure 3 Decline in survival rates following the earthquake (cardiac arrest)

Figure 3 shows that, following the earthquake, the rate of decline in survival rates was particularly steep in coastal areas and in the limited mountainous regions near evacuation shelters. This result can be attributed to the fact that the increased travel time to the nearest RP manifested as a decrease in survival rates. The increase in travel time was likely caused by a reduction in passable road sections due to road damage and traffic restrictions resulting from the earthquake, as well as a decrease in the number of available RPs due to tsunami damage and the construction of emergency temporary housing. Consequently, the number of locations requiring detours or the selection of distant RPs likely increased.

2.3 Population-weighted average survival probability

Using the population P_k from the 250 m population mesh k, survival rates were calculated as spatial distributions, and population-weighted survival rates were used for regional aggregation. Let G denote a district; the weighted survival rate R_G is given by the following equation.

$$R_G = \Sigma_{k \in G}(P_k R_k) \tag{3}$$

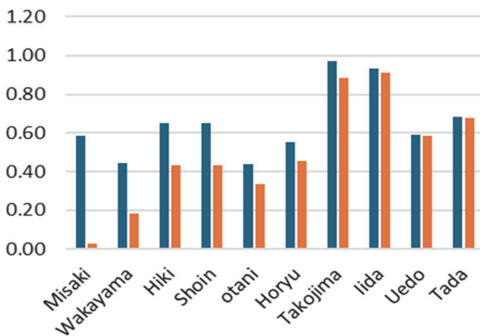

Figure 4 Average survival rates by district

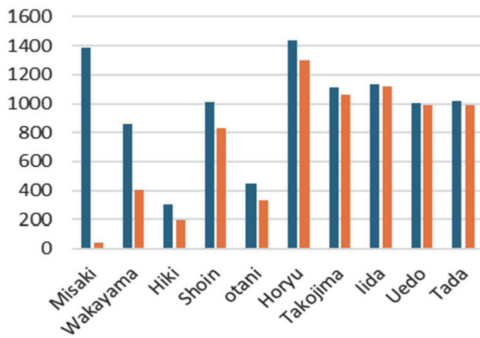

Figure 5 Population-weighted survival rate

Figure 4 shows that the average survival rate by district declined in many districts following the earthquake, suggesting that road damage, traffic restrictions, and a reduction in available RP caused by the disaster reduced access to medical care. However, the extent of this decline varied by district, confirming that the impact of the earthquake was not uniform across Suzu City. Meanwhile, the population-weighted survival rates in figure 5 indicate that the scale of the impact was greater in districts with larger populations. In particular, while the Misaki district showed a moderate average survival rate in figure 4, it exhibited the highest value in figure 5, suggesting that the large population size is strongly reflected in the overall assessment. Conversely, the Hioki and Oya districts showed low values in figure 4 and relatively small values in figure 5, indicating that their contribution to the overall average survival rate and population size is limited.

3 Discussion

The results of this study indicate that in Suzu City following the 2024 Noto Peninsula Earthquake, travel times to the nearest available RP increased at many locations, resulting in an overall decline in access to emergency medical care. This is believed to be due not only to constraints on the available road network caused by road damage and traffic restrictions, but also to the fact that the reduction in accessible RPs led to an increase in the number of locations where residents had to choose more distant facilities or take detours. In particular, in areas with low road network redundancy, a decline in the functionality of even a limited number of road sections tends to directly lead to increased travel times, suggesting significant vulnerability during disasters. Furthermore, the increase in travel time was reflected in a decrease in survival rates. This indicates that reduced access to emergency medical care is not merely a change in travel time but can manifest as a decrease in the likelihood of survival. Particularly for time-sensitive injuries and illnesses, even a delay of a few minutes can have a relatively significant impact on survival rates; therefore, it is meaningful to evaluate changes in the road network during disasters from the perspective of life-saving potential. On the other hand, a comparison of the average survival rate by district and the population-weighted survival rate revealed that the average situation in each district does not necessarily correspond to its impact on the city as a whole. In other words, even if the decline in average survival rates is of the same magnitude, the impact on the city as a whole is relatively greater in districts with larger populations. Therefore, when evaluating access to emergency medical care during disasters, it is important to understand not only the average changes in each district but also the population affected by those changes. This is a useful perspective when considering priorities for road restoration and securing alternative response points (RPs). Although there were some locations where travel times remained unchanged or were calculated to be shorter, given the reduction in available road links and RP following the earthquake, these

results must be interpreted cautiously, taking into account the effects of network connectivity conditions, analysis settings, and the correspondence between pre- and post-disaster data. Therefore, it is appropriate to place primary emphasis on the key finding of this study: that travel times increased across Suzu City as a whole, confirming a trend toward reduced access to emergency medical care.

4 Conclusion

In this study, we evaluated changes in travel time to the nearest available emergency care facility and survival rates, using 250 m population mesh as points of emergency demand, to reflect changes in road network conditions and emergency care facility availability before and after the 2024 Noto Peninsula Earthquake. The analysis revealed that travel time to the nearest emergency care facility increased in many grids following the earthquake, confirming a trend toward reduced access to emergency medical care across Suzu City as a whole. Furthermore, survival rates were found to have decreased in many districts. A population-weighted evaluation revealed that areas with larger populations exert a stronger influence on the overall assessment of a district. Based on the above, it was demonstrated that changes in emergency medical access following the earthquake must be understood not only in terms of average changes but also by considering regional disparities and population distribution. The evaluation framework presented in this study provides fundamental insights that can contribute to considerations regarding road restoration and the securing of alternative emergency response facilities during disasters.

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