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A STUDY OF TSUNAMI EVACUATION TO TALL BUILDINGS IN THE COASTAL AREA OF COLD REGION IN HOKKAIDO, JAPAN

T. Saito[1], Y. Miyamori[2] and S. Mikami[3]

[1] *Assistant Professor, Kitami Institute of Technology, saitota@mail.kitami-it.ac.jp*
[2] *Associate Professor, Kitami Institute of Technology, miyamoya@mail.kitami-it.ac.jp*
[3] *Professor, Kitami Institute of Technology, mikamisi@mail.kitami-it.ac.jp*

Abstract

A lot of governments in Japan updated the tsunami hazard map since the 2011 off the Pacific coast of Tohoku Earthquake. Kushiro City is located in the coastal area of cold region in the eastern Hokkaido, northern Japan. The city is predicted severe tsunami disaster. Kushiro City Government formulated a new tsunami evacuation plan in August 2013. The hazard map shows the area with flood depth and a lot of evacuation buildings specified by the government. However, there are other tall buildings in the flood area. Therefore, this study discusses evacuation planning from tsunami disasters at the low-lying area in Kushiro City by using existing tall buildings as temporary refuges. We performed on-site investigation by using geographical survey to find tall buildings available as temporary refuges. And we estimate the evacuation range of each tall building. We consider two types of the evacuation ranges calculated from such as walking speed and evacuation time, or capacity of buildings and density of population. We make a map of the coverage area of evacuation by using GIS analysis. The result shows that rates of the coverage area of evacuation are different to districts in the city. Serviceability of refuges is influenced by damage to buildings due to seismic ground motion. We estimate the damage to the buildings using a fragility function. In the worst case, the coverage area of evacuation decreases significantly because of the damage to tall buildings. In snowy and cold district in winter, the tsunami evacuation range decreases because of the decrease of walking speed and impossibility to stay outdoors. If it is possible that the early evacuation and more people take in temporary refuges, the evacuation range increases significantly. Therefore, we estimate the effects of escape time on the evacuation range. The result shows that it is difficult to evacuate by the early evacuation only in some districts. Therefore, temporary refuges need to be constructed in such district.

Keywords: tsunami evacuation; field survey; evacuation conditions

1. Introduction

A lot of governments in Japan updated the tsunami hazard map since the 2011 off the Pacific coast of Tohoku earthquake. Kushiro City is located in the coastal area of cold region in the eastern Hokkaido, northern Japan. The city has not experienced severe tsunami disasters since the recorded history of the 19th century [1]. However, "Ainu", an aborigine of Hokkaido, has been brought down past severe tsunami disasters by word of mouth [2]. In addition, geological evidences indicate them as well.

Hence, Hokkaido Government [3] announced new data and maps obtained by the tsunami simulation that is reconstructed on account of the geological evidences of the past huge tsunami disasters. According to the tsunami hazard, the city is predicted severe tsunami disaster.

Therefore, Kushiro City Government [4] formulated a new tsunami evacuation plan in August 2013. The hazard map shows the area with flood depth and a lot of evacuation buildings specified by the government. These evacuation buildings have been chosen by careful consideration for evacuation building such as area, seismic performance and storage of items. However, there are other tall buildings in the flood area as temporary refuges and if people can utilize such buildings, survivability may increase.

Therefore, this study discusses evacuation planning from tsunami disasters at the low-lying area in Kushiro City by using existing tall buildings as temporary refuges.

2. Field survey

2.1 The target site

Fig. 1 shows the location of Kushiro City. The fault model of the tsunami hazard [3] is also shown in the figure. The target site in this study consists of Otanoshike, Tottori, Aikoku, Tetsuhoku and Kyohoku district. This site is a coastal community facing the Pacific Ocean. The site stretches 12 km from east to west and 4 km from north to south. Natural high grounds lie east and west end of the site. Wide marsh spreads in north of the site.

According to the tsunami hazard [3], the tsunami warning time is 30 minutes. The maximum level of tsunami inundation is over 10 meters near the shoreline, also over 5 meters in the site. The number of evacuees estimates about 120 thousand [4]. Therefore, emergency response plans may need to include vertical evacuation refuge.

