STUDY ON TSUNAMI EVACUATION MEASURE CONSIDERING RISKS ON EVACUATION NETWORK

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津波災害は，地震災害と複合的に発生する場合がある．そのような場合，想定していた避難路が地震によって不通となり，最悪の場合には津波が来襲する前に避難場所へ到達できない事態も想定される．このような事態を回避するためには，避難路として選択される可能性がある道路の地震による被災リスクを考慮した避難計画の策定が重要となる．ただし，市街地や住宅地の道路環境は極めて多様で，それら生活道路の地震災害時の導通性については，ほとんど把握されていないのが実情である．また，新たに情報を蓄積するためには多大な時間と労力を必要とする．本研究は，地震災害と複合的に発生する津波災害を前提に，既存の道路データと地理情報データを活用して道路被災リスクを評価し，それを用いて津波避難経路と避難場所を評価・検討する手法の開発を目的とした．

Key Words: *Tsunami disaster, Evacuation service area, road damage risk, network analysis, GIS.*

1. INTRODUCTION

Tsunami attacks are categorized as a catastrophic disaster. It brought quite many destructive impacts on our society, such as human casualties, injuries, and property damages. Some tsunami disasters happen simultaneously with earthquake disasters when hypocentral regions locate close to the coastal area. In that case, a situation on which residents unable to reach their evacuation places before tsunamis attack could be assumed due to the damages of evacuation network by earthquake disasters or others. In order to avoid such dangerous situation, an appropriate evacuation plan, which includes the risks of evacuation route potentially existing on the network, should be considered.

In the case of emergencies, residents may select an evacuation route which is used for their daily living. The conditions of evacuation route both in residential area and district area differ largely depending on the local network. Few local governments appropriately grasp a connectability of local network under the specific disasters, and the connectability of local network does not take into account in their disaster prevention plan.

This study proposes a method of evaluating a service area for the safety tsunami evacuation with considering some risks on evacuation network. In the evaluation of service area, both spatial and network analysis are used on GIS. Two research fields, Hosojima and Odotsu in Miyazaki Prefecture shown in **Fig.1**, are picked up for the case study of evaluating service area under some possible scenarios of network damage. Both fields have a possibility of suffering tsunami disaster with earthquake of Tonankai, Nankai, and Hyuganada[1)].

2. RISK ASSESSMENT ON EVACUATION NETWORK

(1) Factors of risk on evacuation network

It is important for residents to recognize their own safety evacuation route from their house to an evacuation place in the case of emergencies on a day-to-day basis. In addition, a local government has to preserve the safety evacuation route for their residents based on an appropriate planning of disaster prevention. An evaluation of the safety evacuation route includes a complex process, because there are many factors that relate to a connectability of the local network under the tsunami disaster with earthquake.

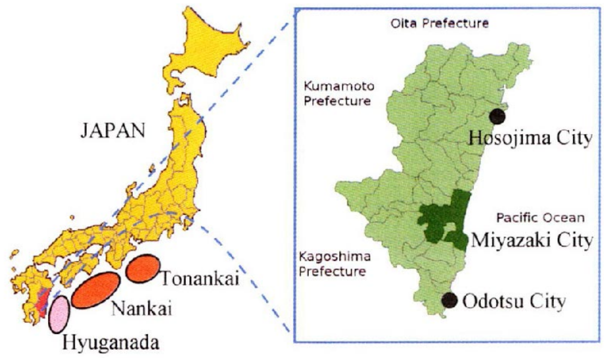

Fig.1. The location of Hosojima and Odotsu on the map with hypocentral region of concerned earthquakes for both districts.

In this study, five factors, inundation depth, road capacity, surface slope, distance from dangerous area, and soil condition, are considered as principal factors that relate to the connectability of the local network under the tsunami evacuation with earthquake. Most of the local governments have these data as administrative documents, and use those data practically for their disaster prevention plan.

