EVALUATION OF HUMAN DAMAGE IN EVACUATION FROM TSUNAMI FOR A COMMON SCENARIO EARTHQUAKE

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Abstract

Damage estimation and disaster prevention plan for Nankai megathrust earthquake which occurrence is assumed in the future have been carried out by cabinet office of Japan lesson from the huge human damage caused by the tsunami generated by The Great East Japan Earthquake in 2011.In damage estimation, buildings, infrastructure, and human damages for earthquakes and tsunami disasters is evaluated separately. Also, to evaluate the maximum case for each damage, several kinds of scenario earthquakes have been selected. Usually, buildings and infrastructure damage is large for a large earthquake On the other hand, human damage is significant for a tsunami occurred by a large earthquake which is different from the earthquake evaluated for the building damage. However, for coast areas on land and islands close to hypocentral region, damages of buildings and human may be the maximum for common scenario earthquake. To evaluate total damage in the area locating near epicenter, human damage and buildings damage for a common scenario earthquake become to be important.

For evaluation of human damage in evacuation from a tsunami, evacuation route is usually assumed to be had no damage from earthquake. Many studies and disaster preventions on the human damage in evacuation from tsunami have not considered hazards of evacuation route such as street-blockades caused by destroy of buildings and liquefaction of the ground. The street-blockades caused by destroy of buildings along the street can be expressed by using the fragility corves of buildings. When evacuation routes are changed by the street-blockades, configuration of the human damage in evacuation from a tsunami seems to be different in the damage without the street-blockades.

In this study, evaluations of human damage in evacuation from tsunami considering street-blockades is carried out for a common earthquake. The author’s proposed evaluation method of the human damage taking account of variances of tsunami run-up speed and walking speed is used in the evaluations. The evaluation method is also extended to evaluation method considering the effect of the street-blockades. The street-blockades is assumed to be occurred by destroy of buildings by large earthquakes. The human damage in the evacuation from tsunami and the street-blockades are evaluated by using area-wide mesh. The area-wide mesh is used to evaluate an overview of the human damage in the evacuation from tsunami under the street-blockades from a view point of macro-perspective. The walking speed and tsunami run-up speed are assumed to follow the normal distribution. The reliability evaluation method for structures is applied to the human damage in the evaluation of the human damage. A way of thinking of the decrement of the walking speed by the street-blockade is also shown. The street-blockades of evacuation routes is evaluated by using fragility curves of buildings for earthquakes. Using the proposal evaluation method, for an area close to hypocentral region, the difference in configuration of the human damage in evacuation from tsunami considered the effect of the street-blockades is shown. Moreover, the decrement effect of the human damage by evacuation awareness of people and new designation of tsunami evacuation facilities is discussed.

Keywords: tsunami evacuation, human damage, variance of walking speed, street-blockade, area-wide mesh

1. Introduction

To estimate the maximum damage for area, large natural disasters due to earthquakes and tsunamis are used to simulate damage prediction. Damages of buildings and infrastructure are usually large for a large earthquake. Human damage is significant for a tsunami. The tsunami occurred by a large earthquake is usually different from the earthquake used for evaluation of building damage. In coast areas close to hypocentral region, damages of buildings and human seem to be the maximum for a common scenario earthquake. To evaluate total damage in the area locating near epicenter, human and buildings damages for a common scenario earthquake become to be significant. For evaluation of human damage in evacuation from a tsunami, evacuation route has been usually assumed to be had no damage from earthquake.

Many studies and disaster preventions on the human damage in evacuation from tsunami have not considered hazards of evacuation route such as street-blockades caused by destroy of buildings and liquefaction of the ground. When evacuation routes are changed by the street-blockades, configuration of the human damage in evacuation from a tsunami seems to be different in the damage with no street-blockades. The authors [1, 2, 3] have proposed an evaluation method of the human damage taking account of variances of tsunami run-up and walking speeds. Moreover, the authors [4] have been extended the evaluation method to the method considering the street-blockades.

In this study, an evaluation method of human damage in evacuation from tsunami considering street-blockades is presented. The evaluation is carried out for a common scenario trench-type earthquake. The variances of tsunami run-up and walking speeds and the effect of the street-blockades are considered in the evaluation method of human damage. The street-blockades of evacuation routes is evaluated by using fragility curves of buildings for earthquakes. The human and buildings damages are evaluated by using area-wide mesh. The damages are evaluated for a real area close to hypocentral region. In the evaluation results, the difference in the human damage distribution by the street-blockades is shown. Moreover, the decrement effect of the human damage by evacuation awareness of people and new designation of tsunami evacuation facilities is discussed.

