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Development of a Road Recovery Model Considering Road Usage Frequency of Emergency Paths in a Large-Scale Disaster

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Abstract: Since the Great East Japan Earthquake in 2011, many cities under threat of being hit by a tsunami have developed a road recovery plan. To improve the effectiveness of the plan, this study proposes a road recovery model considering road usage frequency as an emergency path for a large-scale disaster. Using the list of emergency origin and destination (OD) node pairs at each prioritized level and the list of disrupted roads, which were obtained from an existing road recovery plan, recovering disrupted roads has been repeatedly calculated until all of the shortest times of emergency OD pairs satisfy the constraint. By applying the model to the Kochi prefecture network in Japan, it clarified that the model can reduce the impacts of a disaster compared to the case without road usage frequency. Road usage frequency as an emergency route can be useful as an indicator of road restoration.

Keywords: Road recovery, Priority, Emergency route, Shortest Path, Network Accessibility

1. INTRODUCTION

The 2011 Great East Japan Earthquake induced a large-scale tsunami that caused catastrophic damage from the Fukushima prefecture to the Iwate Prefecture. Many arterial roads, such as national route 45 running from North to South, were disrupted. In such a scenario, road administrators and construction engineers immediately recovered the essential roads to reach the damaged area by implementing the “Teeth of a Comb” process, so named because of shape of the road recovery process resembled a comb.

To reflect this approach in the future implementation of disaster-mitigation strategies, some cities that are vulnerable to future tsunamis have organized a working group, which includes public-sector officials such as road administrators who gather to examine a road recovery plan. The development of such plans includes two primary phases. First, roads that are assumed to be disrupted by a disaster are identified. Then, on the basis of an emergency-transportation road network map, recovery roads are prioritized.

However, according to some plans, it is not always efficient to implement the recovery work. One of the reasons is that the day for recovery is independently calculated for each road without considering the entire road network. In addition, although these plans evaluate which roads should be a priority emergency route, they do not consider the difference of road usage frequency with the same priority. For example, suppose that there are several emergency origin–destination pairs. Some roads are used frequently to connect the two points. By contrast, other roads are not often used for this because the latter case is not always related to the connection of the emergency pair or there are other alternative roads connecting the pair.

This study develops a road recovery model considering the road usage frequency as an emergency route during large-scale disasters. A literature review is presented in Chapter 2, then Chapter 3 explains the methodology of the proposed model, and finally, Chapter 4 shows the applicability of the model by implementing it on the Kochi road network in Japan.

2. LITERATURE REVIEW

Since the road restoration priority plan proposed in the study considers emergency origin–destination paths, immediate disaster recovery actions are highlighted. The method detects which road is critical for the efficient recovery of an emergency path. The objective of the recovery plan is to preferentially select a disrupted road with a high contribution value with respect to the accessibility of the entire emergency path network.

The concept of accessibility is related to whether network vulnerability has been improved or worsened (Berdica, 2002). Many models have been proposed to measure network vulnerability (Chen *et al*., 2007). The network scan method proposed by Taylor *et al*. (2006) identified a critical spot, which was found to lead to the deterioration of overall accessibility. This method adopts an accessibility approach based on the use of the shortest distance between cities as an indicator and finds a solution by comparing all of the results associated with normal network operation. Sohn (2006) proposed an accessibility model that considers the influence of distance-decay and volume of traffic on the transportation network. The model assesses the significance of highway road links that experienced flood damage. Although these researches are useful for accessing network vulnerability, it is not suitable for considering road recovery after a disaster.

Chen and Tzeng (1999) proposed a model for scheduling the road recovery process. Aksu *et al*. (2014) also focused on this and developed a model that illustrates an optimal disaster recovery process by maximizing network accessibility throughout the recovery process. This is more efficient than the model proposed by Chen and Tzeng (1999) because the model includes equipment availability constraints in the restoration process.

As previously mentioned, after the Great East Japan Earthquake, since some cities in Japan have examined a road recovery plan to mitigate the effect of large-scale disasters, it is important to develop a model that can improve the efficiency of the plan. However, there is no study that employs it as an evaluation indicator, which is the primary focus of this study.

The algorithm of the model proposed in this study is quite simple. Specifically, it illustrates the road restoration process by preferentially selecting a recovered road that is used more frequently as an emergency path compared to other disrupted roads. This approach contributes to the improvement of the current road recovery strategy because the current method does not consider this perspective.

3. PROPOSED MODEL

The calculation flow diagram is shown in Fig. 1. This model can identify which disrupted road should be recovered by selecting a road having more usage frequency of an emergency OD pair at each prioritized level as a recoverable road. Each emergency origin and destination (OD) pair has a different priority level. Generally, high-priority emergency pairs connect between comprehensive disaster bases.

Before the calculation, the road network $\boldsymbol{N}$, a list of disrupted roads $\boldsymbol{r}_j$ (j=1, 2, …, r), and a list of emergency OD pairs $\boldsymbol{q}_{m,k}$ (k=1, 2, …, q_m) are created at each level m (m=1, 2, …, p). All the disrupted roads are selected from the road network ($= \boldsymbol{r}_j \subset \boldsymbol{N}$). The size of the road network should be considered based on the magnitude of the disaster. The lists of disrupted roads and emergency OD pairs are obtained from an existing road recovery plan.

