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A study of vulnerability of emergency road network to various hazard

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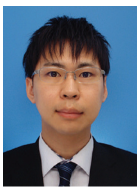

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Professional paper

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A study of vulnerability of emergency transport road network to various hazards

The frequency of natural disasters in Japan has increased in recent times. To ensure smooth transport of goods in the event of a large-scale low-frequency disaster, a network of emergency transport roads has been designed in Japan. However, while the frequency and nature of accidents are diverse, the emergency transport roads have not yet quantitatively grasped the degree of risk a disaster carries. In this study, the risk of this road network is quantitatively evaluated while considering various hazards such as earthquakes, floods, landslides, tsunamis, volcanic eruptions, and storm surges.

Key words:

Stručni rad

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Studija osjetljivosti cestovne mreže u kriznim situacijama na različite katastrofe

Prirodne katastrofe su u posljednje vrijeme sve češća pojava u Japanu. Kako bi se osigurao neometan prijevoz dobara uslijed velikih niskofrekventnih katastrofa, u toj je zemlji razvijena cestovna mreža za promet u kriznim situacijama. Iako su učestalost i priroda nesreća različiti, za takvu prometnu mrežu još uvijek nije definiran kvantitativni stupanj rizika koji katastrofa za sobom nosi. U ovom je radu procijenjen kvantitativni rizik cestovne mreže za promet u kriznim situacijama uslijed različitih katastrofa kao što su potresi, poplave, klizanja tla, tsunamiji, vulkanske erupcije i oluje.

Ključne riječi:
cestovna mreža, krizne situacije, rizik od katastrofe, potres, klizanje tla, poplave

Fachbericht

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Untersuchung der Empfindlichkeit des Straßennetzes in Krisensituationen auf unterschiedliche Katastrophen

Naturkatastrophen treten in letzter Zeit in Japan immer häufiger auf. Um einen ungehinderten Transport von Gütern während niederfrequenter Katastrophen sicherzustellen, wurde in diesem Land ein Straßennetz für den Verkehr in Krisensituationen entwickelt. Obwohl die Häufigkeit und die Art der Unglücke unterschiedlich sind, wurde für ein solches Verkehrsnetz noch immer kein quantitatives Risikoniveau definiert, das eine Katastrophe mit sich bringt. Diese Abhandlung schätzt das quantitative Risiko des Straßennetzes für den Verkehr in Krisensituationen infolge unterschiedlicher Katastrophen wie Erdbeben, Überschwemmungen, Erdrutsche, Tsunamis, Vulkaneruptionen und Stürme ein.

Schlüsselwörter:
Straßennetz, Krisensituationen, Katastrophenrisiko, Erdbeben, Erdrutsch, Überschwemmungen

1. Introduction

In recent years, natural disasters have been occurring more frequently in Japan. This includes large-scale low-frequency disasters, such as earthquakes or volcanic eruptions, and small-scale high-frequency disasters, such as landslides or floods, which are frequently accompanied by sudden heavy rains or torrential rains. A road network for emergency transport has been created to handle such situations in Japan. The network of designated roads is maintained such that smooth transport of supplies can be ensured at the time of large-scale disasters. However, there are few studies that evaluate the degree of disaster risk that can be handled by the network, when the type and frequency of disasters is varied quantitatively. This study evaluates the quantitative risk of emergency transport roads that are affected by various hazards such as earthquakes, floods, and landslides.

Whenever disasters in Japan are mentioned, the name of an earthquake, flood, or volcano comes to mind. For earthquake hazard assessment, the probability of an earthquake with a seismic intensity equal to or greater than 5 has been assessed using historical seismic intensity measurement data. These data have revealed that seismic activity has been increasing over the last 30–50 years [1]. Seismic intensity is an index that shows the strength of an earthquake ground motion. The seismic intensity ranges from level 0 to level 7 and, at that, levels 5 and 6 are divided into two sublevels, which means that there are 10 earthquake intensities in total.

Flood hazard is evaluated based on flood limits of 5.0 m, 3.0 m, and 0.5 m, and the available data are grouped by county, prefecture, and metropolital areas. The relationship between the boundary height and the flooding phenomenon is given by the following: at 0.5 m, flooding occurs in the first floor of the building; at 3.0 m, flooding occurs in the second floor of the building; at 5.0 m, the second floor is submerged with water, and there is a possibility that the third floor might also be flooded.

2. Disaster risk in Japan

Japan is a country that has periodically been subjected to large-scale natural disasters. Because of its natural conditions such as geographical position, topography, geology and climate, Japan is prone to seismic activities, typhoons, intensive rains, or volcanic eruptions, frequently leading to disaster situations. Its climatic conditions, when combined with the country's rugged, steep mountainous topography, often characterizing island countries, can sometimes lead to serious damage from intensive rains caused by typhoons or seasonal rain fronts, floods, or landslides.

Checking the distribution of seismic centres and volcanoes with a map of plate locations on the globe will reveal that places prone to seismic activities coincide with plate borders. Japan is located right on the border of an oceanic plate and a terrestrial plate. Furthermore, as it is surrounded by the sea, it is also vulnerable to tsunamis, which can also cause serious damage. In 2003 alone, Japan recorded 2,179 sensible earthquakes and eruption of four volcanoes [2]. In the future, it is also considered necessary to promote disaster-preventing measures from a national point of view, rather than to leave them to regional level efforts.