(2) Risk value criteria

The values of the risk level on each pass are assigned from 0 to 10 depending on the risk criteria on each factor. The pass is defined as a minimum length of the road between its nodes. **Table 1** shows the risk criteria on each factor employed in this study.

The risk level gradually increases with the risks. For example, the passes in the inundation area more than 1 meter water depth are provided the maximum risk level, because the most of the people unable to walk in the flood more than 1 meter water depth[3]. This study utilizes the tsunami inundation map provided by Miyazaki Prefecture, and assigns the risk level for this factor. The fluid velocity in the flood area also becomes an important factor for the safety evacuation, however this study does not utilize the factor because of the availability of the data from an administration.

The road with smaller capacity has the higher risk not only in the evacuation by foot but also by cars. The residents tend to use their cars for their evacuation, because a car is one of the expensive belongings for them. The evacuation with car sometimes causes the traffic jam and the car accident, and those obstruct the connectability of evacuation network. From the field checks in this study, we assign the maximum risk level to the passes with less than 1 meter in width. On the other hand, we assign the minimum value to the passes with more than 10 meters width, where this capacity covers more than two-lane width.

The slope of the road also gives some influences on the safety evacuation[4]. The steep slope area generally requires more time to walk than that on a plain area. Especially, the slope sometimes makes difficulties to walk for aged person or handicapped people. Based on previous study[4], the risk revel for the load slope is provided as shown in **Table 1.** Also the distance from dangerous facilities that are specified by local government are also assigned to the risk level on the passes.

In case of tsunami attack with earthquake, the soil conditions on specific area become important. This study uses the information of soil conditions that are authorized in disaster prevention plan of local government. The liquefaction area, landfill area, soft ground area and landslide area are evaluated as a higher risk area, and assigned as maximum risk value.

Table 1 Risk factors, risk level criteria and values of risk level.

No	Criteria	Risk value										
		0	1	2	3	4	5	6	7	8	9	10
1	Inundation depth (meter)	0	0.01-0.11	0.12-0.22	0.23-0.33	0.34-0.44	0.45-0.55	0.56-0.66	0.67-0.77	0.78-0.88	0.89-0.99	≥1
2	Capacity (road width) (meter)	>10	9.1-10	8.1-9	7.1-8	6.1-7	5.1-6	4.1-5	3.1-4	2.1-3	1.1-2	≤1
3	Slope (degree)	0	0.01-2.5	2.51-5	5.01-7.5	7.51-10	10.1-12.5	12.51-15	15.01-17.5	17.51-20	20.01-25	>25
4	Dangerous area (distance from) (meter)	>100	-	100-75.1	-	-	75-50.1	-	-	50-25.1	-	0-25
5	Soil condition											
	a. Topography classification	natural dune, mountain	-	-	-	alluvium	-	River side	-	shore	-	landfill
	b. Sediment disasters risk area	none	-	-	-	-	-	-	-	-	-	all symbol
	c. Liquefaction risk area	not liquefaction	-	-	-	-	-	-	-	-	-	liquefaction
	d. Ground stiffness classification	A (mountain)	-	-	B (terrace)	-	-	C (plain area)	-	-	-	D (soft ground)

The averaged risk level on passes is obtained by overlaying raster data of five factors in **Table 1.** In raster overlay, each cell of each layer references the same geographic location. It is important to validate the selection of the risk factors, the configuration of the risk criteria and the evaluation of the risk level. However, few data can be available for confirming the validity of those matters. In this study, we only utilize the administrative data for analysis in order to propose the methodology of evaluating tsunami evacuation measure considering risks on evacuation network.

3. EVACUATION SERVICE AREA

(1) Service area generation

This study defines the service area as the minimum area where the residents can reach the nearest evacuation place from their house by foot within a clearance time. The clearance time is also defined as the minimum time until the approach of the first tsunami wave after the official warning of tsunami evacuation. The service areas are generated with using some network analysis tools on ArcGIS software.