2. Evaluation method of human damage

2.1 Evaluation flow of human damage

The area-wide mesh is used to investigate of overall picture of the human damage including the effect of the street-blockades from a view point of macro-perspective. Population composition, height above sea level, tsunami inundation depth, and seismic intensity are set up for each mesh based on data of a real area. The population, the height above sea level and tsunami inundation depth is introduced of GIS (Geographic Information System) data.

Evacuation route from an evacuation mesh to an evacuation facility is defined as the route along the mesh. Evacuation distance including difference of elevation between mesh is assumed to be 1.5 times of length of plane distance. The human damage probability is evaluated by using relation between evacuation time and tsunami arriving time after earthquake occurrence. The human damage ratio can be obtained by tsunami fragility curve [5]. The street-blockade is evaluated by using the fragility of buildings for earthquakes [6]. Decrement of the walking speed is determined by effective sidewalk width. From the above, the evaluation flow on the human damage in the evacuation from tsunami can be shown in Fig.1.

2.2 Assumptions in evaluation

In this study, the following assumptions are used to the evaluation of human damage in the evacuation from tsunami:

1) The human damage is counted when a person is caught up with tsunami.

2) The human damage is only caused by the tsunami. The damage is not caused with the damage of the buildings.

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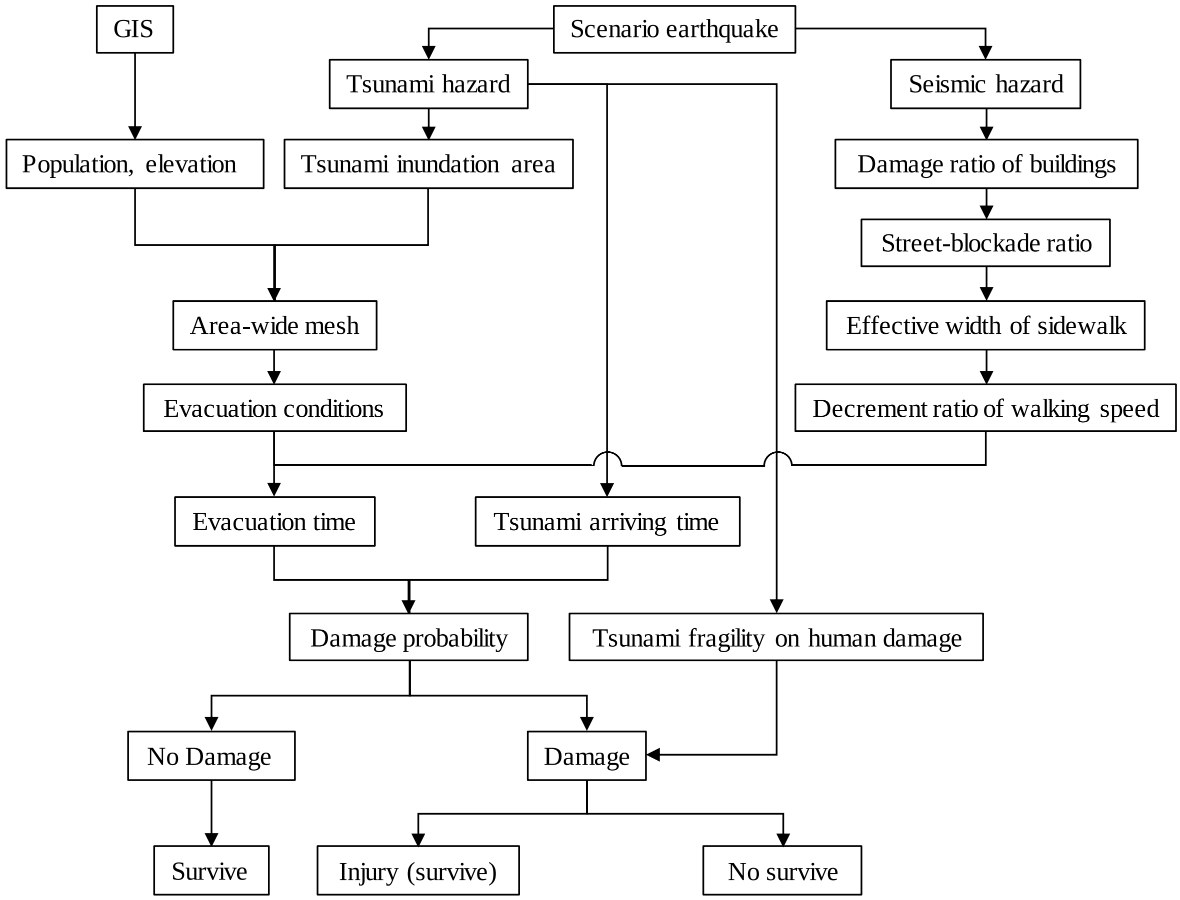

