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An Analysis of Disaster Risk of Emergency Transport Road Using the Reachability Analysis

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Abstract: Since the Great East Japan Earthquake occurred, it is realized again in Japan that maintaining the road network connectivity is important to execute disaster responses quickly. However, even in recent years, such disaster prevention measures are not sufficiently and its execution of effective measures is necessary. To achieve this, understanding the current state of natural disaster risk as vulnerability of road network is indispensable. For this purpose, the reachability of emergency transport network in some prefecture, Japan when considering each kind of natural hazard is analyzed in this study. Specifically, shortest reach distance among prefectural office and evacuation facilities and reachable region from prefectural office when considering passable of road caused by each natural disaster is analyzed. As a result of this analysis, it became clear that many delays of reach caused by detour to evacuation facilities may occur and some facilities may not reach in the worst case.

Keywords: Emergency Transport Road, Natural Disaster, Vulnerability, Natural Disaster Risk

1. INTRODUCTION

Since the Great East Japan Earthquake of March 11,2011 occurred, it is realized again in Japan that maintaining the road network connectivity is important to execute disaster responses quickly. However, even in recent years, such disaster prevention measures are not sufficiently executed is the reality. For example, in the 2016 Kumamoto Earthquake, many important roads such as highways and national roads are closed due to landslide disaster and bridge fall. Moreover, in 2018 July heavy rain, similar situations occurred due to river flood and landslide disasters. The emergency transport road was also included in such closed roads. Emergency transport road is one of the road specified type in Japan in which to execute emergency transports after a disaster. Its detail is as shown in Table 1.

Table 1. Kind and role of emergency transportation road

Kind	Role
Primary	Roads that forming of transport are as follows: Such Arterial high-standard highways and National routes as broad important routes
Secondary	Roads that connect Primary emergency transportation road with municipal offices and important bases
Third	Road that connect Primary and Secondary emergency transport with branches of municipal office

Because of the high risk of disaster in Japan, disaster prevention measures to road must be executed adequately. For this purpose, it is needed that to evaluate disaster risk of road networks and to vulnerability of road networks with this in mind. Many studies about the latter has been conducted so far. D'Este and Taylor (2001), D'Este and Taylor (2003) and Taylor et al. (2006) proposed the vulnerability as theory that similar to connectivity reliability. Kurauchi *et al*. (2009) proposed a theory to evaluate the reachability without connect probability by using the non-overlapping path. In addition, Harada *et al*. (2014) proposed the method which extended the work of Kurauchi et al. (2009) by using the Hansen's accessibility (Hansen, 1959). In recently, several methods with characteristic values of road network such as the following; traffic capacity, traffic volume and link distance and so on (Nouzard *et al*., 2016; Bell *et al*., 2017; Akbarazadeh *et al*., 2019). These previous studies are one of the effective methods to evaluate the vulnerable section on road network, on the other hand, how take disaster risk of road network into its evaluation is not mentioned. Such about disaster risk of road network, Fujiu *et al*. (2018) has been mentioned to emergency transport networks in Japan. Shivaprasad et al. (2018) evaluated the vulnerability of road network around the Kopil River Basin in India when targeted flood disaster. However, it it not mentioned about passable of road similar to Fujiu et al. (2018). Ahn et al. (2011), Kilantis and Sextos(2019) and Robinson et al. (2015) are studies that considering the passable of road which caused by natural hazard. Ahn et al. (2011) evaluated the disaster risk of road network in historical city when considering building collapse and fire caused by the earthquake and proposed the road network improvement using the reliability analysis. On the other hand, although Kilantis and Sextos(2019) focused bridges, tunnels and slops as components of road and evaluated road network recovery process and resilience considering these damage of these component caused by the earthquake, the evaluation is only tried small road network. Robinson et al. (2015) discussed about passable of each road section when focused landslide disaster caused by the earthquake. However, it is not discussed how amount of impact on road traffic is occurred.

As already mentioned, it is needed to execute the effective disaster prevention measures to road network in Japan, a natural disaster-prone country. As reviewed above, many methods or theory to select countermeasure sections of road network are proposed. To use these method or theory effectively, recognize to current state of natural disaster risk of road network is indispensable. When great natural disaster occurred, traffic demands among many cities are expected to generate. From this assumption, not only focused limited extent road network, but evaluation of natural disaster risk of large extent road network is necessary. Secondly, if the important road is damaged and closed, its impact is likely to spread to not only inside the city but other cities. Therefore, in addition to degree of simple natural disaster risk of road network, considering the impact on road traffic which occurred if important road closed is also needed. Moreover, Japan is one of the natural disaster-prone country. Hence, all types of natural hazard are necessary to consider in evaluation of natural disaster risk of road network. Based on the above background, it is analyzed that reachability on among the road network of some prefecture in Japan considering occurrence of road closes caused by each natural disaster in this study. The purpose of this study is understanding the natural disaster risk of emergency transport road network of each prefecture. Note that, reachability is evaluated as reach distance between prefectural office and each evacuation facility and reachable region from each prefectural office in this study.

2. THE CONSTRUCTION METHOD OF EMERGENCY TRANSPORTATION ROADS NETWORK AND THE EVALUATION METHOD OF THE DISASTER RISK ON EMERGENCY TRANSPORTATION ROAD

2.1 The Construction Method of Emergency Transportation Roads Network

In this study, using the GIS data of emergency transportation road which has been published by Japanese National Land Numerical Information download service to construct emergency transportation roads network. Based on the regional disaster prevention plans and the emergency transportation network plans, this data deals with the line shape, the classification, and the type of emergency transportation roads.

2.2 The Evaluation Method of the River Flooding Risk

To evaluate the river flooding risk on emergency transportation roads, it is used flood-assumed area data which has been published by National Land Numerical Information download service on a nationwide scale. This data deals with range of flood-assumed area, flood depth, object river of plan and the design rainfall. Among these, flood depth is divided into 5 or 7 levels as shown in Table 2. In this study, the situation where the roads become impassable by flooding is defined as flood depth which vehicles become unable to travel. Such a flood depth is generally accepted that depth which the floor of the vehicle is submerged. In the light of this, the roads which in a flood-assumed area where flood depth is more than or equal to 0.5 meters is evaluated as segment that may be unusable by the flood. As Figure 1 shows, the flood segments of emergency transportation road are set to matched segments where superimposed emergency transportation road and flood-assumed area.