Out of all the damage caused in Japan between 1955 and 2004 by natural disasters, 2% were due to flooding, 22% to wind action, and 76% to earthquakes [3]. Although Japan takes up only 0.25% of the earth's surface area, it accounts for a large percentage of the world's earthquakes and volcanoes. 18.5% of the earthquakes of magnitude 6 or more occurred in Japan (2004-2013), where 7.1% of active volcanoes (2014) are also concentrated [4].

Disasters cause death, economic and environmental damage, and severe setbacks for social development. Recent large-scale disasters, including the devastating earthquake and tsunami in Japan of March 2011, highlight the value of national preparedness for disaster. Figure 1 shows the number of deaths and missing persons caused by natural disasters (1945-2013). Figure 2 shows the number of deaths and missing persons by type of disaster (Past 20 years: 1994-2013).

The 2011 Great East Japan Earthquake (also known as the 2011 off the Pacific coast of Tohoku Earthquake, Figure 3) had a magnitude of 9.0 – the largest recorded in Japan since instrumental seismic observation began [5]. The massive tsunami it generated hit Japanese coastal areas and caused severe damage, with the number of deaths and missing people reaching 18,490 (Fire and Disaster Management Agency, Japan). The myriad problems that resulted from the 2011 earthquake disaster exemplified the limitations of

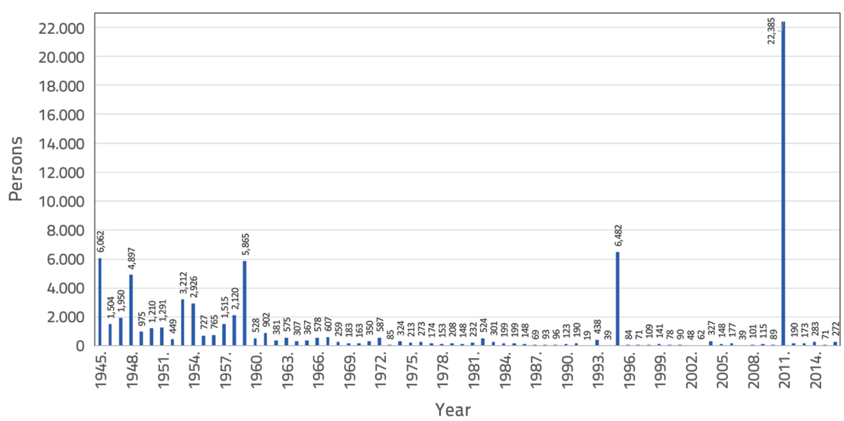

Figure 1. The number of deaths and missing persons caused by natural disasters (1945-2013) [Source: 1945: Rika nenpyo, 1946~52: Japan Weather Disaster Annual Table, 1953~62: National Police Agency, 1963~: Fire and Disaster Management Agency]

scientific understanding of the disaster itself, as well as the increasing vulnerabilities caused by current changes in Japan social structures, [6].

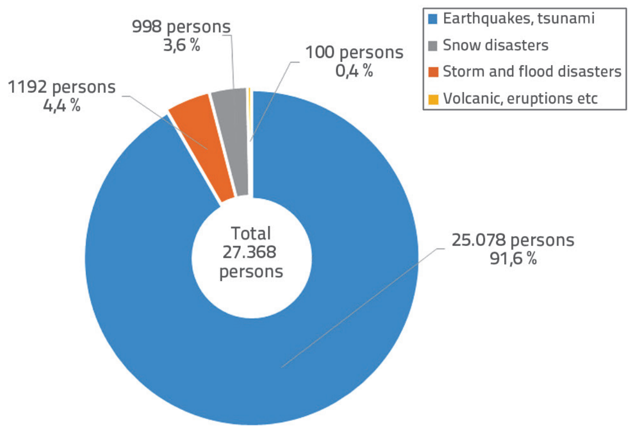

Figure 2. The number of deaths and missing persons by type of disaster (Past 20years:1994-2013) [Source: WhitePaper on Disaster Management, Japan, 2013]

Figure 3. The Great East Japan Earthquake (11 Mar. 2011) Source: The Daily Asahi Shinbun File Photo

Figure 4. Hiroshima landslide (20 August 2014), [6]

On August 20, 2014, a landslide disaster occurred as a result of heavy rains at more than 166 localities in the Asa-minami ward and Asa-kita ward of Hiroshima City, Japan (Figure 4). Serious damage caused by this heavy rainfall included 74 fatalities, 44 injured persons, 3,562 cases of material damage, etc., [7].
The Kinugawa River burst through a flood barrier, sending a tsunami-like wall of water into Joso, about 50 kilometres northeast of Tokyo on 10 September 2015 (AP report), figure 5.