Fig.1 – Evaluation flow of human damage in evacuation from tsunami

3) The evacuation direction is not toward to coast.
4) The evacuation is only walk. On sidewalk is only permitted in evacuation because roadway is crowded by automobiles.
5) The evacuation area and the evacuation facility are designated for each evacuation mesh.
6) The evacuation areas are out of tsunami inundated area.
7) The facilities have no damage from earthquakes and tsunamis.

3. Evaluation method of human damage

3.1 Human Damage Probability

In this study, the reliability evaluation method for structures [7] is applied to the evaluation of the human damage. The human damage probability in this study is defined by a function of tsunami arriving time from earthquake occurrence and evacuation time. The tsunami arriving time and the evacuation time are assumed to follow the normal distribution. The tsunami arriving time is divided into the tsunami propagation time in the sea and the inundation time on land. The time of tsunami on land and the evacuation time can be evaluated from tsunami run-up speed and the evacuation time, respectively. For evaluation of the tsunami run-up time, the variation of the run-up speed is considered. For evaluation of evacuation time of evacuee, the variation of walking speed is considered.

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The evaluation method of the human damage probability in this study is shown in the following. Let the tsunami influence function is represented by using relation between the tsunami propagating and run-up time F_T and the evacuation time F_E is defined. The function can be represented by the following equation.

$$F_I = F_T - F_E \tag{1}$$

where, the evacuation time F_E is the normal random variable with mean value μ_E and standard deviation σ_E. The mean value μ_E is sum of the time t_I from earthquake occurrence to evacuation start and the time t_W from the evacuation start to completed. The mean value can be represented by the following equation.

$$\mu_E = t_I + t_W \tag{2}$$

where, the completed evacuation time t_W is the normal distribution with mean value μ_W and standard deviation σ_W. The completed time can be obtained by the relation between walking speed and moving distance.

The tsunami propagation and run-up time F_T is the normal random variable with mean value μ_T and standard deviation σ_T. The mean value μ_T can be obtained by the sum of tsunami propagation time t_S from earthquake occurrence and tsunami run-up time t_L from coast to an evacuation mesh. The mean value μ_T can be provided as the following equation.

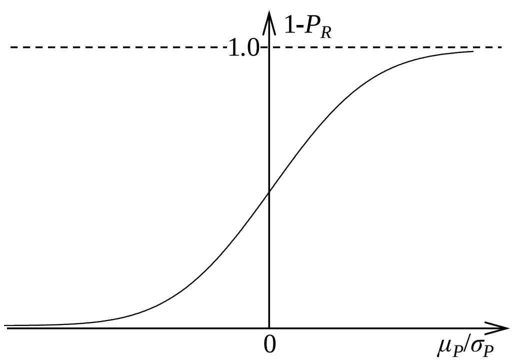
$$\mu_T = t_S + t_L \tag{3}$$

where, the tsunami run-up time t_L is the normal distribution with the mean value μ_L and the standard deviation σ_L. The mean value of the tsunami run-up speed is evaluated by using the equation of the fluid speed defined by the tsunami inundation depth [8]. In this study, average tsunami inundation depth from the coast mesh to the evacuation mesh is considered. The standard deviation of the run-up speed is used by the geometric standard deviation which indicates the adaptation between tsunami height marks on land and tsunami simulation results [9].