(2) Settings for service area generation

This paper deals with two fields of Hosojima and Odotsu district in Miyazaki Prefecture shown in **Fig.1.** Both of the districts face the Pacific Ocean, and residential areas with many wooden houses are close to the shores. The earthquake that might bring the most destructive tsunami damages on both districts is supposed a simultaneous occurrence of Tonankai and Nankai earthquakes with M8.4[1]. This paper refers this earthquake as Tonankai-Nankai earthquake in latter discussions.

The local administration estimates the tsunami around 6 meters in height on both coasts, and also estimates the moderate seismic intensity. In case of Tonankai-Nankai earthquake, it is estimated that the first tsunami wave reaches the coast approximately 25 minutes after the earthquake[5]. The Japan Meteorological Agency officially announced that it takes around 3 minutes for issuing tsunami warning after the earthquake. After the tsunami warning from JMA, the local administration will transmit the evacuation warning through their transmission system such as wireless systems and local community networks. The transmission time from local authorities to the residents usually takes several minutes, and this study estimates 10 minutes for minimum transmission.

In the case of tsunami evacuation, the local authorities strongly recommend the evacuation by foot. The walking speed under the evacuation differs largely depending on an age, a physical strength, a state of health and a degree of handicap. However, it is difficult to take those differences into current investigation, an average velocity of normal walking speed on the plain surface, 4.2 km per hour[4] is employed in this study.

4. CASE STUDY ON HOSOJIMA DISTRICT

Fig.2 shows an inundation area of tsunami caused by Tonankai-Nankai earthquake on Hosojima district. The Hosojima district locates just behind the Hosojima port, and the residential areas with many wooden houses are close to this port. In this district, the local government officially provides 20 evacuation places that could be used to store refugee in the case of natural disasters. The evacuation places were arranged for the disasters by earthquake and flood at first. As shown in **Fig.2,** there are 7 of 20 evacuation places are located within the inundation area of tsunami by Tonankai-Nankai earthquake.

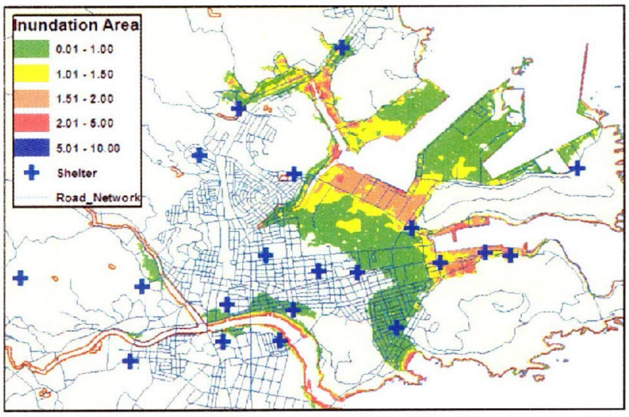

Fig.2 Inundation area and road network in Hosojima district.

(1) Risk of evacuation route in Hosojima district

Fig.3 shows an example of risk level assigned on the road network in Sone area in Hosojima district. The risk level in inundation area tends to show higher value than that in non-inundation area. However, some passes show higher values even in the non-inundation area, because the capacities of those roads are relatively smaller.

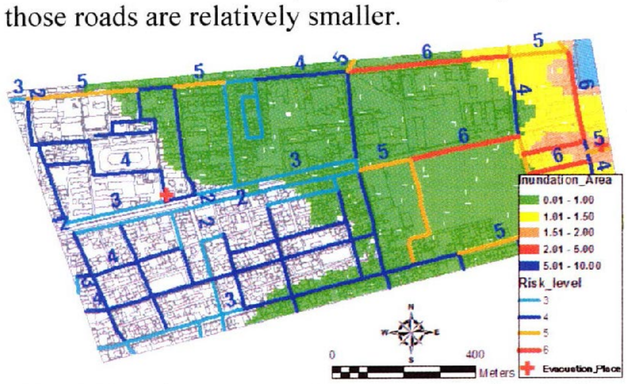

Fig.3 Risk levels on passes in Sone area in Hosojima district.