Table 2. Graded flood depth and the flooding state of the road

Classification of flood depth		Flooding state
5 levels	7 levels	
fewer than 0.5 meters	fewer than 0.5 meters	non-flood
0.5 meters or more but fewer than 1.0 meters	0.5 meters or more but fewer than 1.0 meters	flood
1.0 meters or more but fewer than 2.0 meters	1.0 meters or more but fewer than 2.0 meters	flood
2.0 meters or more but fewer than 5.0 meters	2.0 meters or more but fewer than 3.0 meters	flood
5.0 meters or more	3.0 meters or more but fewer than 4.0 meters	flood
	4.0 meters or more but fewer than 5.0 meters	flood
	5.0 meters or more	flood

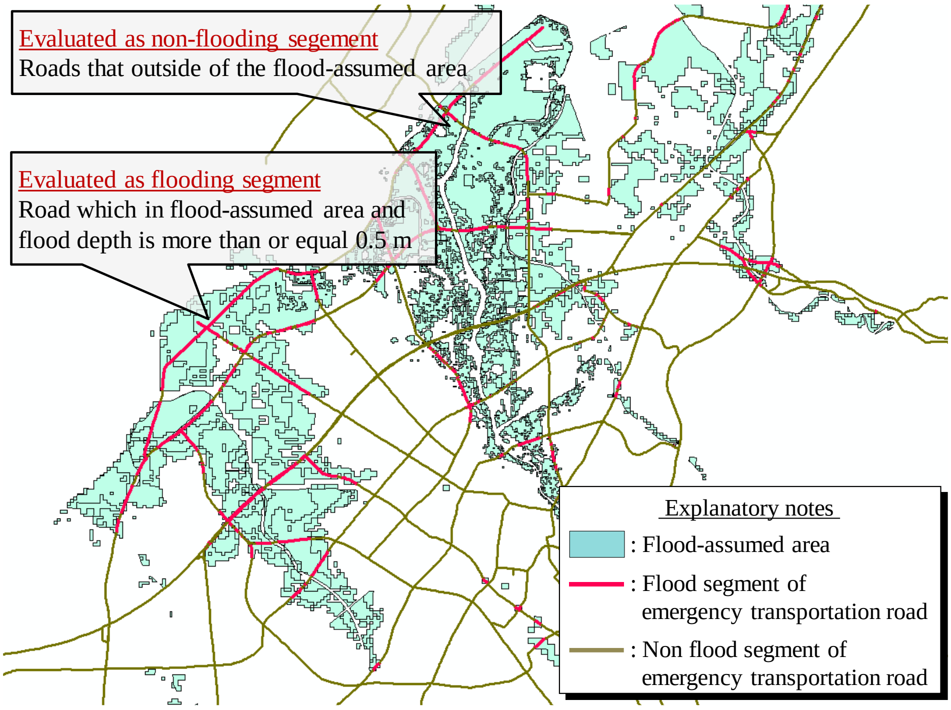

Figure 1. Conceptual diagram of the evaluation of the flood segment

2.3 The Evaluation Method of Risk of Road Blockage Caused by Collapse of Roadside Buildings

To evaluate the risk of road blockage caused by collapse of roadside buildings, it is needed data of buildings such as position, height, building date and structural type. However, it is generally difficult to obtain such data. For this reason, it is created building data that can be grasped height and position of building in this study. To create such data, it is used for Detailed Map 2012 that provided by ESRI Japan. This is a background map database which can used on ArcGIS one of the GIS software, and which contains many geospatial information. To be specific, detailed attribute information of each element which illustrated on map-screen can be get and used for some analysis. For example, building use data and facility name data corresponds to these information. Secondary, explain about building height data. The number of building floors data is included in this map data as building basic attribute. This data has defined that one floor equivalent to 3 meters, therefore, it can be got building height data provided that it multiplies number of building floors by 3 meter. An example of Detailed Map 2012 and created building data is presented in Fig.2.

To risk evaluation of the building collapse, it is needed to data of structure type and age of building. As is summarized in Table 3, the structure type of building is categorized in accordance with specification of Detailed Map 2012. The building that corresponded to a residence is wooden construction, however, this category is also included high-rise buildings like high-rise apartment. Because of this reason, the building more than four-floors is categorized into non-wooden construction. With respect to age of building determination method, the way which determined random based on current status of earthquake resistance, changed to parametric, and so on. The building data that created in this study has high-spatial resolution. It is called for data of age of building which has comparable spatial resolution to apply above-mentioned method. However, such data has not published. Therefore, it is supposed that all buildings are designed under the current building code. By this assumption, the road blockage risk caused by roadside building collapse as this study demonstrates is minimum case.

The building data that created in the above procedure included buildings that built along the road other than emergency transportation road. For this reason, it is extracted the building that built along emergency transportation road and used for analysis.

Next, decide the magnitude of ground motion in which each building is hit based on probabilistic seismic hazard maps that open to the public by Japan Seismic Hazard Information Station. Furthermore, decide the probability complete destruction of each building on the basis of damage function of the building against earthquakes.

To evaluate the load blockage caused by collapse of roadside building, we carried out random number simulation using the above data. It performs a complete destruction judgment of each building, if the building is determined to completely destroy, adjacent emergency transportation road become impassable.

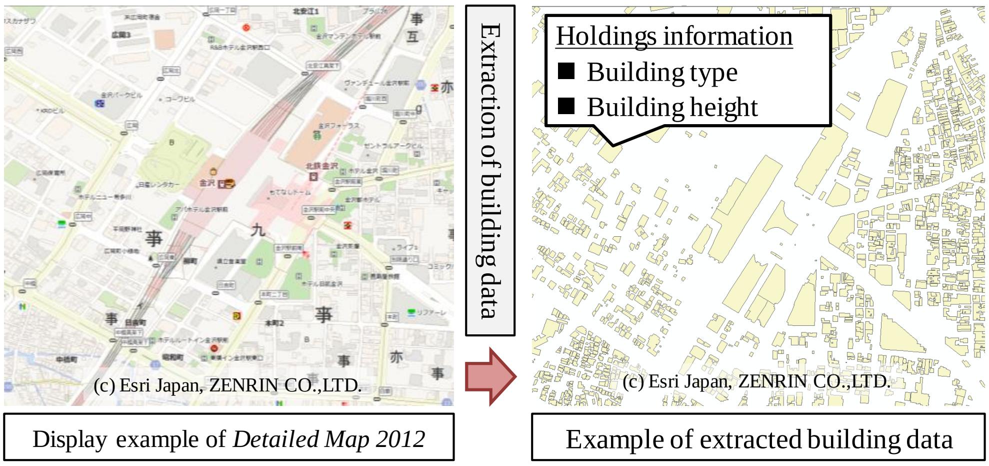

Figure 2. Example of Detailed Map 2012 amd building data

Table 3. Building type and structure of building data in Detailed Map 2012

Building type	Structur of building	Building type	Structur of building
Landmark object (hotel)	non-wooden	Landmark object (public facilities)	non-wooden
Landmark object (commericial facilities)	non-wooden	Landmark object (medical care)	non-wooden
Landmark object (schol)	non-wooden	Landmark object (traffic)	non-wooden
Landmark object (sparetime and leisure)	non-wooden	Frame of the general house (other) 3-stories or less	wooden
landmark object (landmark object)	non-wooden	Frame of the general house (other) 4-stories or more	non-wooden

2.4 The Evaluation Method of Risk of Road Blockage Caused by Landslide Disaster

To assess the risk of landslide disaster on emergency transportation road, in the same way as evaluation of river flooding risk, it is used landslide disaster hazard area data which has been published by National Land Numerical Information download service. This data organized such as range of landslide disaster caution area, type of disaster and type of designation of landslide disaster caution area. As Figure 3 shows, damaged section due to landslide disaster is set to matched segments where superimposed emergency transportation road and landslide disaster caution area.