2.2 Evacuation refuges

We performed on-site investigation by using geographical survey to find tall buildings available as temporary refuges from 2012 to 2013 [1, 5, and 6]. We used a distance meter by laser beam to measure the height of

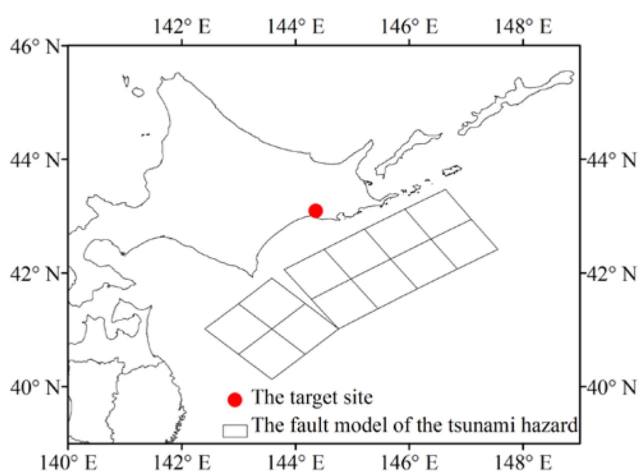

Fig. 1 - The location of Kushiro City

Table 1 - Number of evacuation buildings

	Otanoshike	Tottori	Aikoku	Tetsuhoku	Kyohoku	All
Evacuation buildings	24	96	135	217	245	717
Newer buildings	16	74	120	153	147	510
Older buildings	8	22	15	64	98	207
Percentage of older buildings	33 %	23 %	11 %	29 %	40 %	29 %

buildings and a digital camera with GPS. We made notes of the location, height, exterior, roof, outside stairs of buildings. And we made the database of GIS from the notes.

As the result of investigation, a total number of 717 buildings were chosen as evacuation refuges. The buildings specified by the government were included the list. The type of buildings was not considered. However the buildings did not include a wooden house such as a personal house.

2.3 Simple evaluation of seismic performance of evacuation refuges

In the specific case of earthquakes generating a near source tsunami, the evacuation refuges need to use after the seismic ground motion immediately prior to the tsunami. It should consider the seismic performance of the buildings chosen in this study. The Building Standard Law of Japan updated in 1981. Therefore, we compare the residential maps with 1978 [7] and 2011 [8] to evaluate simply the seismic performance.

If the building is found in the older map, it is judged the older building. In addition, we check the pictures taken during the on-site investigation and the website of Kushiro City Government and schools whether seismic performance is updated or not.

Table 1 lists the number of evacuation buildings. The result of evaluation of seismic performance of evacuation refuges also lists. 29 % of buildings evaluated older.

3. A range of refuge for tsunami evacuation

3.1 Definition of evacuation range

A range of refuge for tsunami evacuation shows a circle on a map. The center is the building, the radius is the travel distance of each buildings. The evacuation range depends on warning time, travel time, walking speed, capacity of buildings and density of population. Therefore, we consider two types of the evacuation ranges calculated from such as walking speed and evacuation time, or capacity of buildings and density of population [9 and 10].

At first, evacuation range based on walking speed is calculated by

$$L_1 = P_1 \times \left(T - t_1 - H/P_2\right)/1.5 \tag{1}$$

where L_1 is the evacuation range, P_1 is the walking speed, T is the warning time predicted the tsunami, t_1 is start time of evacuation, H is maximum depth of tsunami and P_2 is the elevation speed. Referring to [11], L_1 is divided by 1.5 to change straight distance to actual distance.

On the other hand, evacuation range based on capacity of buildings is calculated by