Figure 5. Overflow of the Kinugawa River (10 September 2015) Source: *Jiji Press/AFP/Getty Images*

3. Emergency transport road

The Great Hanshin-Awaji earthquake, or Kobe earthquake, occurred on 17 January 1995 at 05:46 a.m. in the southern part of Hyōgo Prefecture, Japan. The earthquake was remarkable for exposing the vulnerability of the infrastructure. Authorities who had proclaimed the superior earthquake-resistance capabilities of Japanese construction were quickly proven wrong by the collapse of numerous allegedly earthquake-resistant buildings, rail lines, elevated highways, and port facilities, in the Kobe area. Road capacity drastically decreased due to collapse of elevated structures such as highways and railways, collapsed roadside buildings, collapse of road pavements, etc. Also, after the disaster, a large number of different traffic demand situations occurred in connection with evacuation activities, emergency rescue activities, relief activities, and restoration activities. However, since the main trunk road responsible for East-West traffic of the country was damaged, an emergency transport route was set up on the 18th day after the accident. Today, an emergency transport road system, positioned as shown in Table 1, is in operation.
Based on the lessons learned from the Great Hanshin–Awaji Earthquake, the emergency transport road network has been set up to provide a seamless emergency transport immediately after an earthquake on high-speed automobile national highways and general national highways, and on the trunk road that is designated by the governor for contact between the disaster prevention bases. The emergency transport road is categorized as the primary road for each prefecture.

Table 1. Classification of emergency transport roads and their position

Classification of emergency transport road	Position
Primary	High-standard trunk roads, wide-area main routes such as general national highways, and roads that form the framework of transport on access roads.
Secondary	Road connecting the primary emergency transport road, municipal government office and important disaster prevention bases.
Tertiary	Roads connecting the primary and secondary emergency transport roads, municipal office branches and other roads.

Table 2 Total length of each road type for transport in emergency situations

Type of road / Classification of roads	National highway & highway [km]	Prefectural road [km]	Municipal roads [km]	Total length [km]
Primary	45928,63	8077,59	1063,40	55069,62
Secondary	13368,92	22380,69	2428,48	38178,09
Teritary	799,69	3152,69	714,29	4666,67
Unspecified	93,58	23,11	-	116,69
Total	60190,82	33634,08	4206,17	98031,07

There is a little difference in the name and selection criteria, but basically a primary road covers a wide area of national highways, highways, and trunk roads.

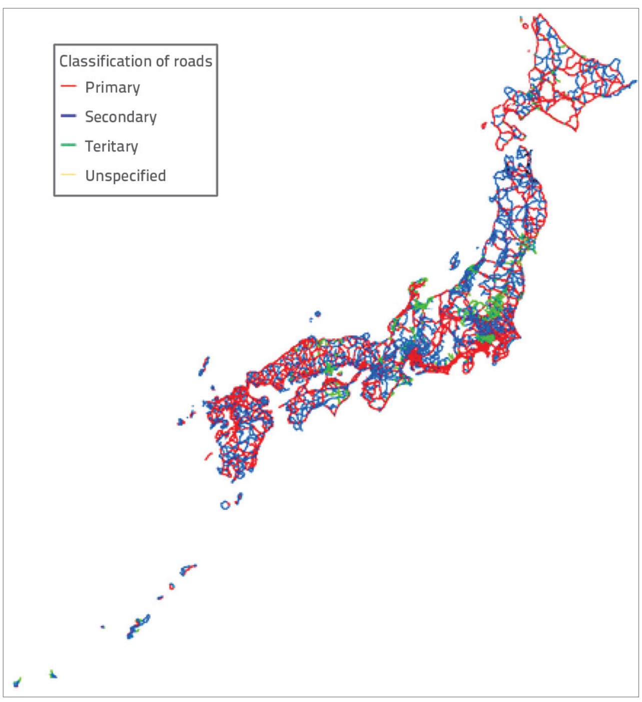

Figure 6. Road network diagram for transport in emergency situations

It is also shaped in such a way that secondary and tertiary roads can connect with the primary road and enable mutual communication with disaster prevention bases and government offices. Table 2 shows the total length of each specified type of road for transport in emergency situations, and Figure 6 shows the road network diagram for transport in emergency situations. The emergency transport roads cover a major part of national high-speed highways and general national highways, as well as the total extension for a high ratio. Therefore, it is believed that a sufficiently wide area has been secured via the emergency transport road network.

4. Method for analysis of disaster risk for emergency transport roads

4.1. Data sources for emergency transport road network

Emergency transport roads, as developed based on national numerical land information data, are considered in this study [8]. These data define: route shape, division of emergency transport roads, road classification, route names using local disaster prevention plans, and documentation on emergency transport road network as prepared by individual metropolises and districts.

4.2. Earthquake damage risk

We analysed the emergency transport road damage risk using the probabilistic seismic motion prediction map published by the J-SHIS Earthquake Hazard Station [9]. The predicted seismic motion shown in this map is calculated using a 250 square meter mesh unit. The earthquake risk on the emergency transport road is analysed by superimposing this mesh data and linear data of the emergency transport road using the GIS. The following ten predicted values can be obtained from the above-mentioned probabilistic seismic-motion prediction map. The earthquake risk of emergency transport roads is analysed for each of these ten predicted values.