(2) Scenarios used in service area simulation

Many damaged conditions can be considered when the tsunami attacks the district after earthquake. In this study, six scenarios are considered as shown in **Table 2** with focusing the connectability of the local network under the tsunami disaster with earthquake.

Table 2 Scenario of network damage considered in Hosojima district.

Scenario	Evacuation Building Used (unit)	Blocking Road
Case-1	All (20 shelters)	Unblocking
Case-2	Shelters free from inundation (13 shelters)	Unblocking
Case-3		on bridge
Case-4		on road whose risk level higher than 8
Case-5		on road whose risk level higher than 7
Case-6		on road whose risk level higher than 6

Case-1 uses all evacuation places, and the evacuation passes are preserved even under the earthquake. In other cases, only evacuation places out of the inundation area can be used, and the network condition differs depending on the damages by earthquake. In Case-3, the brides are damaged by earthquake, and unavailable in the evacuation network. In Case-4, Case-5, and Case 6, on the other hand, the passes with risk level higher than 8, 7 and 6 are blocked in the network, respectively.

(3) Simulation result

Fig.4 shows the service areas on each scenario. The service areas are colored over the inundation areas with purple. The difference of service areas can be grasped spatially on the map. It can be seen that the number of the facilities available for the resident's evacuation strongly relates to the preservation of service area.

Fig.5 shows the percentages of the service area covered on the inundation area on each scenario. In Case-1, only 66% of inundation area can be covered even in the case of utilizing all shelters and evacuation passes. In Case-2, the service area decreases largely due to the unavailability of shelters within the inundation area. This means that the arrangement of evacuation places for tsunamis is very important for the expansion of service area in this district.

The service area decreases further in Case-3. There are some bridges crossing the channel to Hosojima port. The result says that the bridges are also an important infrastructure for the safety evacuation in this district. On the other hand, the service area in Case-4 and Case-5 are the same as in Case-2, it is because blocking on road whose risk level higher than 7 is located on out of service area in Case 2, so it does not influence the area of service area. The area becomes smaller in Case-6 when blocking road on road whose risk level higher than 6. Both the number of available shelters and connectability of bridges are more sensitive for preserving the service area than the difference of risk level used for blocking the evacuation route.

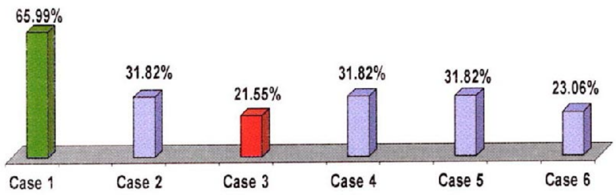

Fig.5 Percentage of service area covered on the inundation area in Hosojima district.