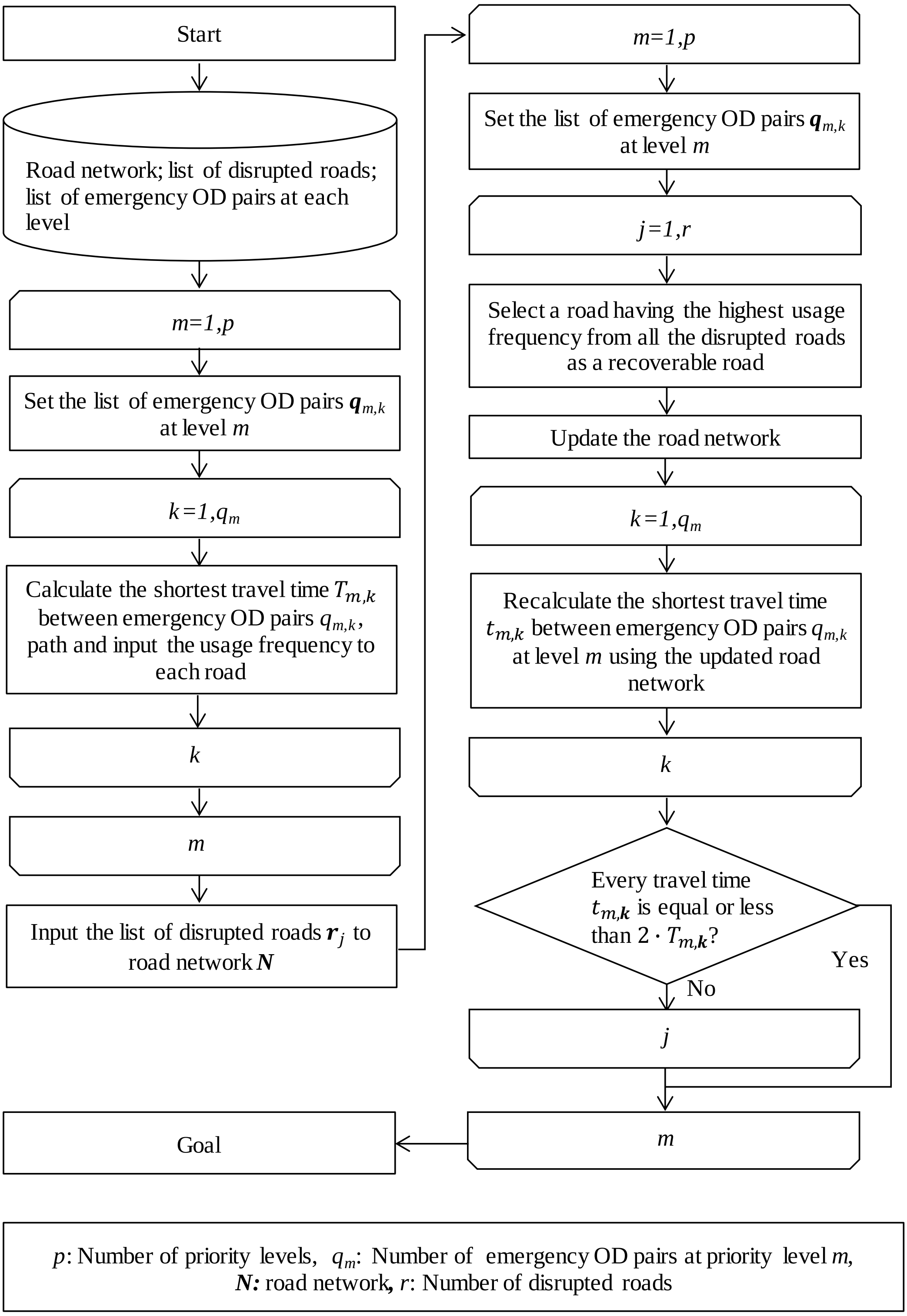

Figure 1. Calculation flow

Since the proposed model is based on disaster prediction, ideally, it is better to consider multiple disaster scenarios.

First, the shortest travel time $T_{m,k}$ and path between emergency OD pairs $q_{m,k}$ are calculated at each level m using the normal road network, which does not consider road disruption. The shortest time and path are calculated using Dijkstra's algorithm. Note that the shortest time and path between emergency OD pairs is recorded. By performing the process, it is possible to determine which roads (paths) are frequently used as the shortest path for each emergency OD pair, and the usage frequency is inputted to each road.

Then, input the list of disrupted roads $\boldsymbol{r}_j$ to the road network $\boldsymbol{N}$. Some of the disrupted roads have a relatively high usage frequency as the shortest path for each emergency OD pair, and others have less usage frequency. Note that the proposed model never selects a disrupted road which is not used as a recoverable road.

Thereafter, the calculation procedure moves to the main loop. The process calculates which disrupted road should be preferentially recovered considering the emergency OD pairs at level m. First, from the list of disrupted roads $\boldsymbol{r}_j$, a road having the highest usage frequency as an emergency OD pair is selected as a recoverable road. Then, the shortest time $t_{m,k}$ of emergency OD pairs $q_{m,k}$ are recalculated using the updated road network. The relationships between disrupted roads and recovered roads are considered in the updated network. In other words, the number of disrupted roads decreases as the number of recovered roads increases. Note that all of the shortest times calculated in the loop are equal to or greater than the value that was calculated in the normal road network because it considers the impact of the disrupted road. Of course, depending on the progress of road restoration, some of the shortest times cannot be calculated because of the impact associated with road disruption.

This procedure is looped until all of the shortest times of emergency OD pairs satisfy the requirement at each level. Whether a recalculated shortest time $t_{m,k}$ is equal to or less than twice the shortest time $T_{m,k}$ calculated in the normal network is set as a requirement. Of course, if there is more than one pair for which the shortest time due to the road disruption cannot be calculated, the procedure is looped.