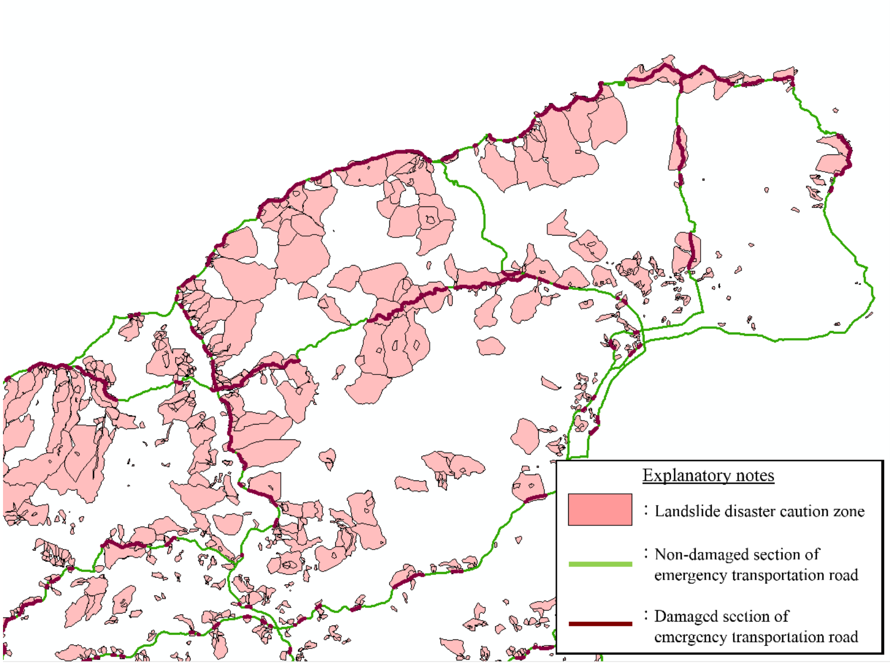

Figure 3. Conceptual diagram of the evaluation of the risk of landslide disaster on emergency transportation road

2.5 The Construction Method of Emergency Transportation Network Considering the Disaster Risk

Figure 4 shows a conceptual diagram of construction method of emergency transportation road network considering the disaster risk. Such emergency transportation road network is removed the affected section from normal time network. In brief, the flooded road section, roadblock section caused by building collapse or landslide disasters is deleted. Moreover, to network analysis, it is needed to the link between the emergency transportation road network and the destination. This link created as the shortest straight line connecting from the destination to the nearest emergency transportation road.

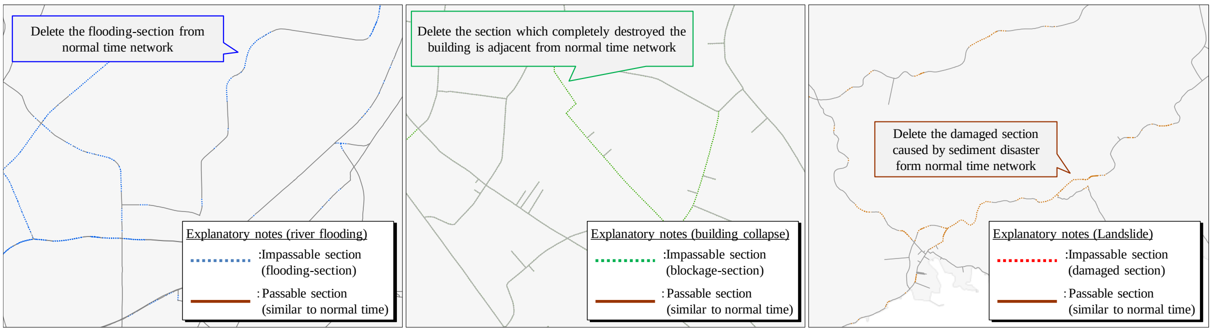

Figure 4. Conceptual diagram of construction method of emergency transportation road network considering the disaster risk

3. A REACHABILITY ANALYSIS BETWEEN PREFECTURAL OFFICE AND EVACUATION FACILITIES

3.1 Analysis Conditions for Reachability Analysis

Object area of this study is set to Niigata, Toyama, Ishikawa, Fukui and Gifu prefecture and it is constructed the normal time emergency transportation road network such as Fig.5 shows. Moreover, number of object evacuation facilities is presented as Table 4. Object disaster is earthquake, river flooding, landslide disaster and each complex disaster. Collapse of the road side building caused by earthquake, road flooding caused by the river flooding and road blockage caused by the landslide disaster are conceived as impassable of emergency transportation road. Moreover, by the occurrence of impassable section, even if the bypass cannot be reached from the prefectural office to evacuation facilities, it is assessed as state of unreachable that. Conversely, if it can reach the evacuation facility but reaching distance is increased owing to bypassed, it is assessed as state of delay. Note that state of delay is only focused on reach distance but increased of travel time is not taking into account. This is an analysis condition based on the difficulty of prediction of traffic demands that occurs after disaster due to many uncertain exists. Distance is an important characteristic value of road network, so this analysis condition is considered to be appropriate. On the other hand, travel time is also important characteristic value of road network in the same way as distance, therefore, how considering its in this analysis is one of the future works.

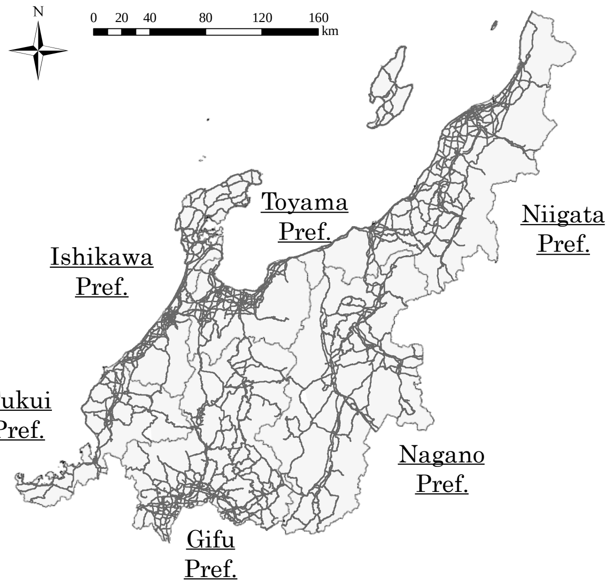

Figure 5. Figure of emergency transportation road network in normal time

Table 4. Number of the subject of evacuation facilities

Niigata Pref.	Toyama Pref.	Ishikawa Pref.	Fukui Pref.	Nagano Pref.	Gifu Pref.
2,853	1,197	1,022	1,509	3,822	2,906

3.2 Reachability Analysis Between Prefectural Office and Evacuation Facilities Considering the Emergency Transportation Road Flooding

Emergency transportation road section that is likely to flooding and emergency transportation road network considering this flooding-road section is presented in Fig. 6. The aim of this study is to clarify the flood risk on emergency transportation road has influence on reachability. Therefore, all of emergency transportation sections that flood-depth conceived more than or equal 0.5 meters is set to impassable sections. The result of reachability analysis between prefectural office and evacuation facilities is presented in Table 5. Note that, some of evacuation facilities include flood-damaged facilities when targeting river floods. In analysis, dealing with these damaged facilities as available ones is unsuited. Therefore, in this study, it is assumed that the evacuation facilities which flooding are expected are unavailable, and excluded them from analysis. By this, the available evacuation facilities are reduced in comparison to Table 4, and the numbers of facilities as show in in Table 5 remained as analysis target. Moreover, reachable area between prefectural office and evacuation facilities is presented in Fig 7 and Fig 8. Table 5 shows that, it seen that there many flood risks on emergency transportation road that influence on reachability. Following insights offered by Fig 8 and geographical features of the target area: First, there are many flood risks on emergency transportation road that positioned plain and nearby river. Second, if prefectural office is positioned plain and nearby river, it is great influence on reachability from the prefectural office to the outside. Finally, since many flood risks exists on emergency transportation road crossing the river, it is needed to ensure the alternate route.