- Probability of occurrence of earthquake motion with seismic intensity of 5 or less within the next 30 years.
- Probability of occurrence of earthquake motion with seismic intensity of more than 5 within the next 30 years.
- Probability of earthquake motion with seismic intensity of 6 or less within the next 30 years.
- Probability of occurrence of seismic ground motion with seismic intensity of more than 6 within the next 30 years.
- Measured seismic intensity expected to occur with a probability of 3% or more over the next 30 years.
- Measured seismic intensity expected to occur with a probability of 6% or more over the next 30 years.
- Measured seismic intensity expected to occur with a probability of 2% or more over the next 50 years.
- Measured seismic intensity expected to occur with a probability of 5% or more over the next 50 years.
- Measured seismic intensity expected to occur with a probability of 10% or more in the next 50 years.
- Measured seismic intensity expected to occur with a probability of 39% or more over the next 50 years.

4.3. Landslide disaster risk

The risk of damage due to sediment-related disasters is analysed from the viewpoint of how much sediment-related disaster risk zones are included in emergency transport. The national land numerical information is used for the analysis of areas in which sediment-related disasters occur [8]. The sediment-related disaster warning areas are classified into 4 groups according to the type of disaster: debris flow / steep slope collapse, landslide, avalanche. The risk of damage is analysed for each of these groups. Also, since different disaster occur in different areas, the regional distribution must also be taken into account in the analysis. Therefore, in this research, the analysis is conducted by prefecture unit as follows:

- linear data about emergency transport roads are combined in GIS with the data on areas in which sediment-related disasters occur, and the zones in which these data overlap are defined
- areas defined in step above are correlated with areas traversed by emergency transport roads.

4.4. Flooding disaster risk

The risk of damage caused by flooding as well as the risk of damage caused by sediment-related disasters is analysed in terms of how much flooded areas overlap with the areas traversed by emergency transport roads. Here, the National Land and Numeral Information is also used in the analysis of flood-prone areas [8]. Depending on the flooding depth, these areas are divided into four basic groups: areas in which the flooding depth is 0.5 m, areas in which the flooding depth is 1 m, areas in which the flooding depth is 2 m, and areas in which the flooding depth is 5 m. As emergency transport roads are mostly used by passenger cars, only the areas in which the flooding depth is equal to or greater than 1 m are taken into account in this research. The analysis is conducted by prefecture units as follows:

- Linear data on emergency transport roads are combined with the data on the flood-prone areas, and the zones in which such data overlap are defined.
- The areas defined in step 1) are correlated with the areas traversed by emergency transport roads.

5. Analysis and result of disaster risk for emergency transport roads

5.1. Earthquake disaster risk

The earthquake risk for emergency transport roads was defined by overlapping data on the assumed seismic intensity distribution with the emergency transport road data. Analysis results for ten values considered in the analysis are presented in figure 7: probability of seismic action of various intensities (less than 5, more than 5, less than 6, and more than 6) on emergency transport roads is presented in maps 1 - 4 using ten colours (probability values range from 0 to 1); seismic intensity on emergency transport roads that can be expected in the next thirty and fifty years is presented in maps 5 - 10 using six colours (from less than 4.5 to more than 6.5). There is a high probability that higher-intensity earthquakes will occur on the Pacific side of the area under study in the analysed period. A high earthquake risk also exists at the contact of tectonic plates Itoigawa-Shizuoka, as shown in map 3. In case of seismic action equal to or smaller than 6 the highest level of damage will occur in Kanto region, and a relatively high damage is also expected in Tokai and Tonankai regions.

5.2. Landslide disaster risk

The risk of damage to emergency transport roads due to landslide is defined in all main urban areas (metropolises) and districts on the basis of overlap of areas traversed by emergency transport roads with areas where landslides occur. The overlap ratio is defined as follows: (areas of overlap of road data and landslide data) / (areas in which emergency transport roads are situated). The risk is analysed for all disaster types: debris flow, steep slope collapse, and landslide. Furthermore, the aggregate result of the primary road alone is described in this paper. Figure 8 shows a graph that plots the overlap ratio for each disaster on the primary road.