$$L_2 = \sqrt{\frac{C/D}{\pi}} \tag{2}$$

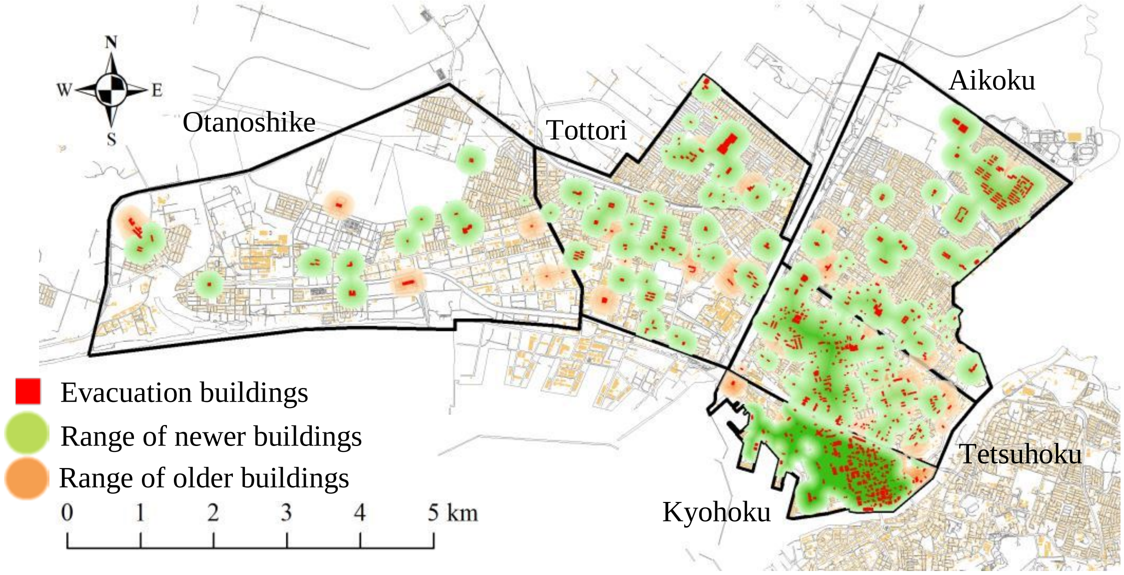

Fig. 2 - Tsunami evacuation range in the standard case

Table 2 - the rates of the coverage area in the standard case

	Otanoshike	Tottori	Aikoku	Tetsuhoku	Kyohoku	All
Population (persons)	17,556	30,176	38,735	21,589	5,413	113,469
Area (km^2)	15.9	8.7	8.8	4.4	2.6	40.5
Population density (persons / km^2)	1,104	3,470	4,392	4,904	2,042	2,802
Buildings	24	96	135	217	245	717
The rates in the standard case	14 %	47 %	43 %	78 %	85 %	39 %

where L_2 is the evacuation range, C is capacity of the building and D is the density of population. L_2 is different from each building due to the difference of the capacity. C is calculated by “the area of the buildings * the number of available floor / the square footage per occupant”.

The evacuation range in this study is defined by shorter of L_1 and L_2. We make a map of the coverage area of evacuation by using GIS analysis.

3.2 The evacuation range in the standard case

We set the parameters in Eqs. (1) and (2) in the standard case.

Referring to investigation of 2011 Tohoku earthquake [11], the walking speed P_1 is 0.62 m/sec and start time of evacuation t_1 is 22 minutes (1,320 sec). Referring to tsunami hazard assessment [4], the warning time predicted the tsunami T is 30 minutes. The maximum level of tsunami inundation H is found the GIS data of hazard map [3]. Referring to the guideline [9], the walking speed to go up a stair P_2 is 0.21 m/sec.

C is calculated by “the area of the building * the number of available floor / the square footage per occupant”. The area of the building gets the GIS data of the map of Kushiro City [12]. Referring to FEMA [13],