4. APPLICATION OF THE PROPOSED MODEL TO THE KOCHI ROAD NETWORK

This chapter applies the proposed model to the Kochi prefecture road network. Shikoku is one of the four main islands: Hokkaido, Honshu, Shikoku, and Kyushu. There are four prefectures located there: Tokushima, Kagawa, Ehime, and Kochi. Municipalities and the population in Kochi Prefecture are shown in Fig. 2. The total population of the prefecture is about 705,000, and Kochi-shi occupies 47% of the population. In short, most of city functions are located within Kochi-shi. In addition, population and development are concentrated in the coastal area, and an express way connects these cities.

4.1 Outline of the Data

Disrupted roads and emergency OD pairs were obtained from the Kochi prefecture road recovery plan. The latest version of the recovery plan was published by the exploratory committee of the Kochi road recovery plan in March 2017. This report consists of two primary components.

The first component is the disaster impact estimation. A disrupted road is determined based on the distribution of earthquakes and tsunamis. There are two scenarios of road disruption. One is the scenario based on the frequency of the type of disaster. The magnitude of the disaster is calculated with reference to the Nankai Earthquake on December 24, 1854. Another is the scenario based on the maximum magnitude of the disaster. It is calculated with reference to the committee on the earthquake model of the Nankai Trough organized by the Cabinet office on August 29, 2012. The magnitude of the earthquake is simulated using the latest scientific knowledge. The data used in this chapter are based on the maximum

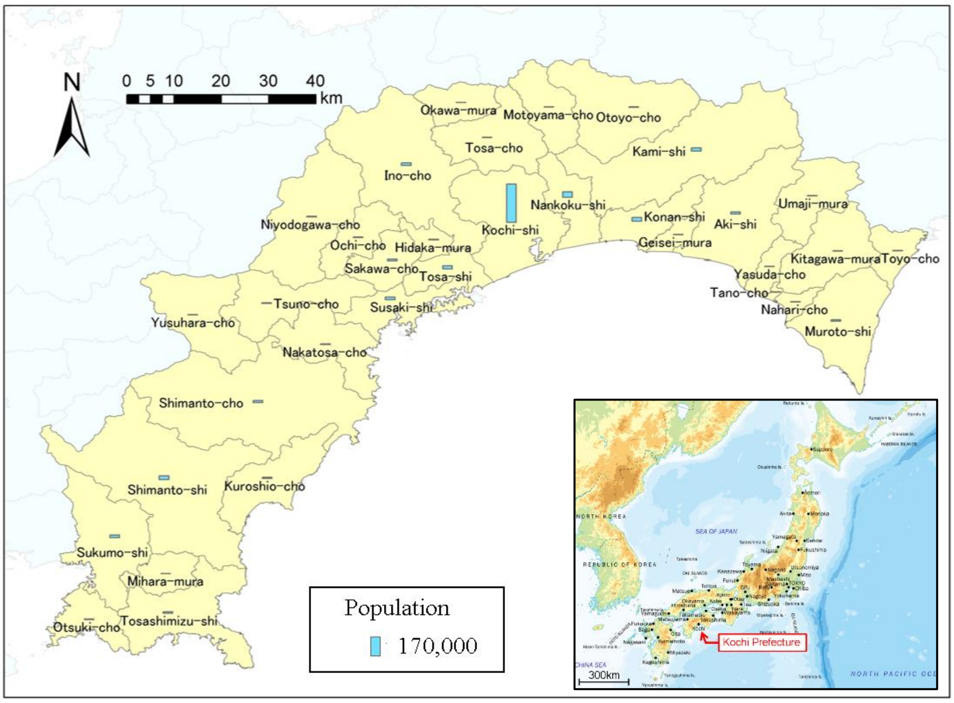

Figure 2. City in Kochi prefecture

magnitude of the disaster.

The second component is the day of road recovery. This is calculated based on the route between a disaster prevention facility and emergency route in a descending order of priority. The list of routes is created by referring to the emergency OD pair described in 4.1.3. Each route has a length simulated by the first component, and the day for road recovery is independently calculated, with consideration of the number of machines and workers.

4.1.1 Road network

Kochi prefecture’s road network is mainly created based on the road traffic census conducted in 2015, as shown in Fig. 3. Several roads which were constructed after 2015 have been added. The sand color area in Fig. 3 is Kochi prefecture, and all of the roads are arterial roads. The numbers of nodes and links in Kochi prefecture are 828 and 1137, respectively. The total lengths of the highways, national roads, major local roads, and other roads are 118.1, 1256.7, 966.2, and 1153.6 km, respectively. Since there are many areas where industries and economies are developed and anticipated to be affected by a disaster in the coastal region, high-standard arterial roads have been developed.