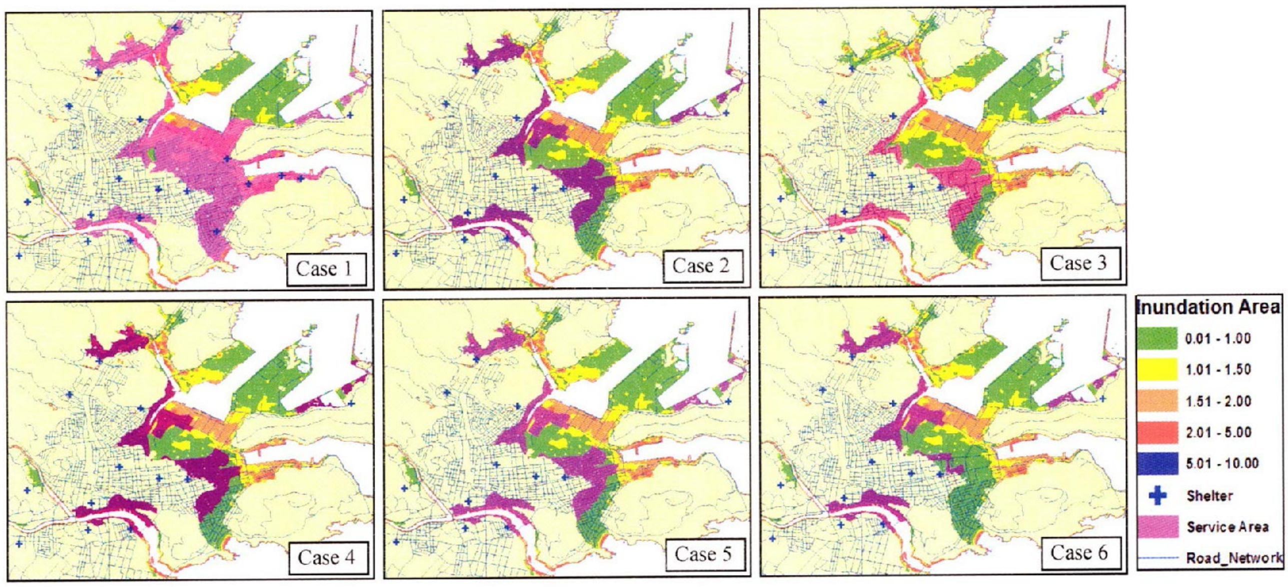

Fig.4 Map of service area on each scenario in Hosojima district.

5. CASE STUDY ON ODOTSU DISTRICT

Fig.6 shows an inundation area of tsunami caused by Tonankai-Nankai earthquake on Odotsu district. The Odotsu district locates between the Pacific Ocean and Hosoda River. The figure shows that mostly resident areas are inundated by tsunami attack. The government has provided 5 facilities that could be used for the tsunami evacuation. Two of five evacuation shelters (S-3 and S-4) are located in an inundation area.

The distribution of the risk level on the passes in this district is shown in **Fig.7.** A few buildings with more than third floor are in this district, and most of them are single-story or two-story wooden houses. Furthermore, many passes with less than a few meters width mostly form a local network.

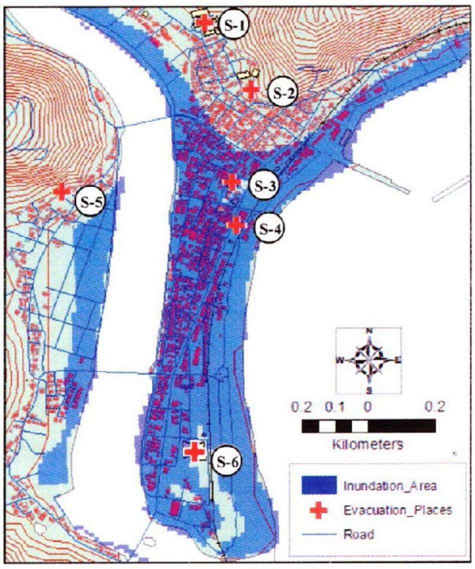

Fig.6 Inundation area and road network in Odotsu district.

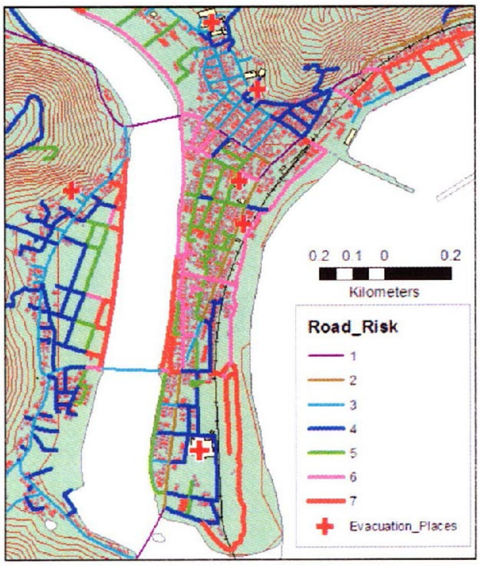

Fig.7 Evacuation road risk level in Odotsu district.