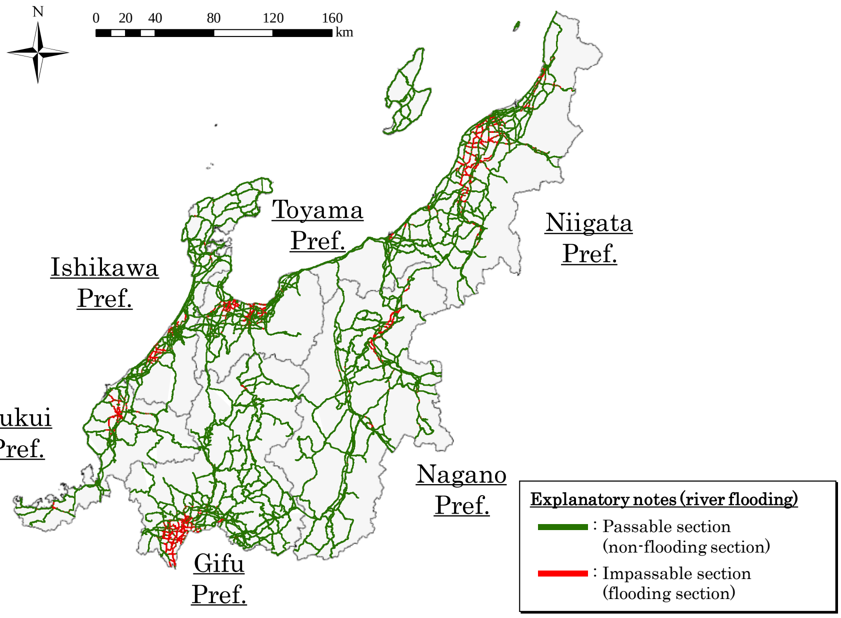

Figure 6. Figure of emergency transportation road network considering the flood risk

Table 5. Result of reachability analysis in case of considering the river flood

Prefectures	Niigata Pref.	Toyama Pref.	Ishikawa Pref.	Fukui Pref.	Nagano Pref.	Gifu Pref.
Number of subject of evacuation facilities	2,188	784	846	1,061	3,414	2,145
Number of unreachable evacuation facilities	848	783	666	1,061	1,410	2,145
Rate of unreachable evacuation facilities	38.8%	99.9%	78.7%	100.0%	41.3%	100.0%
Number of delay occurrences	1,240	0	96	0	1,599	0
Rate of delay occurrences	56.7%	0.0%	11.3%	0.0%	46.8%	0.0%

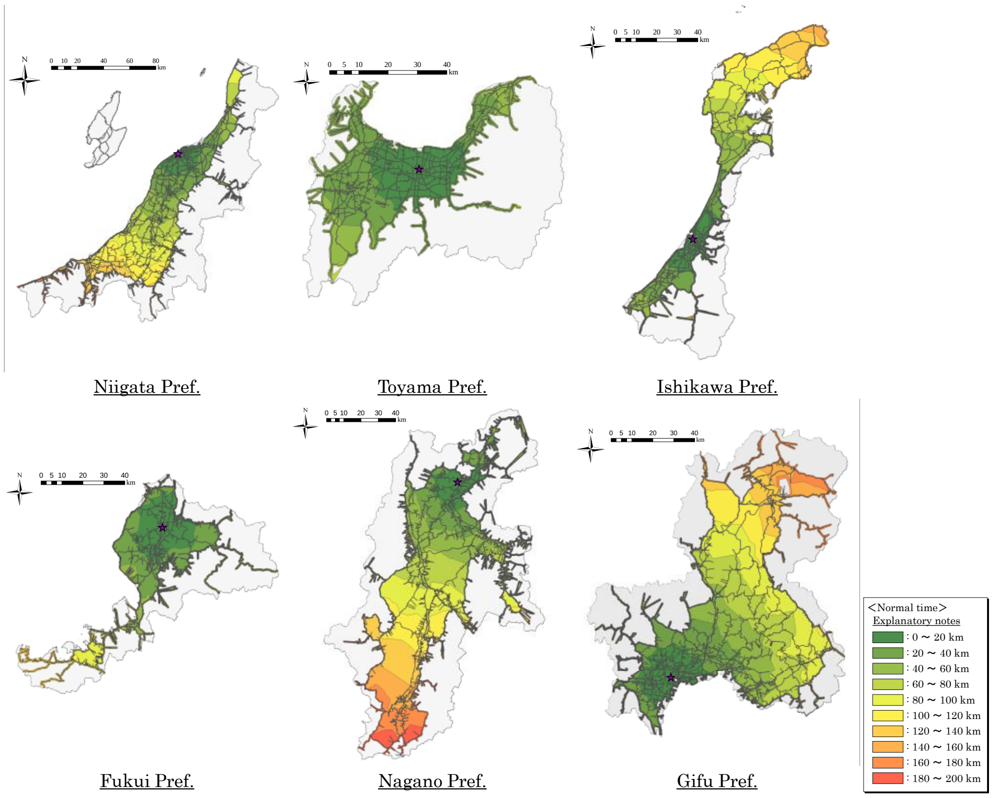

Figure 7. Figure of reachable area from prefectural office in each prefecture (normal time)