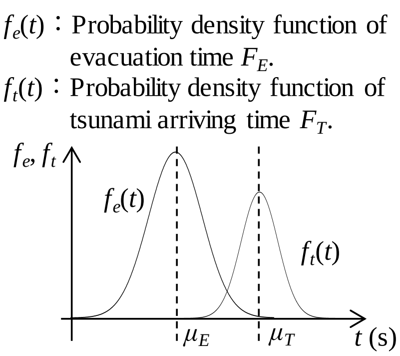
The probability of the human damage in the evacuation from tsunami can be provided the following equation.

$$P_R = 1 - \Phi\left(\frac{\mu_P}{\sigma_P}\right) \tag{4}$$

where, Φ is the standard normal distribution function with the mean value 0 and the standard deviation 1. The function Φ becomes survival probability of human. In addition, the survival probability can be obtained by $1 - P_R$. The survival probability curve, and the probability density functions of F_E and F_T are shown in Fig.2. μ_P and σ_P are provided by the following equations, respectively.



(a) Survaival probability curve



(b) probablity density curves of F_E and F_T

Fig.2 – Survival probability curve of human in evacuation from tsunami

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$$\mu_P = \mu_T - \mu_E \tag{5}$$

$$\sigma_P = \sqrt{{\sigma_T}^2 + {\sigma_E}^2} \tag{6}$$

3.2 Decrement ratio of walking speed by street-blockade

In this study, the street-blockade is assumed to be caused by completely destruction and partial destruction of buildings. The destroy ratio can be obtained by using fragility of buildings for wooden and non-wooden structures [6] shown in Fig.3. The partial destruction ratio is also obtained by a difference completely destruction number and partial destruction number of buildings. The street-blockade ratio is evaluated for each mesh by using the completely and partially destruction ratios. Effective sidewalk width W_{es} by the street-blockade of each mesh can be obtained from the following equation.

$$W_{es} = (1 - R_d) W_s \tag{7}$$

where, W_s is the sidewalk width in normal period and R_d is the street-blockade ratio represented by the following equation.

$$R_d = \begin{cases} 1.28 D_{rb} & (W_s < 3\text{m}) \\ 0.604 D_{rb} & (3\text{m} \le W_s < 5.5\text{m}) \\ 0.194 D_{rb} & (5.5\text{m} < W_s \le 13\text{m}) \end{cases} \tag{8}$$

where, D_{rb} is the destruction ratio represented by the following equation [10].

$$D_{rb} = D_c + D_p / 2 \tag{9}$$

where, D_c and D_p are the completely and the partially destruction ratio of buildings, respectively. In addition, the completely destruction number of buildings can be obtained by multiplying and the number of buildings. The partially destruction number of buildings can be also evaluated by difference between totally destruction number of buildings and the completely destruction number of buildings.

Decrement of the walking speed is assumed to be proportional to the effective width of the side walk. The decrement ratio of the walking speed may be expressed by using consideration of the decrement ratio of walking speed of crowded with people [11]. In this study, the sidewalk width is assumed to be proportional to the decrement ratio of the degree of crowded people per area. In evacuation, decrement of the walking speed is not considered for W_{es} more than 1.5m, the speed is linearly deteriorated with proportional to W_{es} within 0.5m to 1.5m and impassable for less than 0.5m. The decrement ratio R_w may be evaluated by the following equation.

$$R_w = \begin{cases} 1.0 & (1.5\text{m} < W_{es}) \\ 0.8 W_{es} - 0.2 & (0.5\text{m} \le W_{es} < 1.5\text{m}) \\ 0 & (W_{es} < 0.5\text{m}) \end{cases} \tag{10}$$

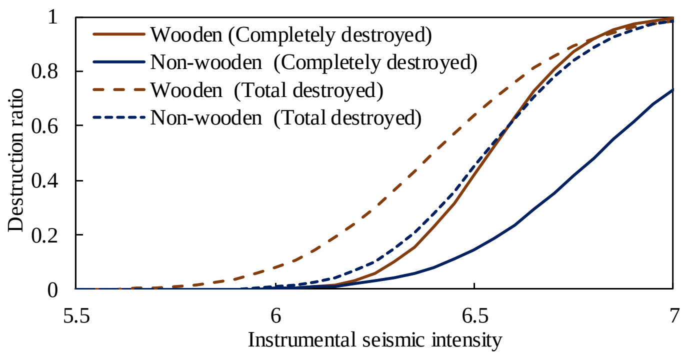

Fig.3 – Fragility curves of buildings for earthquake

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The walking speed in evacuation can be evaluated by multiplying R_w and the walking speed in normal period.

4. Evaluation of Human Damage

4.1 Evaluation conditions

The human damage in evacuation from a scenario earthquake-generated tsunami using the evaluation method is discussed under the following conditions:

1) No street-blockade

2) Street-blockade

3) Street-blockade and new designation of evacuation facilities.