(1) Scenarios used in service area simulation

Table 3 shows the scenarios used in the simulation for Odotsu district. In Case-1 all of the facilities are available for the evacuation, and the evacuation passes are also preserved even under the earthquake. In other cases, evacuation places except S-3 are available, because S-3 is a single-story structure that locates in an inundation area. From Case-2 to Case-5, the network conditions are different depending on the damages by earthquake. In Case-6, an additional evacuation place (S-6) is virtually arranged to preserve the reduced service area. The building is a hospital that has a third floor, and its roof can be used for a temporal evacuation place. No other building can be found as additional evacuation place in this district because of the insufficient capacity to store the refugees.

Table 3 Scenarios of network damage considered in Odotsu district.

Scenario	Evacuation Building Used (unit)	Blocking Road
Case-1	All (5 shelters)	Unblocking
Case-2	4 shelters	Unblocking
Case-3	4 shelters	on bridge
Case-4	4 shelters	on road whose risk level higher than 7
Case-5	4 shelters	on road whose risk level higher than 6
Case-6	4 shelters and 1 proposed shelters in hospital	on road whose risk level higher than 6

(2) Simulation result

Fig.8 shows the service areas on each scenario. The service area is colored with orange over the inundation area. The service area in Case-5 becomes the smallest among the scenarios, and non-serviced area can be seen on both sides of the district that facing the Pacific Ocean and Hosoda River.

Fig.9 shows the percentages of the service area covered on the inundation area on each scenario. In Case-1, around 87% of inundation area can be covered in the case of utilizing all shelters and evacuation passes. The percentage of service area in Case-3 shows almost the same as in Case-1 and Case-2. This means that the damage of bridges in this district gives no influence on the service area.

On the other hand, the Case-5 shows the minimum percentage of service area, where the evacuation passes with risk level higher than 6 become unavailable condition. The local network in this district consists of the smaller capacity passes, and it increases the vulnerability to tsunami disaster.

Case-6 shows the expansion of the reduced service area in Case-5. An additional evacuation place increases only 11% of service area, and the expanded area can be seen only on the southern part of this district as shown in **Fig.8**. Furthermore, no improvement can be seen on both sides of the non-serviced areas, which are generated near the densely residential regions in Case-5. This means that an alternative evacuation facility has to be built newly near the middle of this district to preserve the service area in Case-5.

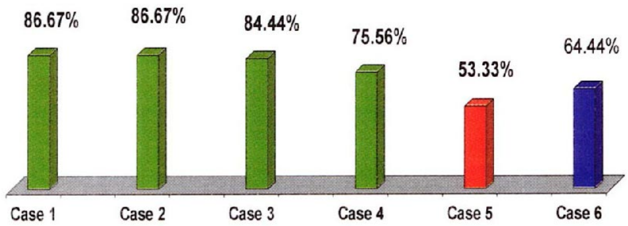

Fig.9 Percentage of service area covered on the inundation area in Odotsu district.