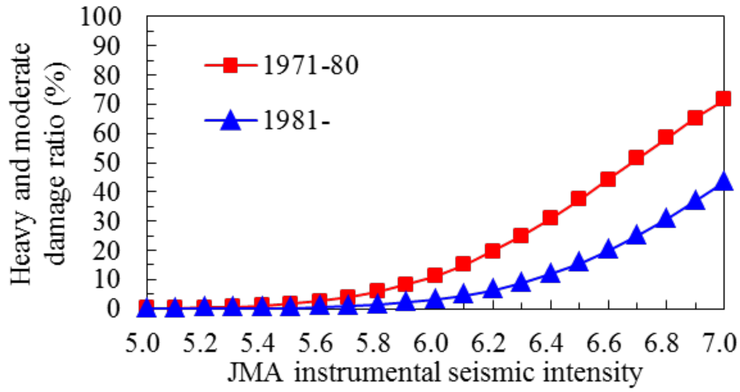

Fig. 3 - The fragility curves for non-wood-frame buildings

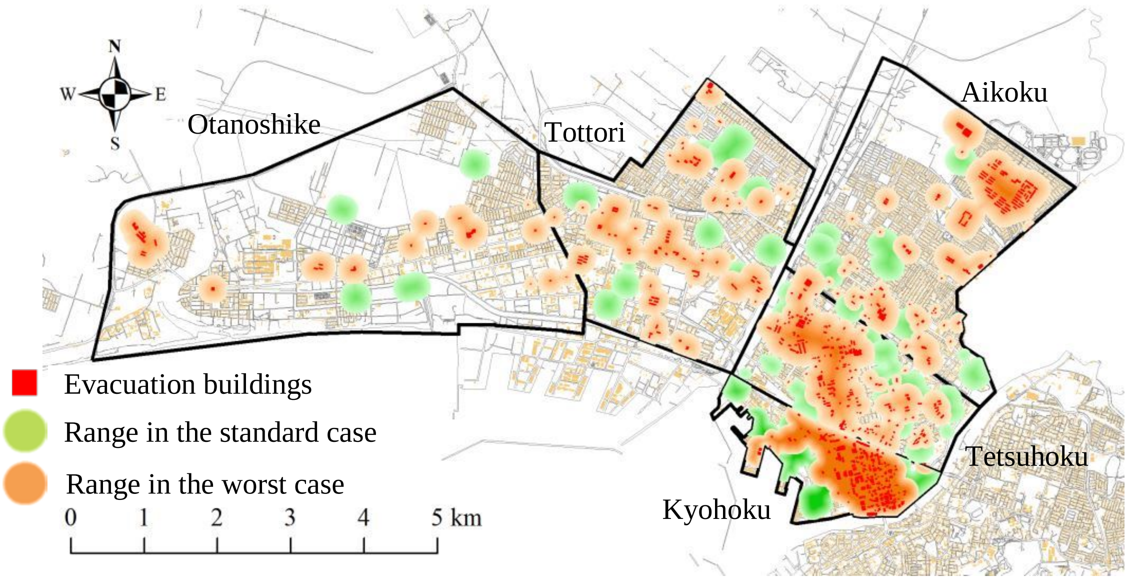

Fig. 4 - Tsunami evacuation range in the worst case

Table 3 - The rates of the coverage area in the worst case

	Otanoshike	Tottori	Aikoku	Tetsuhoku	Kyohoku	All
Buildings in the standard case	24	96	135	217	245	717
The rates in the standard case	14 %	47 %	43 %	78 %	85 %	39 %
Buildings in the worst case	20 (-4)	86 (-10)	124 (-11)	194 (-23)	215 (-30)	639 (-78)
The rates in the worst case	10 % (-4 %)	35 % (-12 %)	33 % (-10 %)	61 % (-17 %)	62 % (-23 %)	29 % (-10 %)

the square footage per occupant for a tsunami refuges is 3 square meter per person. The density of population *D* is calculated by the population [14] and the area of each district.