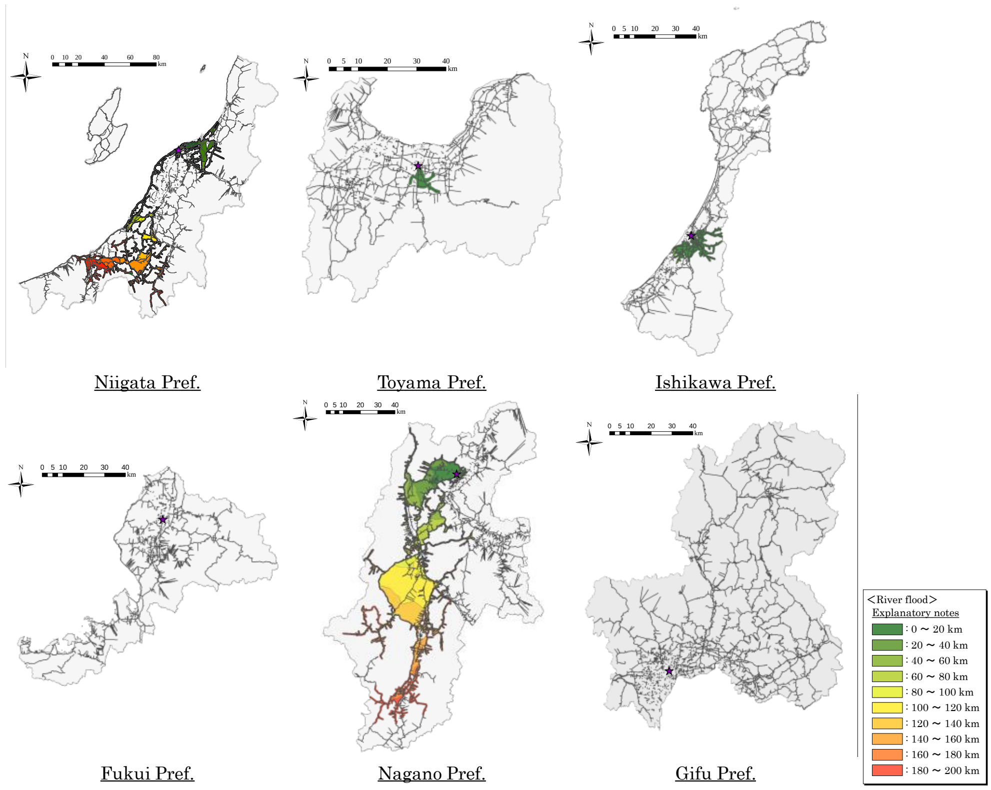

Figure 8. Figure of reachable area from prefectural office in each prefecture (considering the river flood)

3.3 Reachability Analysis Between Prefectural Office and Evacuation Facilities Considering Collapse of Roadside Buildings Caused by Earthquake

In this study, distribution of seismic intensity by Japan Meteorological Agency (JMA) for a 2% probability of exceedance within 50 years (Fig 9) of the probabilistic seismic hazard maps published by Japan Seismic Hazard Information Station is used as design earthquake. Moreover, the fragility curve shown in damage assumption of Tokyo by The Great Nankai Trough Earthquake (Fig 10 and Fig 11) is applied as damage function of buildings. Note that the fragility curve used for analysis is only the curve shown by the red border in Fig 10 and Fig 11 owing to assumption of age of the building. The probability of complete destruction of each building are given by the method above and mentioned in 2.3. Next, it is conducted the complete destruction judgment of each building by random number simulation. In this simulation, to generate a 0.1 increments of random numbers in the range from 0 to 100, moreover, if the generated number is less than the probability of the complete destruction of the building, the building is completely destroyed and to impassable adjustment emergency transportation road. In, addition, in this study puts the focus on the development of analytical methods, the simulation is performed tentatively only at once.

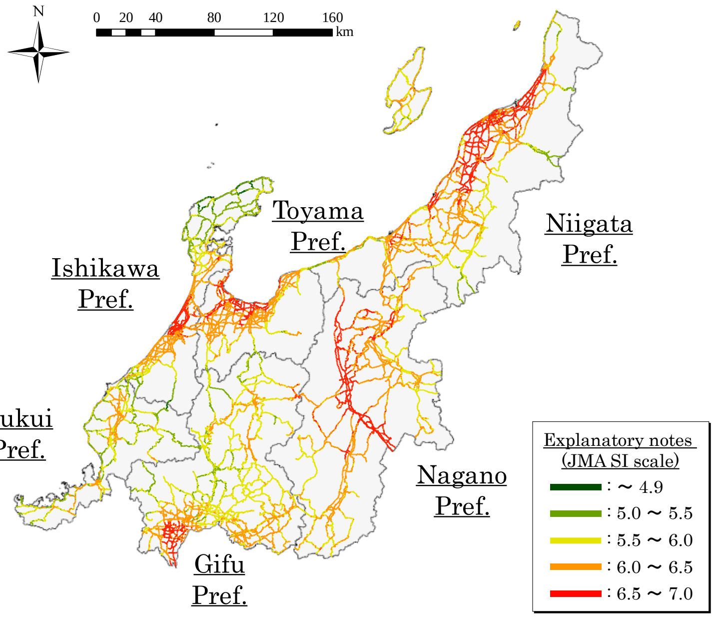

Figure 9. Distribution of seismic intensity by JMA for a 2% probability of exceedance within 50 years

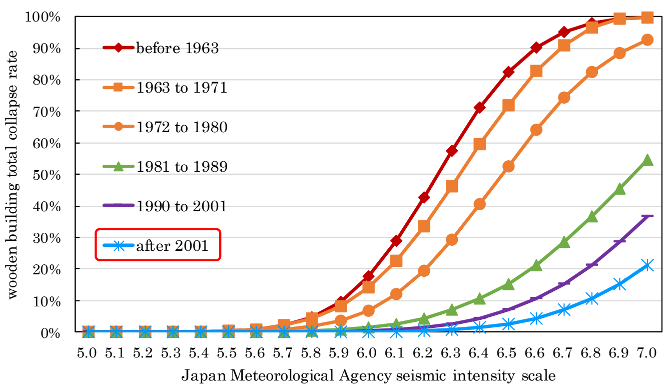

Figure 10. Fragility curve of wooden building

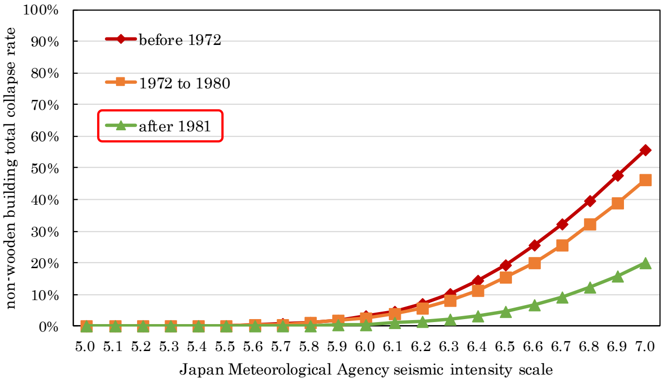

Figure 11. Fragility curve of non-wooden building

The emergency transportation road network considering the road blockage caused by the road side building collapse is shown in Fig 12. The reachable area from prefectural office considering the road side building collapse caused by earthquake is shown in Fig 13. The result of the reachability analysis is presented in Table 6. As can be seen form Fig 9, there are many emergency transportation roads that anticipated high seismic intensity by JMA. In Niigata prefecture and Nagano prefecture, it is high risk of road blockage caused by road side building collapse in such a road. Namely if sparse parts of the network are such a road, it is necessary to caution as a vulnerable part. In these prefectures, it is found that actually unreachable area occurs owing to impassable of vulnerable part is shown in Fig 13. On the other hand, if there are many emergency transportation roads that anticipated high instrumental seismic intensity by JMA, provided that such roads exist in dense part of network, there is a chance that can be replace by other road. However, if the road blockage occurs on the shortest route from the prefectural office to evacuation facilities, delays occur. In order to rapid deal with disaster, it is important to understand the road which has high road blockage risk.