4.1.2 Disrupted road

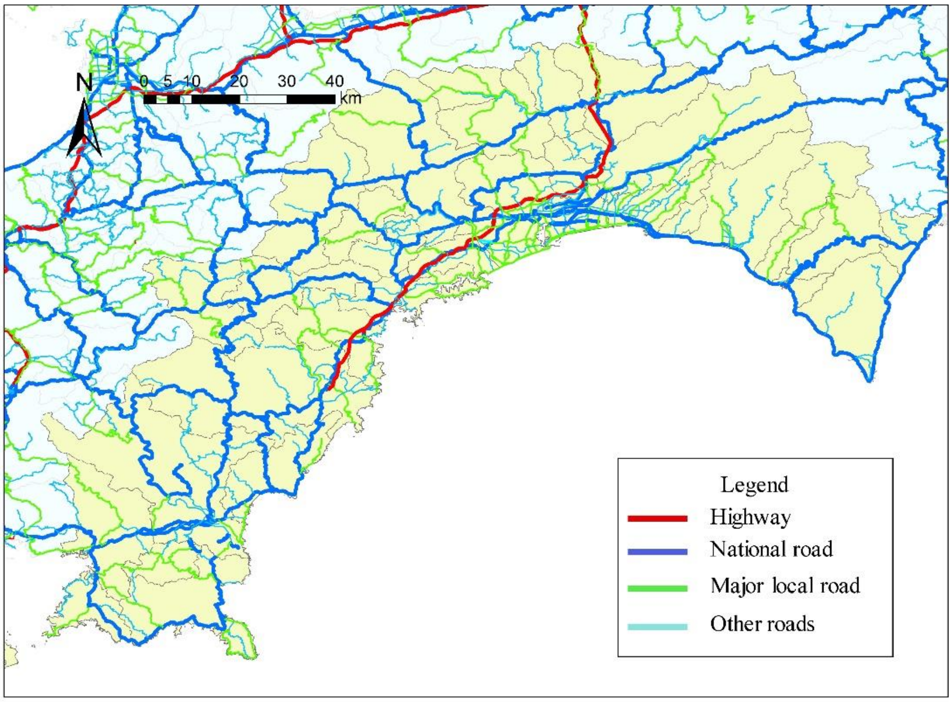

Figure 3. Kochi prefecture road network

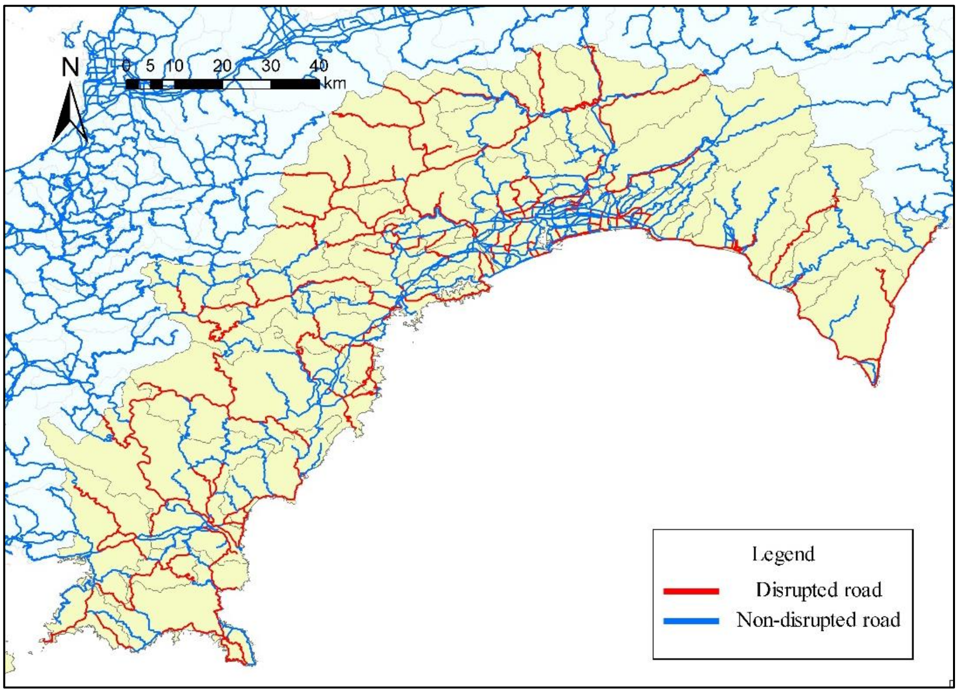

Figure 4. Disrupted road

The disrupted roads are illustrated in Fig. 4. The number of disrupted roads is 385. Not only the roads in coastal areas but also those in mountainous areas are assumed likely to be affected by a disaster. In the west part of the prefecture, since there are some roads that are connected in parallel, they might work as an alternative road when there is a disaster. By contrast, in the eastern part of the prefecture, since there is virtually only one route that connects two cities, it might be difficult to reach in a disaster.

4.1.3 Emergency OD pair

Table 1. Type and number of bases at each level

Type of facility	Level of priority			
	wide-area disaster prevention base (level 1)	A (level 2)	B (level 3)	C (level 4)
comprehensive disaster base	14			
prefectural police headquarter	1			
airport	1			
self-defense force base	1			
city office		66	15	14
police station		18	104	138
fire station		38		
school		11		
community hall		18	72	102
welfare facility		2	76	28
hospital	23	106	5	
harbor		4	5	5
heliport		1	23	23
lifeline base			56	60
water distribution facility			25	35
wastewater treatment facility			3	16
petroleum facility				10
park		9	16	45
athletic facility		6	41	8
others		14	21	28
Total	40	293	462	512

This table is created based on Kochi prefecture Road recovery plan

The plan calculates the day for road recovery. First, the base related to disaster prevention is selected. The priority of the base is divided into four levels. Level 1 is the base with the highest priority, and it has wide-area disaster prevention bases. Level 2 (A) is to protect peoples' lives, level 3 (B) is to extend peoples' lives, and level 4 (C) is to recover the damaged city. The numbers of emergency OD pairs at each level are 45 (level 1), 312 (level 2), 452 (level 3), and 430 (level 4). The types and numbers of bases at each level are shown in Table 1. Note that the total number of bases at each level shown in the table is different from the number of emergency OD node pairs.

After the procedure, the plan compiles a list of routes connecting the facilities at each level. The emergency OD pair used in this study was created from this list of routes; in other words, the data do not consider the route shown in the report because the objective of this study was to examine which road should be recovered to connect each emergency OD pair. The emergency OD pair at each level is shown in Fig. 5. The path length of higher levels such as a wide-area disaster prevention base is likely to be longer than the others.