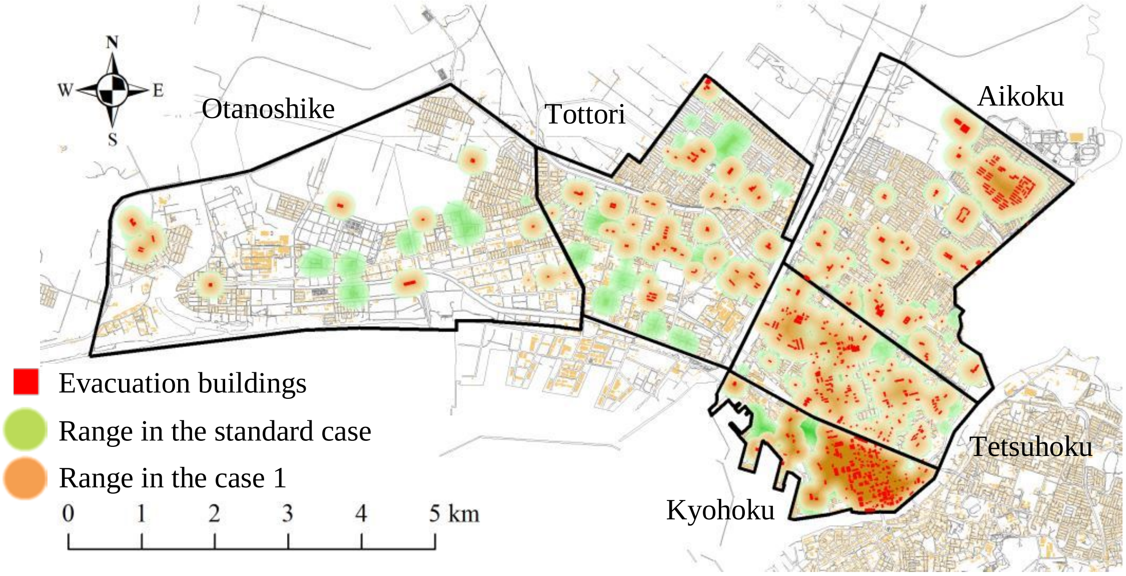

Fig. 5 - Tsunami evacuation range in the case 1

Table 4 - The rates of the coverage area in the case 1

	Otanoshike	Tottori	Aikoku	Tetsuhoku	Kyohoku	All
Buildings in the standard case	24	96	135	217	245	717
The rates in the standard case	14 %	47 %	43 %	78 %	85 %	39 %
Buildings in the case 1	13 (-11)	59 (-37)	113 (-22)	157 (-60)	193 (-52)	535 (-182)
The rates in the case 1	7 % (-7 %)	28 % (-19 %)	34 % (-9 %)	65 % (-13 %)	73 % (-12 %)	28 % (-11 %)

Fig. 2 shows tsunami evacuation range in the standard case, and Table 2 lists the rates of the coverage area of evacuation. A green circle is a range of a newer building, an orange also indicates an older building area, and a red point is an evacuation building. A black line is a border of districts. The rates of the coverage area of evacuation are calculated by "coverage area / area of the district".

In Fig. 2, the rate of the coverage area of evacuation about all districts is 39 %. However, the result shows that rates of the coverage area are different to districts in the city. The rates of the coverage area of central urban districts (such as Kyohoku and Tetsuhoku) are higher than the rates of suburb (such as Otanoshike).

4. Damage due to seismic ground motion

4.1 Seismic intensity in this study

In the specific case of earthquakes generating a near source tsunami, the evacuation refuges need to use after the seismic ground motion immediately prior to the tsunami. However, seismic hazard is not discussed in the tsunami hazard assessment. Hence, during the 2011 Tohoku earthquake, over 6.0 of JMA instrumental seismic intensity was observed by 20 sites of K-NET and KiK-net [15]. The average of these seismic intensity is 6.175. Therefore, seismic intensity in this study is assumed 6.2.