Table 6. Result of reachability analysis in case of considering the building collapse

Prefectures	Niigata Pref.	Toyama Pref.	Ishikawa Pref.	Fukui Pref.	Nagano Pref.	Gifu Pref.
Number of subject of evacuation facilities	2,856	1,197	1,022	1,509	3,822	2,906
Number of unreachable evacuation facilities	209	116	75	86	586	65
Rate of unreachable evacuation facilities	7.3%	9.7%	7.3%	5.7%	15.3%	2.2%
Number of delay occurrences	463	423	128	5	1,015	376
Rate of delay occurrences	16.2%	35.3%	12.5%	0.3%	26.6%	12.9%

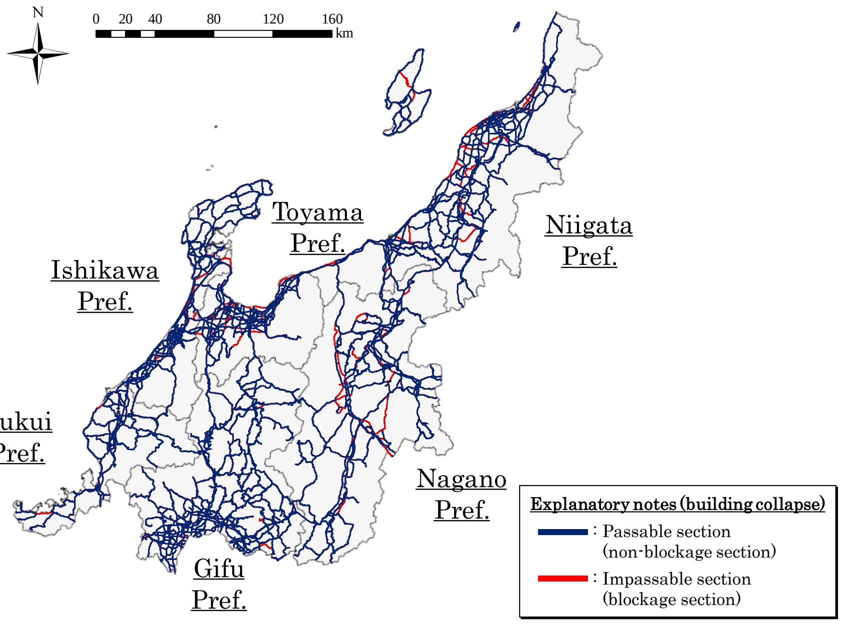

Figure 12. Figure of emergency transportation road network considering the building collapse

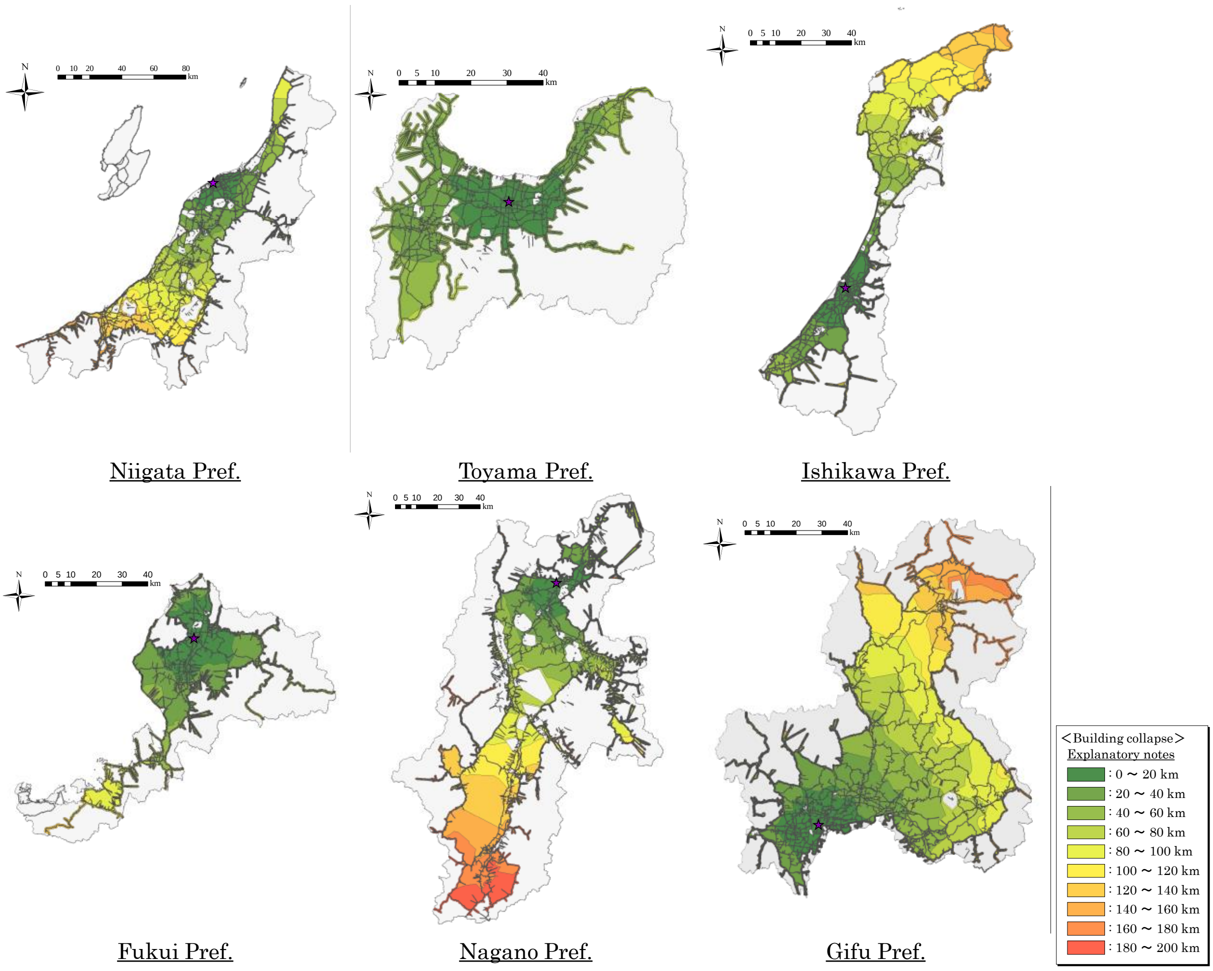

Figure 13. Figure of reachable area from prefectural office in each prefecture
(considering the building collapse)

3.4 Reachability Analysis Between Prefectural Office and Evacuation Facilities Considering Landslide Disaster

Road sections that is likely to blockage caused by landslide disaster and emergency transportation road network considering this is presented in Fig. 14. The result of reachability analysis is shown in Table 7. Fig 15 is presented the reachable area from prefectural office considering landslide disaster. As can be seen from Fig 15 and Table 7, Since there are many mountains in Japan, many disaster risks of landslide disaster exist on emergency transportation road in mountains areas. Moreover, Occurrence of isolated areas is worried, owing to road network in such areas is often vulnerable. For example, in Nagano prefecture, around the prefectural office has been surrounded by mountains, there is a possibility of isolated as shown in Fig 15. Development of alternate road and implementation of landslide disaster measures of emergency transportation road is important.