4.2 Calculation Result

4.2.1 Road usage frequency

The road usage frequency as the shortest path of an emergency OD node pair at each level is shown in Fig. 6. Since the emergency OD node pairs at level 1 connect the important facilities of each area, highway and national roads in the coastal areas tend to be often used. On the other hand, OD node pairs at level 4 connect locations within an area, and local roads tend to be more frequently used than those in other levels.

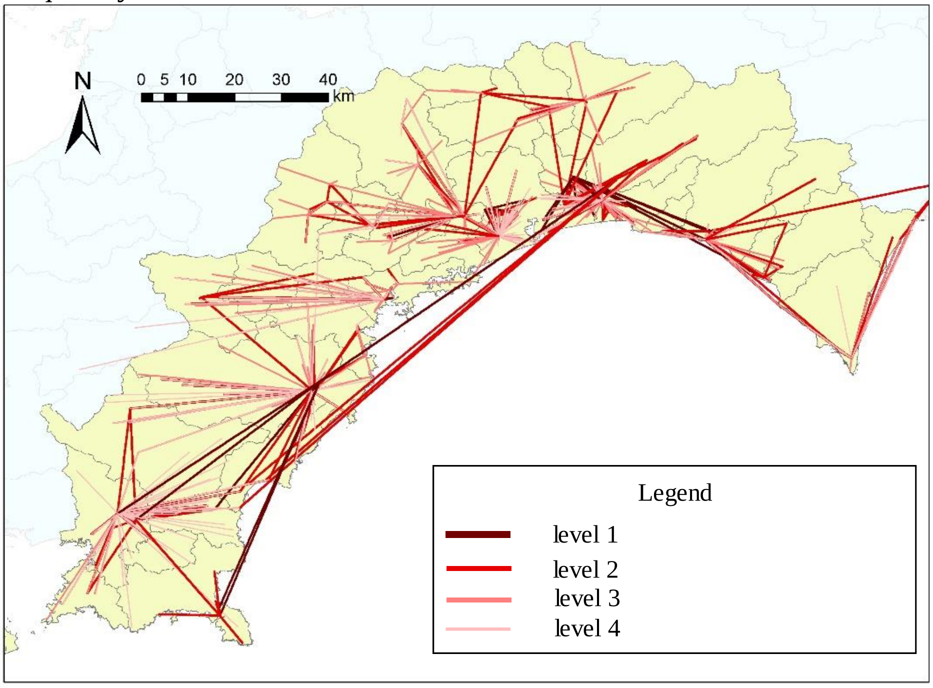

Figure 5. Emergency OD pair at each level

The numbers of roads which are used once or more than once at each level in the list of disrupted roads, 385, are 73, 195, 242, and 194, respectively. Also, the total number of roads which are used once or more than once at all levels of the disrupted roads is 311. In other words, 81% of disrupted roads are used once or more than once.

4.2.2 Changes in the number of recovered roads

The changes in the number of recovered roads at each level are shown in Fig 7. The vertical axis shows the number of roads that meet the requirement: the travel time at the road recovery stage is less than or equal to twice the usual travel time at each level. Since it is not known whether a road satisfies the requirement at the initial point at each level, the number of values matches the number of emergency OD node pairs at each level. The horizontal axis shows the changes in the number of recovered roads. The number of disrupted roads is the value of the maximum number of the axis, which is 385. After all of the roads in the previous level satisfy the requirement, the calculation at the next level begins.

The number of recovered roads required to satisfy the constraint at all levels is 310. The value almost matches the number of roads which are used once or more than once at all disrupted road levels (311).

The result is quite similar, and even if the value of the requirement changes because OD node pairs are not connected, there are roads that are rarely used but are still disrupted.

4.2.3 Example of the disrupted road selected as a recovered road

To understand which disrupted road is selected as a recovered road, this subsection explains Fig. 8. The background in the figure shows the disrupted roads and emergency OD pairs in level 1.

Fig. 8(1) shows four disrupted roads selected as recovered roads at the earliest stage. The usage frequencies of each road circled in the figure are 20, 19, 19, and 18. As shown in the brown path, these roads are connected to many emergency OD pairs.

Fig. 8(2) in the figure shows three roads selected as recovered roads in the middle stage. The usage frequency of each road circled in the figure is nine for each. This is less than the number in Fig. 8(1) because these roads are only routes connecting several brown paths.