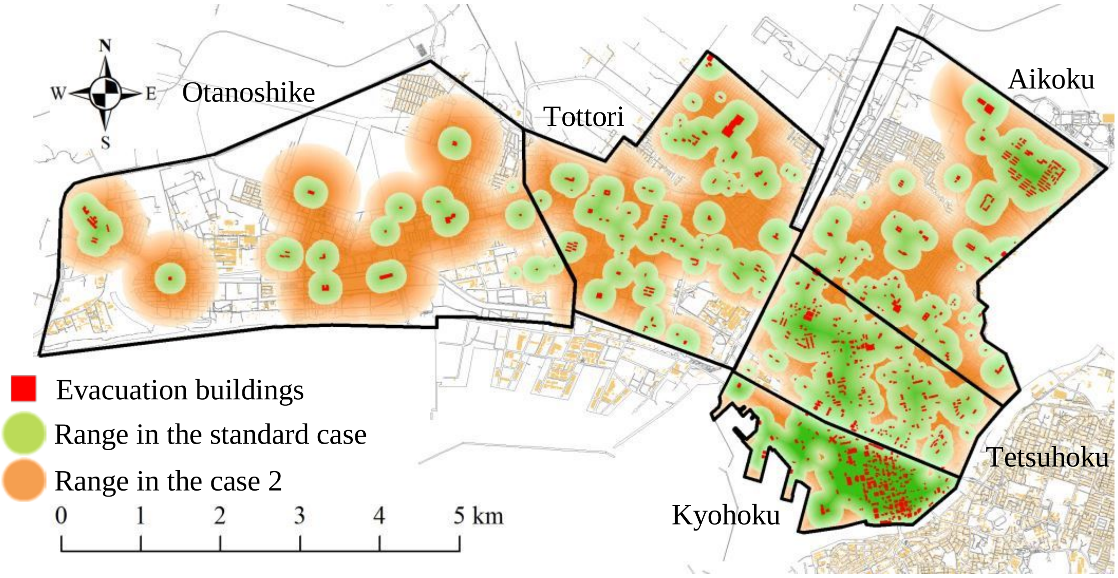

Fig. 6 - Tsunami evacuation range in the case 2

Table 5 - The rates of the coverage area in the case 2

	Otanoshike	Tottori	Aikoku	Tetsuhoku	Kyohoku	All
The rates in the standard case	14 %	47 %	43 %	78 %	85 %	39 %
The rates in the case 2	59 % (+45 %)	90 % (+43 %)	79 % (+36 %)	98 % (+20 %)	100 % (+15 %)	77 % (+38 %)

4.2 Fragility curves for buildings

Cabinet Office, Government of Japan [16] uses the fragility curves for buildings as shown in Fig. 3 about seismic hazard assessment.

In this study, the conditions of the fragility curves for buildings are as follows. The structural type is non-wood-frame buildings (such as RC and Steel buildings), damage level is heavy and moderate, and construction period is 1971-80 as older buildings and after 1981 as newer buildings.

4.3 The worst case: minimum ratio of coverage area

In the fragility curves, the damage ratio of newer buildings is 6.4 % and the ratio of older buildings is 19.6 %. We discuss the worst case which is the minimum ratio of coverage area.

Fig. 4 shows the evacuation range in the worst case. In Table 3, the number of buildings and the rates of coverage area are compared the standard case. The rates of the coverage area in this case are lower than the standard case. Large buildings and solitary buildings have a significant influence of evacuation range damaged by seismic ground motion. The result indicated that the seismic performance of these buildings is especially important for not only seismic safety but also tsunami evacuation.

5. The effects of evacuation conditions

5.1 Case 1: in snowy and cold district in winter

In snowy and cold district in winter, an evacuation route is covered with snow and a road surface might be frozen. Takeuchi [17] shows the walking speed of snow condition is decreased by 16.7 % to compare with dry

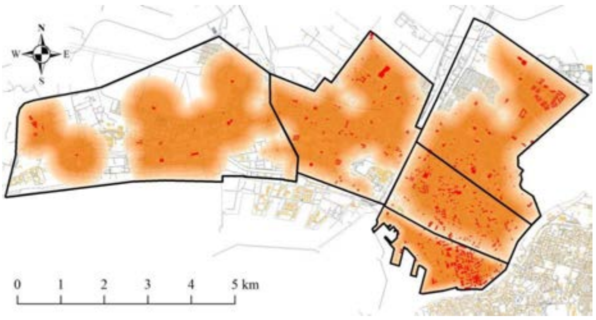

Fig. 7 - Start time of evacuation 0 min.

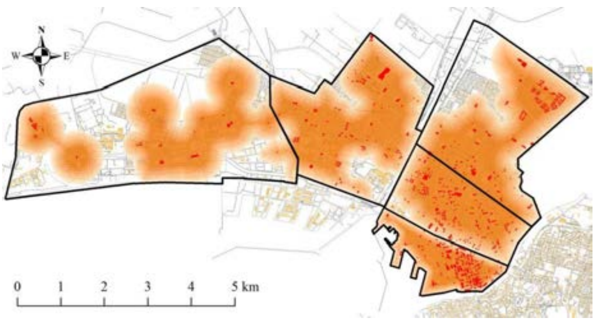

Fig. 8 - Start time of evacuation 5 min.