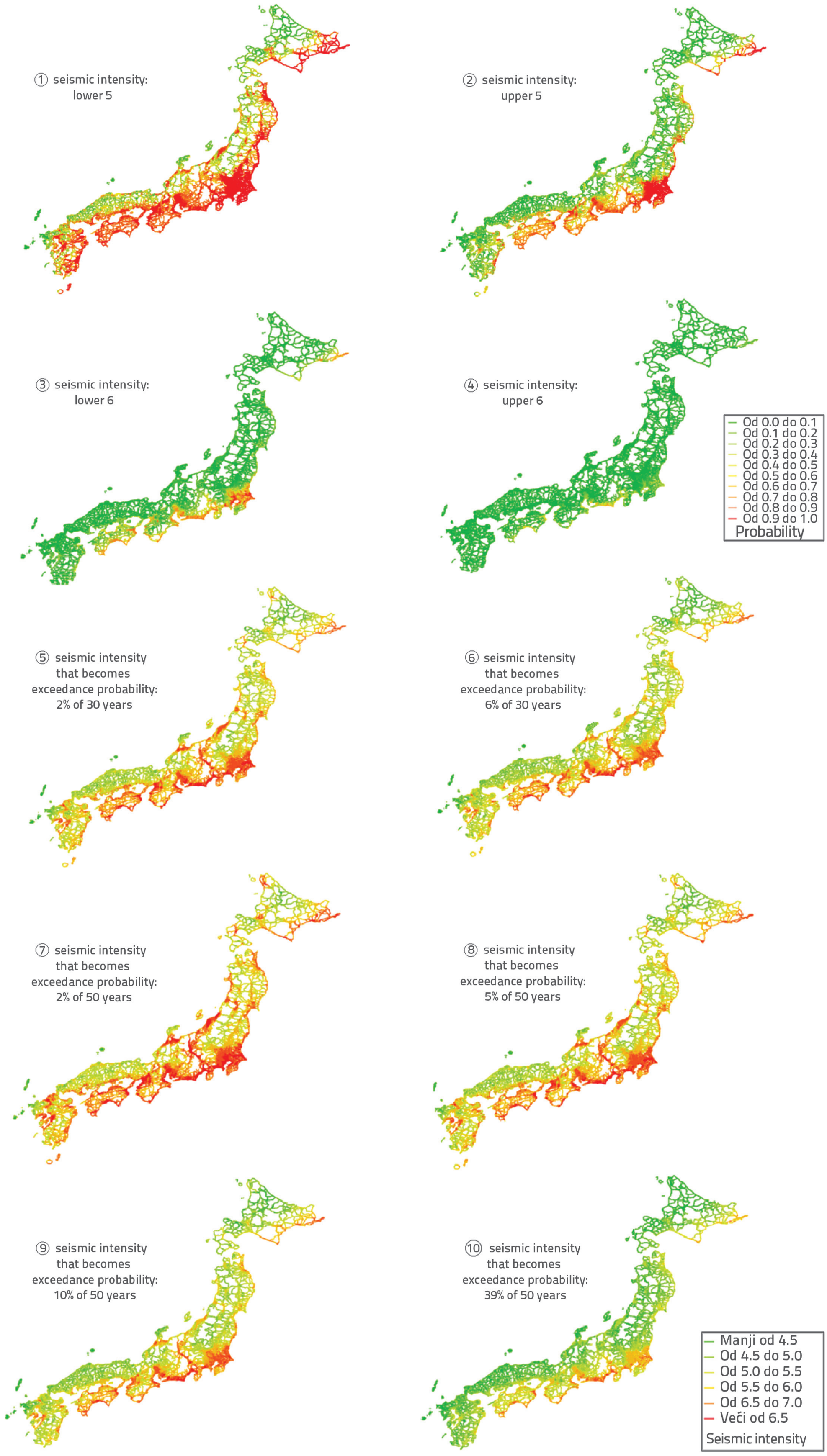

Figure 7. Emergency transport road disaster risk viewed with different predicted seismic intensities

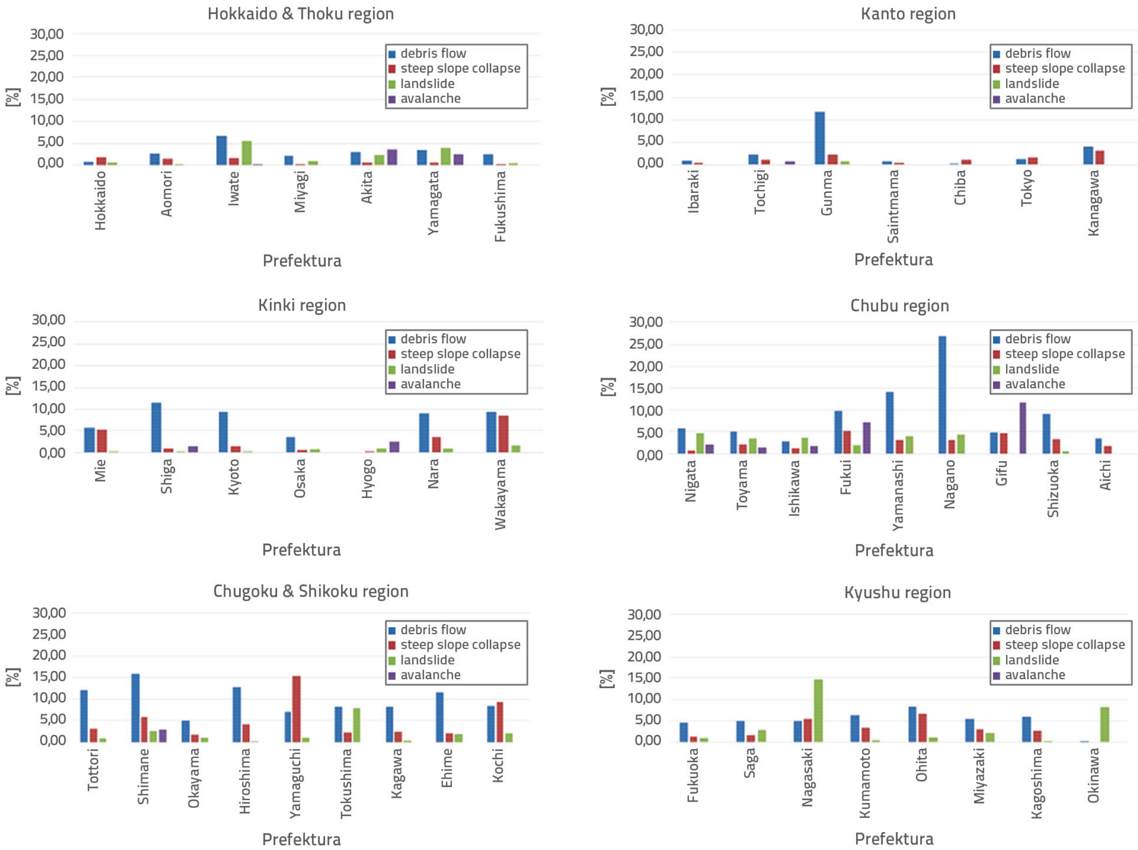

Figure 8. Overlap ratio of landslide disaster and emergency transport roads (primary roads)