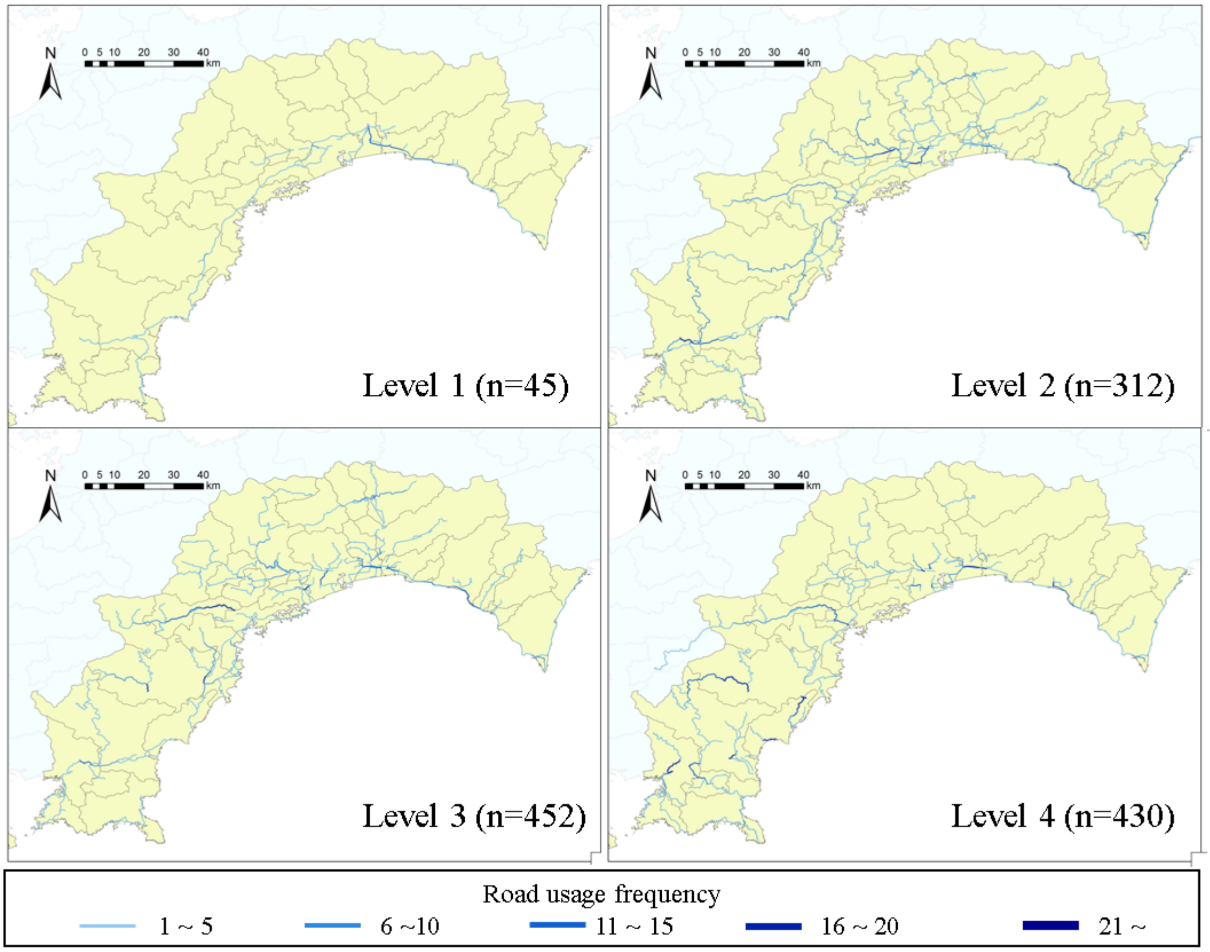

Figure 6. Road Usage Frequency at each level

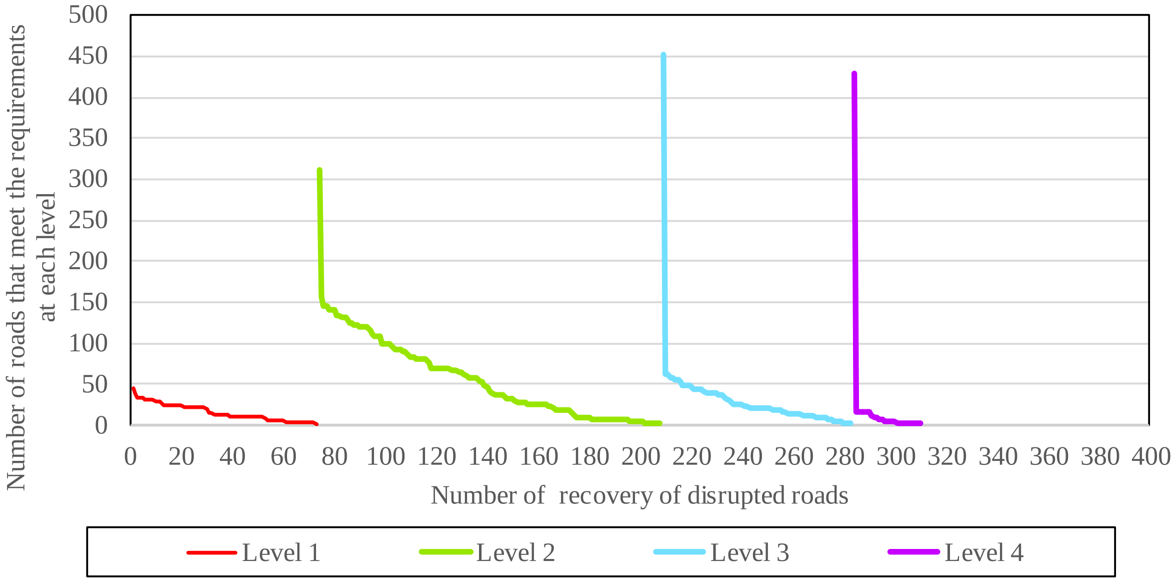

Figure 7. Number of roads that meet the requirements at each level

Fig. 8(3) shows one road selected as a recovered road in the last stage. The road usage frequency circled in the figure is one. As shown in the figure, there are two brown paths