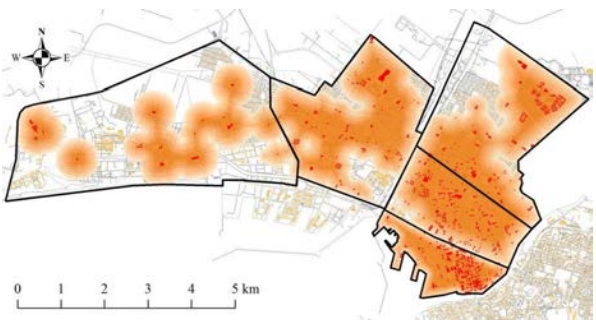

Fig. 9 - Start time of evacuation 10 min.

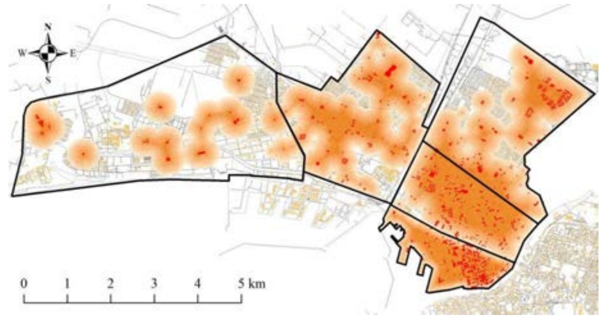

Fig. 10 - Start time of evacuation 15 min.

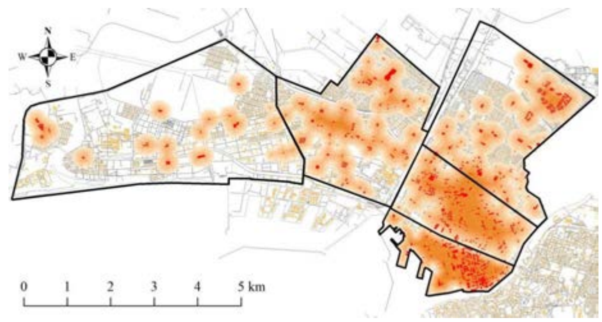

Fig. 11 - Start time of evacuation 20 min.

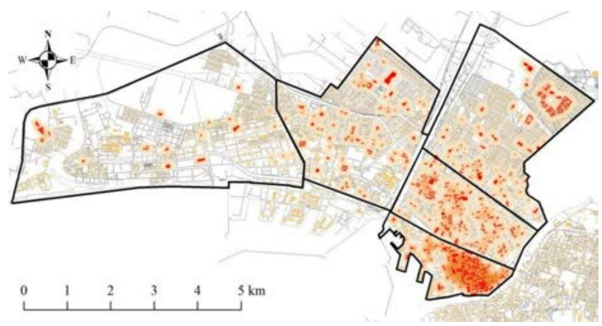

Fig. 12 - Start time of evacuation 25 min.

condition. In addition, it is difficult that people stay outdoors in an environment below the freezing point. Therefore, we set that the walking speed is 0.52 m/sec and evacuees cannot stay roofs of the buildings in this case. Other parameters are the same as the standard case.

Fig. 5 shows the evacuation range in the case 1. In Table 4, the number of buildings and the rates of coverage area are compared the standard case. If the evacuation floor of the building is only roof, the building cannot use for evacuation in this case. Therefore, a total number of 182 buildings cannot use. The rates of the coverage area in this case are lower than the standard case. Especially, the rate in Tottori is decreased by 19 %. This indicates that the particular measures may need to consider in snowy and cold district.

5.2 Case 2: early evacuation and minimum square footage per occupant

In the parameters in Eqs. (1) and (2), it is possible to improve the start time of evacuation t_1 and the square footage per occupant in the standard case. In the 1993 southwest off Hokkaido earthquake, the average of evacuation start time is 5.3 minutes (318 seconds) [18]. In addition, if all space in the building is available, the square footage per occupant can be 1 square meter per person. Therefore, we set that the start time of evacuation is 5.3 minutes and the square footage per occupant is 1 square meter per person in this case. Other parameters are the same as the standard case.