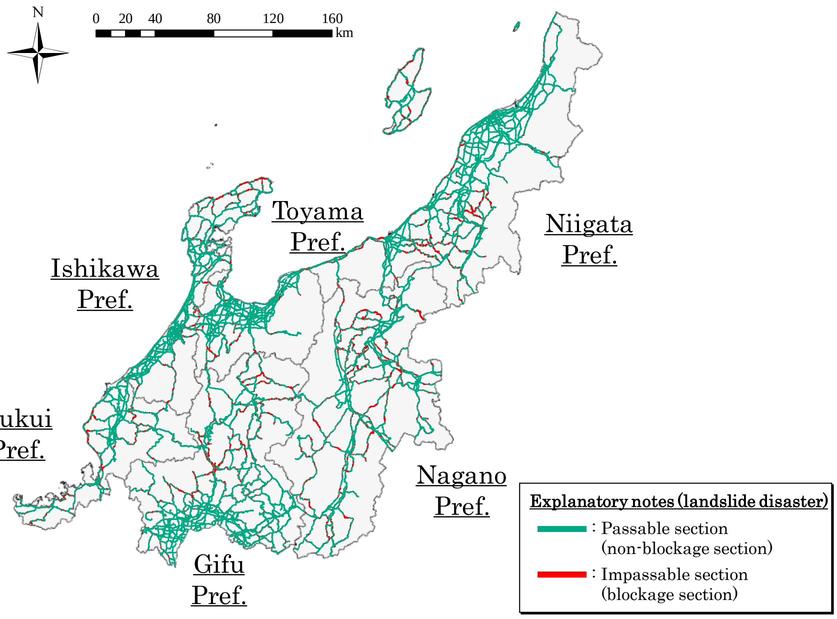

Figure 14. Figure of emergency transportation road network considering the landslide disaster

Table 7. Result of reachability analysis in case of considering the landslide disaster

Prefectures	Niigata Pref.	Toyama Pref.	Ishikawa Pref.	Fukui Pref.	Nagano Pref.	Gifu Pref.
Number of subject of evacuation facilities	2,853	1,197	1,022	1,509	3,822	2,906
Number of unreachable evacuation facilities	1,761	282	440	960	3,596	1,170
Rate of unreachable evacuation facilities	61.7%	23.6%	43.1%	63.6%	94.1%	60.9%
Number of delay occurrences	170	328	90	153	3	312
Rate of delay occurrences	6.0%	27.4%	8.8%	10.1%	0.1%	10.7%

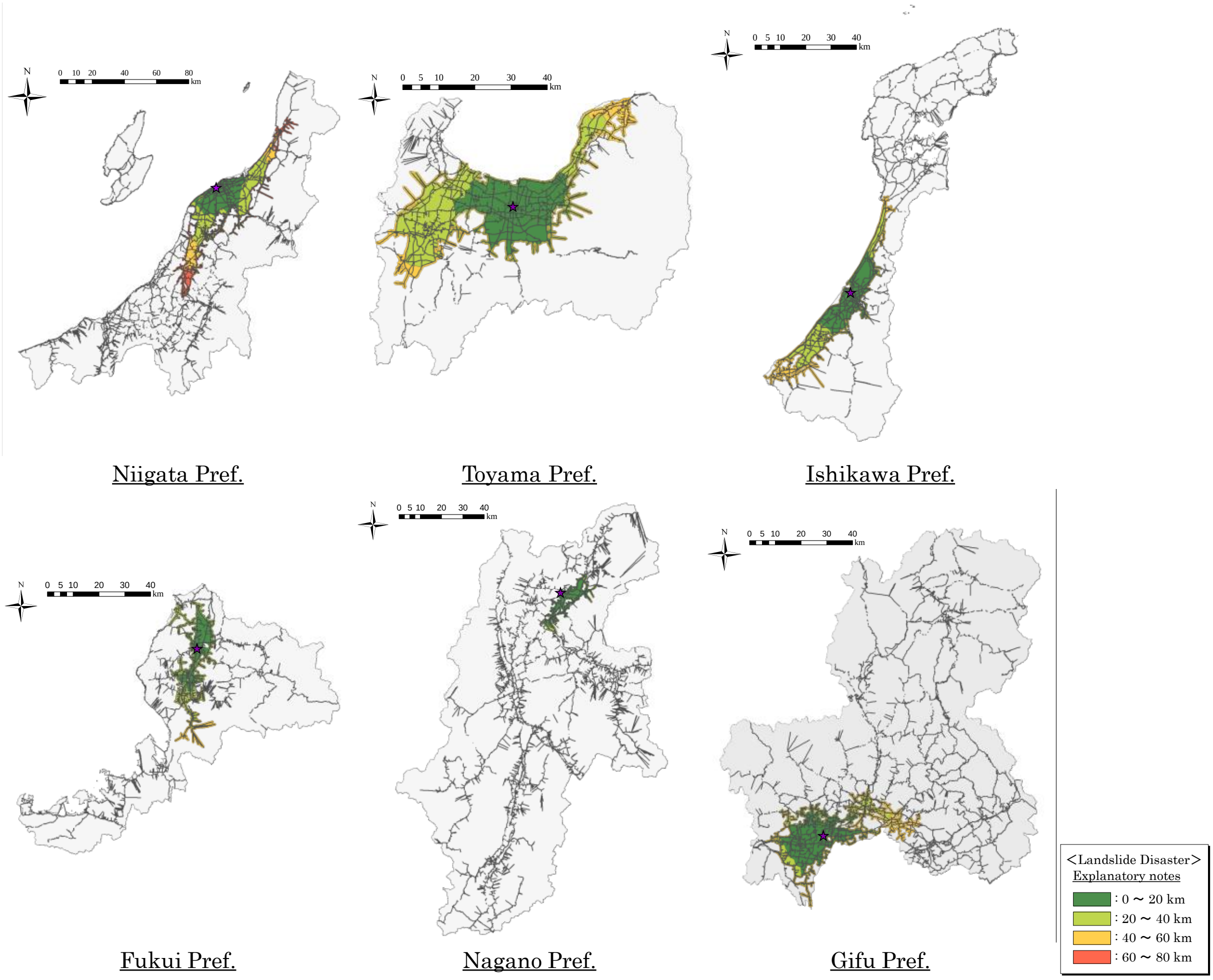

Figure 15. Figure of reachable area from prefectural office in each prefecture (considering the landslide disaster)

3.5 Reachability Analysis Between Prefectural Office and Evacuation Facilities Considering Complex Disaster

In case of considering the complex disaster, complex case of river flood and earthquake, earthquake and landslide disaster, river flood and landslide disaster are analyzed. Due to limited space, only exhibit the complex case of earthquake and landslide disaster in this paper. In cases of complex disaster, it is considered that damages caused by each disaster are occurred at the same time. Namely, it is conceived the network considering all impassable sections in each disaster case. Emergency transportation road network in case of complex disaster is presented in Fig 16. The result of reachability analysis is shown in Table 8. Fig 16 is presented the reachable area from prefectural office considering complex disaster. On the whole, impact of landslide disaster is predominant. Impact of landslide disaster is concentrated in mountains areas. On the other hand, impact of building collapse is concentrated in urban area. Therefore, as can be seen from Fig 17, it is considered the possibility of overlap of damages is low. However, it is suggested the possibility that damages of target areas are over a wide range, it is necessary to sufficiently vigilance.