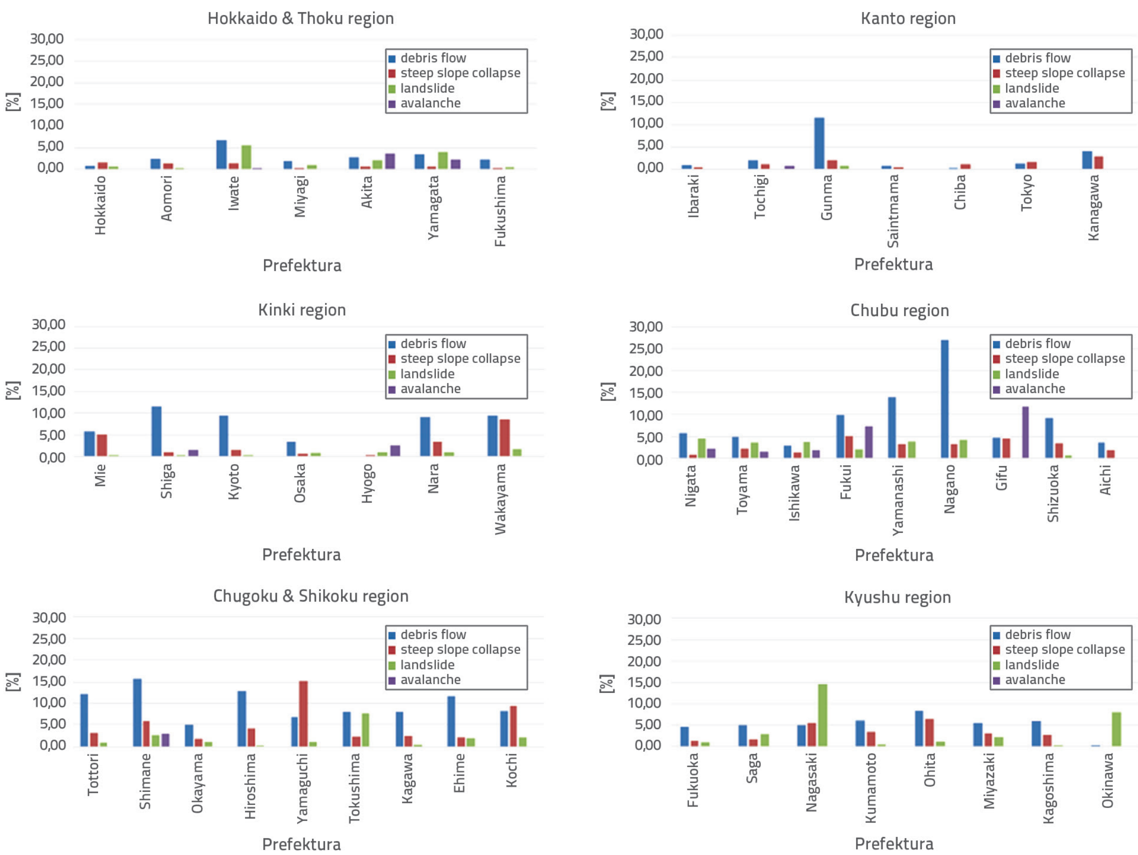

Figure 9. Overlap ratio of landslide disaster and emergency transport roads (secondary roads)

The following can be concluded based on results shown in Figure 8: overlap ratios are much greater in regions Chubu, Chugoku, and Shikoku compared to other regions; the highest risk of debris flow exists in Nagano prefecture; the highest risk of steep slope collapse exists in Yamaguchi prefecture; the highest risk of landslide exists in Tokushima prefecture; and the highest risk of avalanche exists in Gifu prefecture. The analysis of overlap ratio for each secondary road disaster can be seen in Figure 11.

The secondary road analysis does not show a large difference in values when compared to primary road results. While the risk of avalanche or landslide seems to have increased, the overall risk of each disaster has increased only slightly in most of the metropolitan cities and districts. This analysis focuses on a greater number of prefectural and municipal roads that are situated in mountainous ares, which is also the reason for greater percentage of disasters. Due to smaller pavement width and steeper slopes, landslides are quite frequent on mountainous roads.