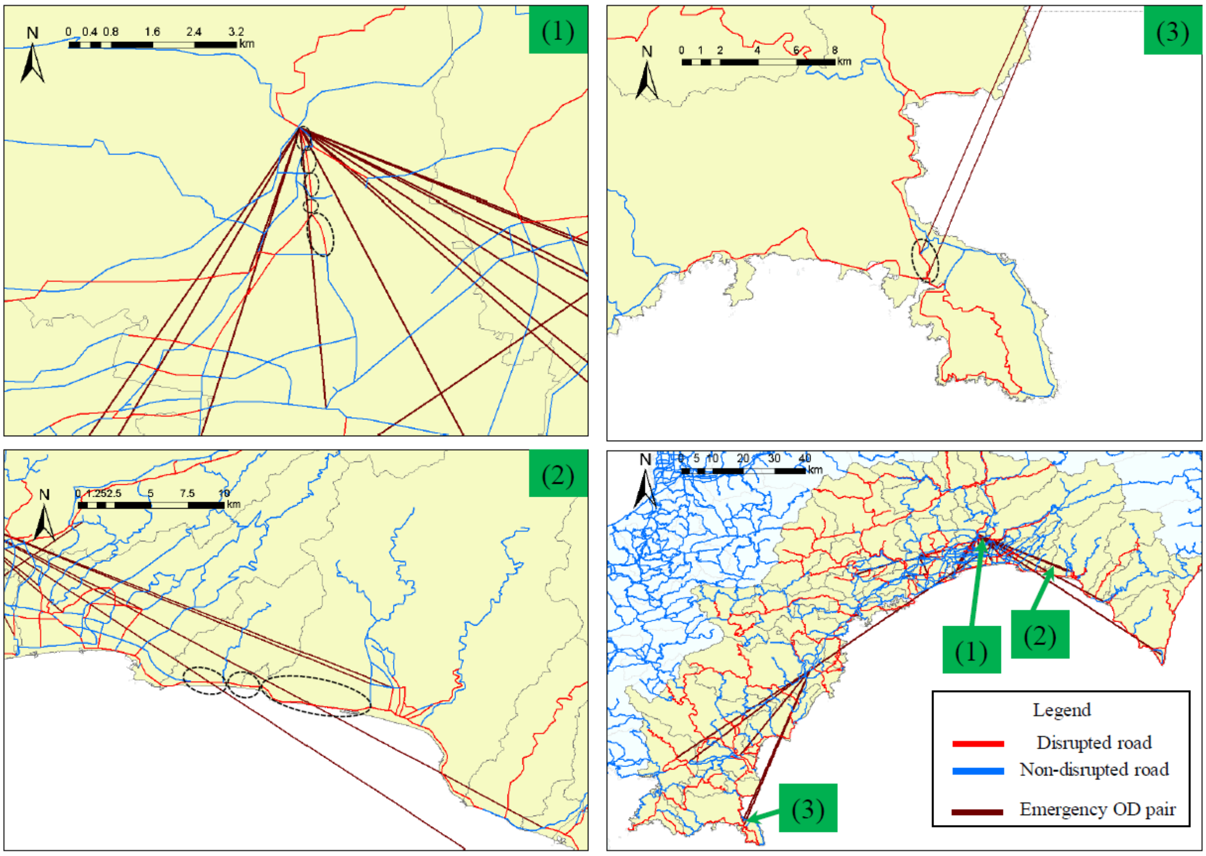

Figure 8. Example of the disrupted road selected as a recovered road

around the road; however, the disrupted roads connecting this road are already selected as a recovered road.

Overall, this clarified that the roads selected as recovered roads in the early stage are likely to play a role in connecting more emergency OD pairs.

4.2.4 Comparison analysis with case without considering road usage frequency

To examine the significance of considering road usage frequency, this subsection compares the results with and without considering road usage frequency. The index for evaluation is Accessibility (ACC), which is calculated using Eq. (1).

$$\mathrm{ACC} = \sum_{k} D \cdot f\left(c_{ij}\right), \tag{1}$$

which is commonly used in a related field proposed by Hansen. Here D is the attractiveness of the emergency OD pair, k is the number of emergency OD pairs at each level, and $f\left(c_{ij}\right)$ is the attenuation function, expressed as Eq. (2):

$$f\left(c_{ij}\right) = \exp\left[-\alpha \cdot c_{ij}\right], \tag{2}$$

where c_{ij} represents the distance between the origin and the destination of each emergency OD pair and α represents the parameter for the adjustment of the variance of the function.