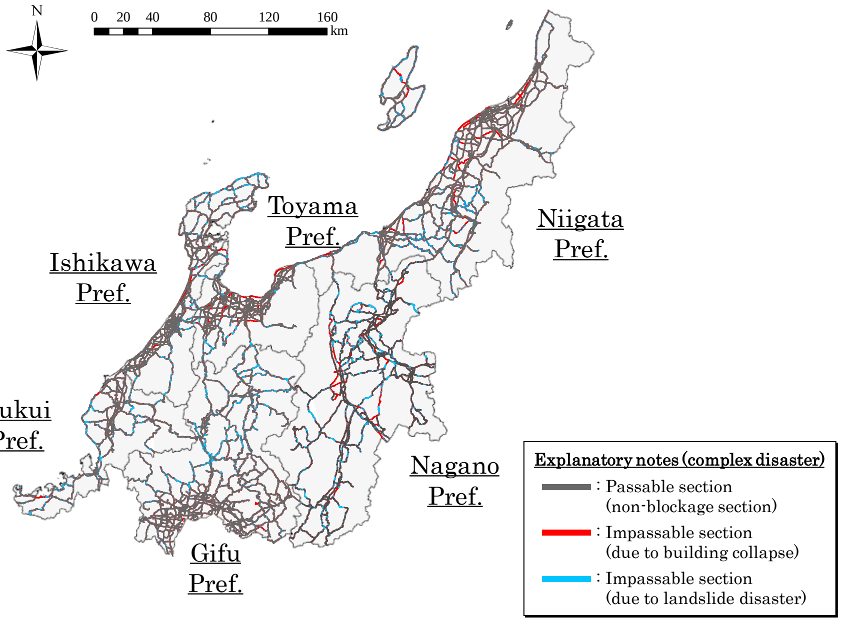

Figure 16. Figure of emergency transportation road network considering the earthquake and landslide disaster

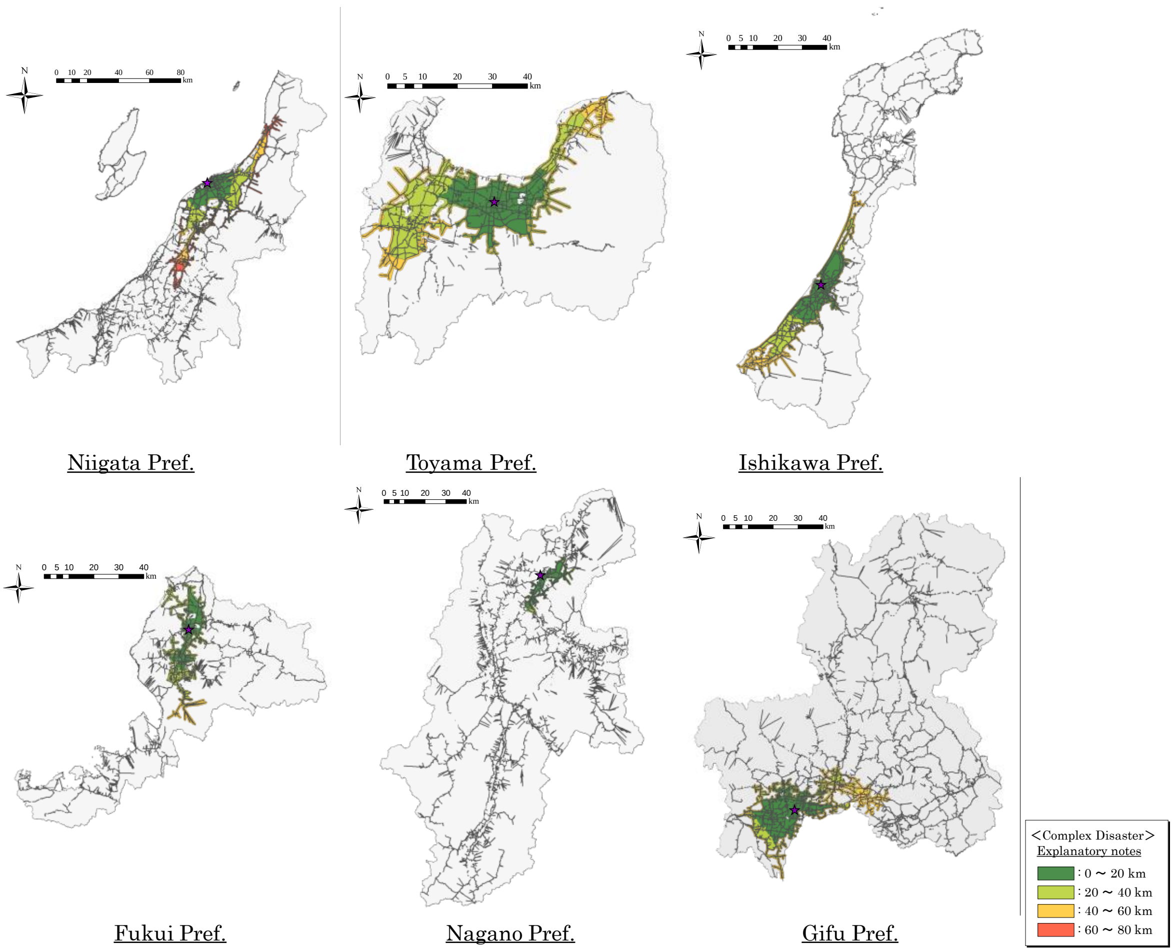

Figure 17. Figure of reachable area from prefectural office in each prefecture (considering the earthquake and landslide disaster)

Table 8. Result of reachability analysis in case of considering the earthquake and landslide disaster

Prefectures	Niigata Pref.	Toyama Pref.	Ishikawa Pref.	Fukui Pref.	Nagano Pref.	Gifu Pref.
Number of subject of evacuation facilities	2,853	1,197	1,022	1,509	3,822	2,906
Number of unreachable evacuation facilities	1,870	374	484	974	3,623	1,808
Rate of unreachable evacuation facilities	65.5%	31.2%	47.4%	64.5%	94.8%	62.2%
Number of delay occurrences	361	560	156	153	2	591
Rate of delay occurrences	12.7%	46.8%	15.3%	10.1%	0.1%	20.3%

4. CONCLUSIONS AND FURTHER STUDIES

In this paper, it is analyzed the possibility of disaster risk considering the road flooding caused by river flood, road blockage caused by building collapse, road blockage of landslide disaster, and complex case of earthquake and landslide. On the basis of this analysis result, it is analyzed the reachability between prefectural office and evacuation facilities that targeted Niigata prefecture, Toyama prefecture, Ishikawa prefecture, Fukui Prefecture, Nagano prefecture and Gifu prefecture.

In analysis of impact of river flood, it is suggested the possibility that there are many dangerous site on emergency transportation road. On the other hand, the possibility that all flood-assumed areas that flood-depth is 0.5 meters or more are flooding at the same time is low, it is necessary to refine the analytical method.

In analysis of impact of building collapse caused by earthquake, it is suggested possibility that the unreachable area is occurred when building collapse happened in vulnerable parts of the network. In future research, it will consider to elements other than building collapse as an impact of earthquake, while at the same time refining the analytical method of building collapse.

In analysis of impact of landslide disaster, due to the influence of landslide disasters is consistent with structurally vulnerable places in the network, it showed the possibility that the isolated areas are occurred. In future research, it will refine the analytical method such as to assess the presence or absence of landslide disaster stochastically.

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