Figure 10 shows a graph analysing the overlap ratio for each disaster on tertiary roads. Eighteen selected metropolitan cities and districts are analysed for the study of tertiary roads. Compared to primary and secondary roads, tertiary roads exhibit a higher disaster risk in various prefectures. This is due to avalanches in Gifu prefecture. Avalanches cause large-scale damage so that tertiary roads become impassable at many points. Avalanches are most frequent in areas devoid of vegetation where the slope gradient ranges between 35° and 45°. Tertiary roads passing through mountainous areas are for the most part situated on such terrain. The terrains with shrubs and trees are much more stable. Road damage and interruption of traffic on emergency transport roads in metropolitan cities and districts result in high disaster risk on tertiary roads.

5.3. Flood disaster risk

The risk of damage to emergency transport roads due to flooding is defined in all prefectures based on the ratio of overlap between areas traversed by emergency transport roads and flood-prone areas. The damage risk is analysed for the flood depths of 0,5 m, 1 m, 2 m and 5 m. The flood 0.5 m in depth is not considered a "submerged state" as the road can still be used by passenger cars. The overlap ration analysis is given in Figure 11.

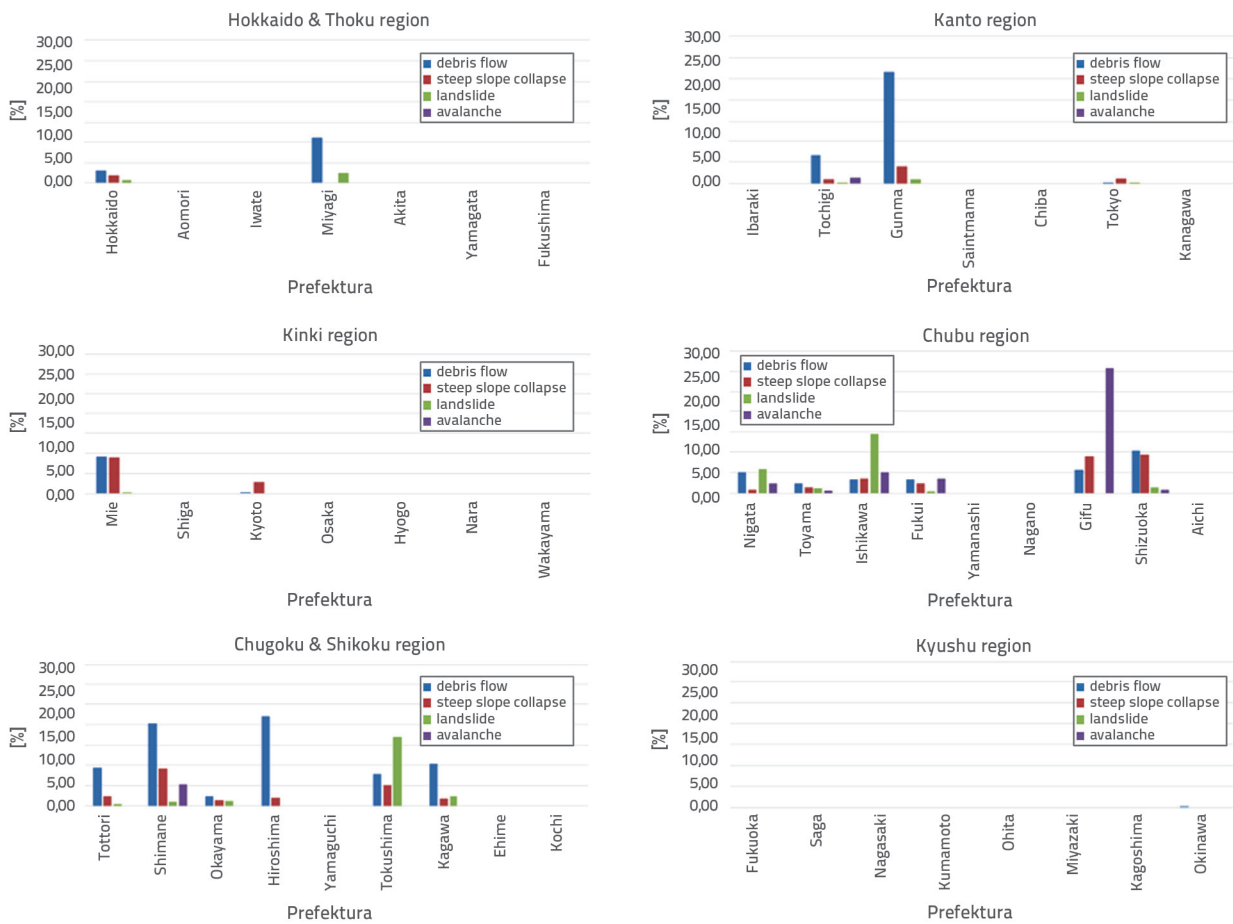

Figure 10. Overlap ratio of landslide disaster and emergency transport roads (tertiary roads)