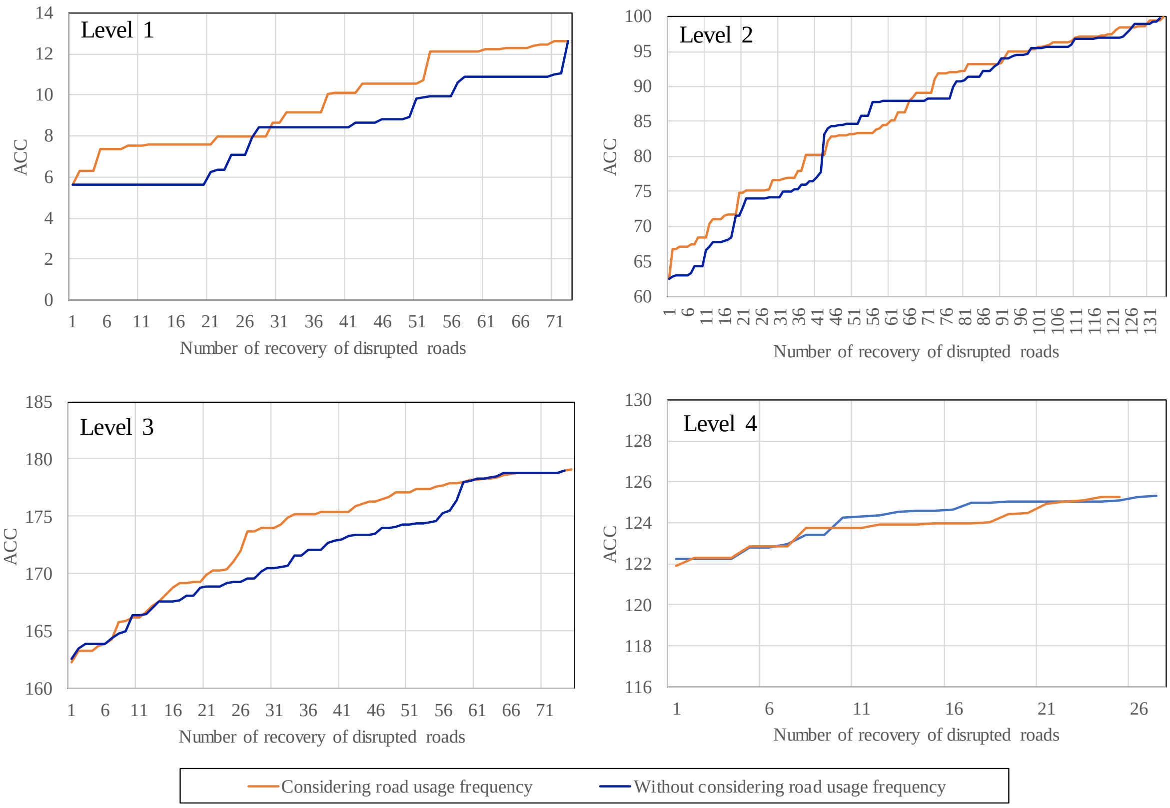

Figure 9. Comparison of changes in ACC

That is, as c_{ij} and α decrease, $f(c_{ij})$ increases and becomes less susceptible to distance attenuation.

In this study, since the shortest time of emergency OD pairs is calculated separately at each level, one was assigned for all values of D. For α, it must be set depending on the situation or emergency. On the basis of the parameter used by Kondo *et al*. (2010) and Osawa *et al*. (2017) a value of 0.1 was assigned.

The comparison results are shown in Fig 9. The graph depicts the relationship between the improvement of ACC and the recovery of disrupted roads.

From level 1 to level 3, the value of the proposed case is likely to be higher than the case without considering road usage frequency. The result clearly indicates that ACC can improve faster by recovering a road by considering road usage frequency. It explains that the proposed model can connect emergency OD pairs faster. By contrast, in level 4, there is no significant difference between the two values. It is assumed that most of the disrupted roads are already recovered at that stage.

5. CONCLUSION

Since a large-scale disaster disrupts many roads, it is important to consider which road should be recovered preferentially to minimize the impact of the disaster. The current road recovery plans used in this study calculate the recovery days for emergency paths at each level. However, it is unknown which disrupted roads are more important in each group of priority because each emergency path is calculated independently.

This study proposed a road-recovery-planning model that considers road usage frequency as an emergency route when there is a large-scale disaster. Using the list of emergency OD pairs in the present plan at each level of priority, the usage frequency of each road is counted. On the basis of the frequency, it is possible to determine which road should be preferentially recovered.

By applying the model to an actual network, we clarified that the roads connecting more emergency OD paths are preferentially recovered. Also, by comparing the results with and without considering road usage frequency, we were also able to clarify that the speed of improving ACC calculated by the proposed model is generally higher. Thus, the results suggest that road usage frequency as an emergency route can be useful as an indicator of road restoration.

However, since the proposed model treats the road as a number of sections, the situation may be different in the same section. Further study is needed to address these points.

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REFERENCES

Aksu, D.T., Ozdamar, L. (2014) A mathematical model for post-disaster road restoration: Enabling accessibility and evacuation. *Transportation Research Part E: Logistics and Transportation Review,* 61, 56-67.

Berdica, K. (2002) An introduction to road vulnerability: what has been done, is done and should be done. *Transport Policy,* 9, 117-127.

Chen, A., Yang, C., Kongsomsaksakul, S., Lee, M. (2007) Network-based accessibility measures for vulnerability analysis of degradable transportation networks. *Networks and Spatial Economics*, 7, 241-256.

Chen, Y.W., Tzeng, G.H. (1999) A fuzzy multi-objective model for reconstructing the post-quake road-network by genetic algorithm. *International Journal of Fuzzy Systems*, 1, 85-95.

Committee of road recovery plan, Shikoku, Japan, for preparing for Nankai Trough Earthquake, https://www.skr.mlit.go.jp/road/dourokeikai/pdf1/honpen.pdf (in Japanese)

Council on road recovery in Shikoku region , https://www.skr.mlit.go.jp/road/dourokeikai/ (in Japanese)

Kochi Prefecture (2017) Road recovery plan in Kochi Prefecture, http://www.pref.kochi.lg.jp/soshiki/170701/2015022700218.html (in Japanese)

Kondo, R., Shiomi, Y., Uno, N. (2010). Road network and medical facilities planning model considering accessibility and connectivity, *Infrastructure Planning Review*, 27, 337-344.

MATLAB documentation (shortestpath), https://www.mathworks.com/help/matlab/ref/graph.shortestpath.html

Osawa, S., Nakayama, S., Fujiu, M., Takayama, J., Mizokami, S. (2017) A study on decision method for restoration priority rank in road network based on accessibility index after natural disaster, *Journal of Japan Society of Civil Engineers, D3 (Infrastructure Planning and Management),* 73, 281-289. (in Japanese)

Sohn, J. (2006) Evaluating the significance of highway network links under the flood damage: An accessibility approach. *Transportation Research Part A: Policy and Practice*, 40, 491-506.

Taylor, M.A., Sekhar, S.V., D'Este, G.M. (2006) Application of accessibility based methods for vulnerability analysis of strategic road networks. *Networks and Spatial Economics,* 6, 267-291.

Tohoku Regional Ministry of Land, Infrastructure, Transport and Tourism, http://infra-archive311.jp/en/gaiyou.html