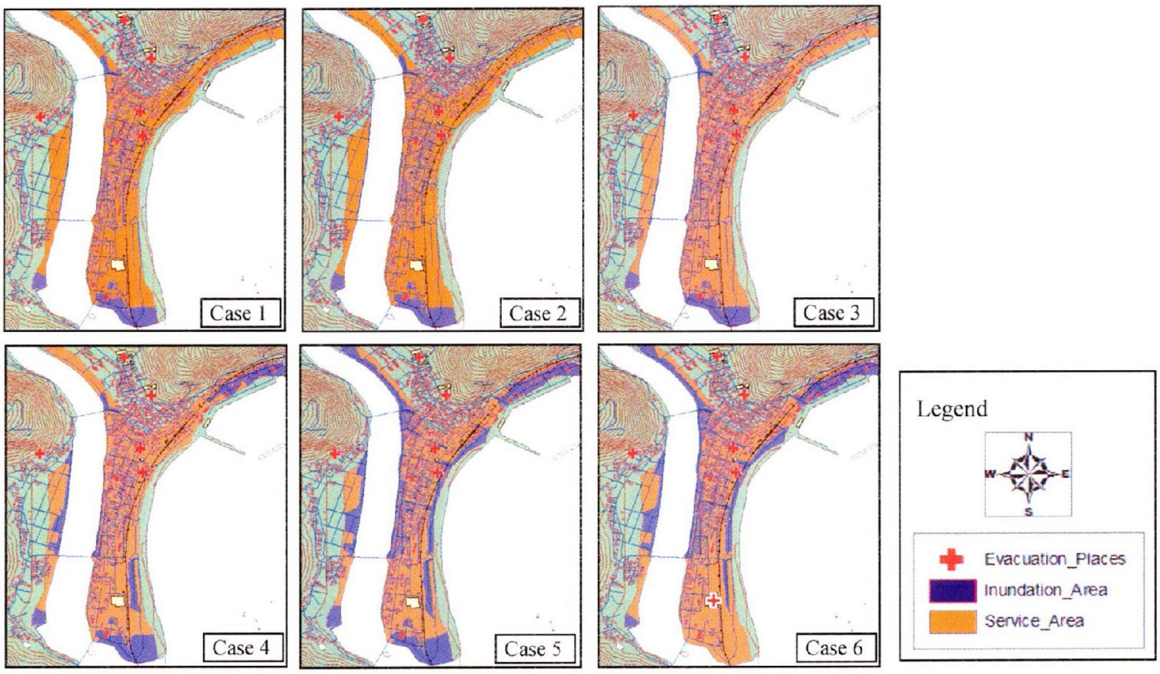

Fig.8 Map of service area on each scenario in Odotsu district.

6. CONCLUSIONS

This study proposed a method of evaluating service area for the safety tsunami evacuation with considering some risks on evacuation network. In the evaluation of risk level on local network, only information provided from local government were used in order to preserve the applicability of the method to a general disaster prevention plan.

The method was applied for two research fields, Hosojima and Odotsu in Miyazaki Prefecture. In case study in Hosojima district, it was cleared that the arrangement of evacuation places is very important to preserve and expand the service area. Furthermore, the connectability of the network including bridges is also an important factor in this district to preserve the service area.

On the other hand, the damage of bridges in Odotsu district gives no influence on the service area. In order to preserve and expand the service area in this district, an alternative evacuation facility has to be provided newly near the non-serviced area.

It is important to validate the selection of the risk factors, the configuration of the risk criteria and the evaluation of the risk level. Also, an appropriate evaluation of the weight on each risk factor has to be considered in the investigation of service area, though this study used a uniform weight. Above matters are going to be studied in further researches.

REFERENCES

1) Takahashi, S., Tsunami disasters and their prevention in Japan-toward the performance design of coastal defense, *International Symposium Disaster Reduction on Coasts*, Monash University, Melbourne, Australia, 2005.
2) Wei Xu.: Development of a methodology for participatory evacuation planning and management: Case study of Nagata, Kobe, Thesis, Kyoto University, 2007.
3) Tonegawa Research Group, Flood of Tonegawa, The history of watershed from generation to generation, Sankai-do, pp 109-116, 1995 (in Japanese).
4) Li, L. and Liu, X.: Simulating human walking on special terrain: up and down slopes, *Computer & Graphics*, Vol.24, pp 453-463, 2000.
5) Miyazaki Prefecture, Earthquake disaster mitigation plan in Miyazaki Prefecture, pp.30, 2007 (in Japanese).