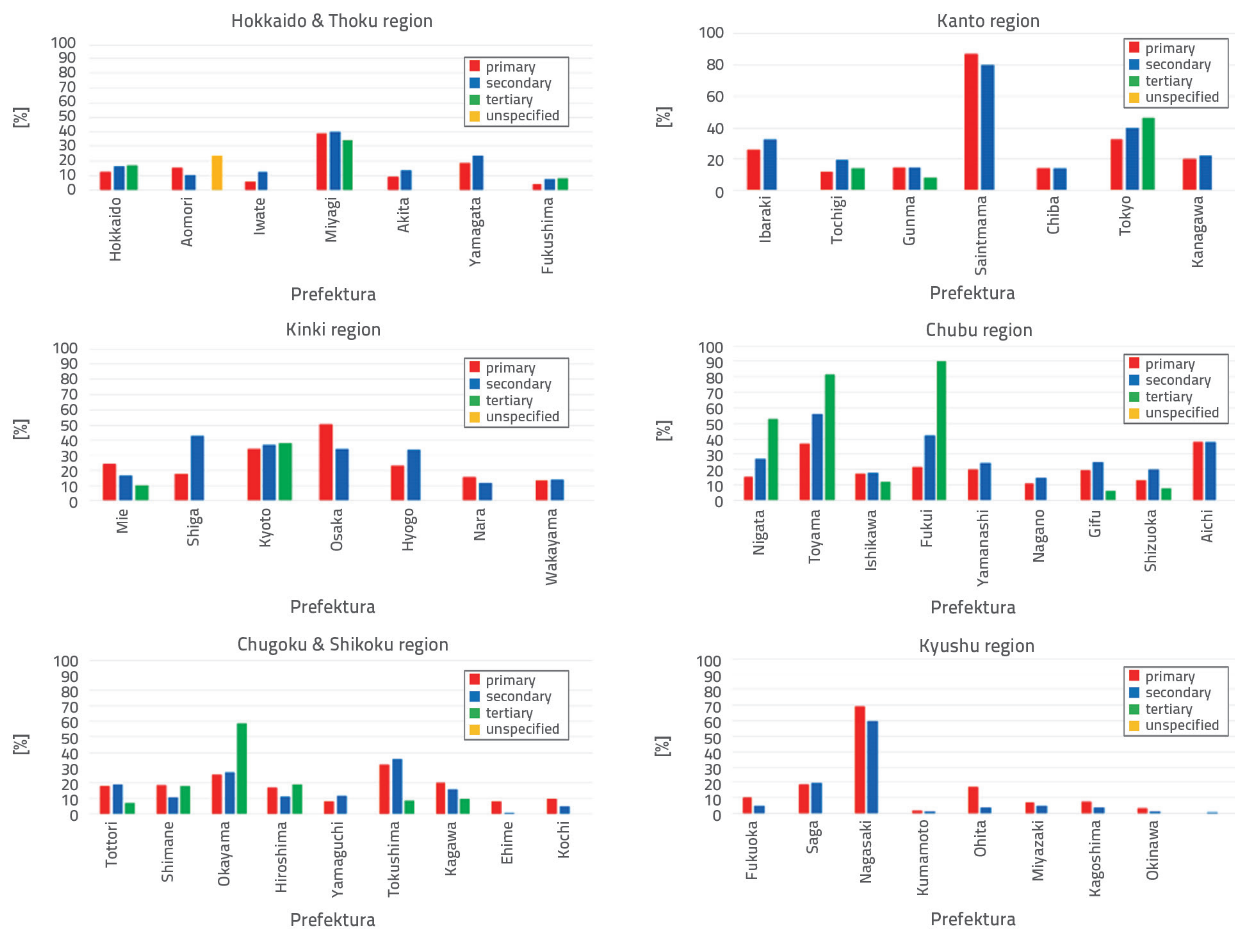

Figure 11. Overlap ratio of flood-prone areas and emergency transport roads

The following results have been obtained in the analysis: in case of primary and secondary roads the highest overlap ratio has been noted in Saitama prefecture; in case of tertiary roads, the highest overlap ratio has been observed in Nigata prefecture and in Hokuriku region of Toyama prefecture. In Saitama prefecture, roads are concentrated around the river, and Hokuriku region is affected by heavy rains throughout the year. Tertiary rads are found in Toyama and Nigata prefectures, and primary and secondary roads connect disaster prevention bases. The overlap ratio in the tertiary road network is high, which means that in the area with high concentration of such roads there is a great risk of damage to emergency transport roads and disaster prevention centres.

6. Conclusion

The risk of damage to emergency transport road network is estimated in this study based on three factors, i.e. earthquakes, landslides, and floods. It is stated in the paper that an emergency transport road is likely to be impassable to traffic at the time of a disaster. Regarding the earthquake, the study shows that a huge risk is present not only for the Pacific side of the area under study but also for the tectonic dislocation. The Itoigawa–Shizuoka tectonic line fault spreads toward the north-south road network. An overlap is frequently observed in hilly and mountainous areas because of frequent landslides. When considering a road in a mountainous region that becomes impassable to traffic because of a landslide, it does not suffice to consider only the road itself, but also its substitution characteristics. A difference regarding flood risk is observed between metropolitan cities and districts. Unlike landslides, floods affect great areas and the risk of road being closed to traffic is greater. In the light of the above, the authors conclude that the disaster risk to emergency transport roads is large even if individual hazards, such as earthquakes, landslides, and flooding, are considered.

Future research should focus of the importance of emergency transport roads, with a particular emphasis on alternative issues such as the extent to which the roads are affected by avalanches and typhoons, combined with various kinds of seasonal hazards. The final objective is to define probability of a hazard occurring in real life.

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