Table 6 - The effects of escape time on the evacuation range

Start time of evacuation	The rates of the coverage area					
	Otanoshike	Tottori	Aikoku	Tetsuhoku	Kyohoku	All
0 min.	71 %	92 %	82 %	98 %	100 %	83 %
5 min.	60 %	90 %	79 %	98 %	100 %	77 %
10 min.	49 %	87 %	77 %	98 %	100 %	72 %
15 min.	36 %	81 %	72 %	96 %	99 %	64 %
20 min.	21 %	66 %	59 %	92 %	92 %	51 %
25 min.	7 %	32 %	33 %	70 %	70 %	29 %

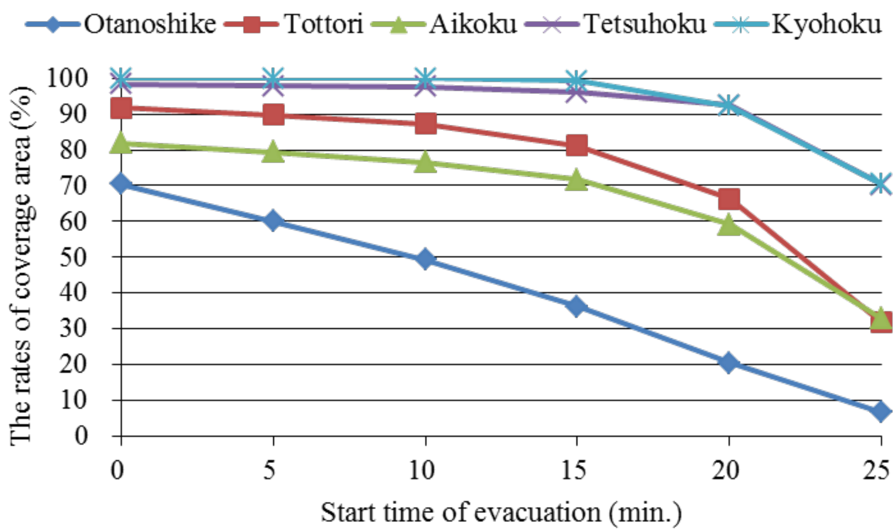

Fig. 13 - The effects of escape time on the evacuation range

Fig. 6 shows the evacuation range in the case 2. In Table 5, the rates of coverage area are compared the standard case. The evacuation range increases significantly. It is important to take measures which improve both L_1 and L_2.

6. The effects of escape time on the evacuation range

Survivability will increase for early evacuation discussed in the case 2. The early evacuation will be realized by continuing evacuation drill and it will be gradually improved. Therefore, we estimate the effects of escape time on the evacuation range. In this case, the start time of evacuation t_1 is set 0, 5, 10, 15, 20 and 25 min. The square footage per occupant is 1 square meter per person. Other parameters are the same as the standard case.

Figs. 7-12 show the evacuation range for each start time. Table 6 lists the rates of coverage area. In Fig. 7, it is difficult to evacuate by the early evacuation only in Otanoshike and Aikoku. Therefore, temporary refuges need to be constructed in such district.

Fig. 13 shows the change of the rates of the coverage area to the start time of evacuation. In Fig. 13, the rate in Otanoshike decreases linearly. In other districts, the rates begin to decrease when the start time of evacuation is 15 minutes. Therefore, it is important that the evacuation start until 15 minutes after earthquake happen.

7. Conclusions

This study discusses evacuation planning from tsunami disasters at the low-lying area in Kushiro City by using existing tall buildings as temporary refuges. We performed on-site investigation by using geographical survey to find tall buildings available as temporary refuges. And we estimate the evacuation range of each tall building.

We consider two types of the evacuation ranges calculated from such as walking speed and evacuation time, or capacity of buildings and density of population. We make a map of the coverage area of evacuation by using GIS analysis. The result shows that rates of the coverage area of evacuation are different to districts in the city.

Serviceability of refuges is influenced by damage to buildings due to seismic ground motion. We estimate the damage to the buildings using a fragility function. In the worst case, the coverage area of evacuation decreases significantly because of the damage to tall buildings.

In snowy and cold district in winter, the tsunami evacuation range decreases because of the decrease of walking speed and impossibility to stay outdoors. If it is possible that the early evacuation and more people take in temporary refuges, the evacuation range increases significantly. Therefore, we estimate the effects of escape time on the evacuation range. The result shows that it is difficult to evacuate by the early evacuation only in some districts. Therefore, temporary refuges need to be constructed in such district.

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