4.1.1 Area-wide mesh and population

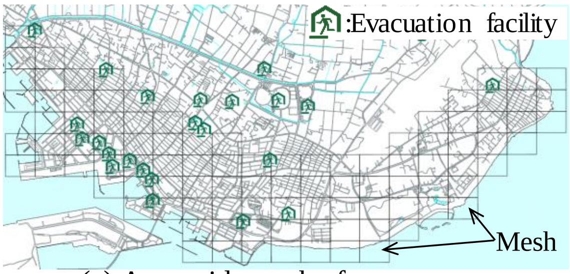
The area-wide mesh and population distribution of target area is shown in Fig.4(a), (b), respectively. The mesh size is 250m x 250m and the total population in the area is 26,250.

4.1.2 Tsunami inundation depth and seismic intensity

Tsunami inundation depth and seismic intensity used in this study are based on a scenario earthquake which is Yaeyama islands southern offshore earthquake with moment magnitude scale Mw 9.0. The maximum class of the damage in the target area is evaluated by the earthquake.

The tsunami inundation depth distribution is used the evaluation results on the damage estimation of the area. The inundation depth distribution is shown in Fig.4(c). The average inundation depth in the area is 9.46m. In addition, the maximum tsunami height is 22m and the arriving time of the first wave of the tsunami is 16 minutes on the damage estimation.

Seismic intensity of the area in the damage estimation for a scenario earthquake is 6- which indicates in the range of greater or equal 5.5 and less than 6.0 of measured seismic intensity defined by Japan Meteorological Agency. In the evaluation of the destruction of buildings, the upper value of the measured



(a) Area-wide mesh of target area

(b) Population

(c) Tsunami inundation depth

(d) Buildings

Fig.4 – Distributions of population , tsunami inundation depth and buildings in area-wide mesh

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Table 1 – Population ratio for evacuation awareness

Evacuation awareness	After earthquake	After work	Urgency evacuation	No evacuation
Strong	80%	10%	5%	5%
Middle	50%	25%	15%	10%
Weak	15%	35%	30%	20%

Table 2 – Start time of evacuation

Evacuation after an earthquake	Evacuation after finished work	Urgency evacuation
5 min.	15 min.	Tsunami arriving time

seismic intensity is used.

4.1.3 Buildings and streets

Total number of buildings in the target area is 8,087 (wooden structures: 813, non-wooden structures: 7,274). The number of buildings on each mesh was verified by counting visually. The distribution of the buildings is shown in Fig.4(d).

Street and sidewalk widths of the area were analyzed by using the real statistical data. In this study, the street width is used the average width calculated from area and total length of the streets. As the calculation result, the average street width is 7.3m. The sidewalk is located at both sides of the street in this study. The sidewalk width was calculated by the area and total length of the sidewalks. As the calculation result, the sidewalk width of one side is 1.2m.

4.1.4 Evacuation behavior

Population ratio for the evacuation behavior was divided into four type: evacuation immediately, evacuation after work, urgency evacuation and no evacuation. The division was set based on damage evaluation method [12]. The population ratio for evacuation awareness was set up by combining the following: strong awareness, middle awareness and weak awareness. The evacuation awareness ratios for the population are shown in Table 1. The start time of evacuation for several conditions are also shown in Table 2.

4.1.5 Walking speed

The mean value and standard deviation of walking speeds [13] used in this study are 1.34m/s and 0.167m/s, respectively. In addition, the mean value of the walking speed is only deteriorated by the effect of the street-blockade and the standard deviation of the walking speed is assumed to be not variable for the blockade.

4.2 Evaluation results

4.2.1 Evaluation results with no street-blockade

The human damage for several evacuation awareness under no street-blockade condition are shown in Fig.5. The large number of the damage is shown with deep color. The number of the damage with increasing of strong evacuation awareness becomes small.

The numbers of the human damage for several awareness are shown in Table 3. The human damage with the strong awareness decreased to 38% of the damage with the weak awareness. The evacuation awareness is large influence to decrease the human damage.

4.2.2 Evaluation results with street-blockade

The number of destruction distribution of buildings by the earthquake is shown in Fig.6. The number of damaged buildings is relatively small because of 90% of buildings are non-wooden type. In this study, the numbers of the completely destroyed and the partially destroyed buildings are 162 and 72, respectively.

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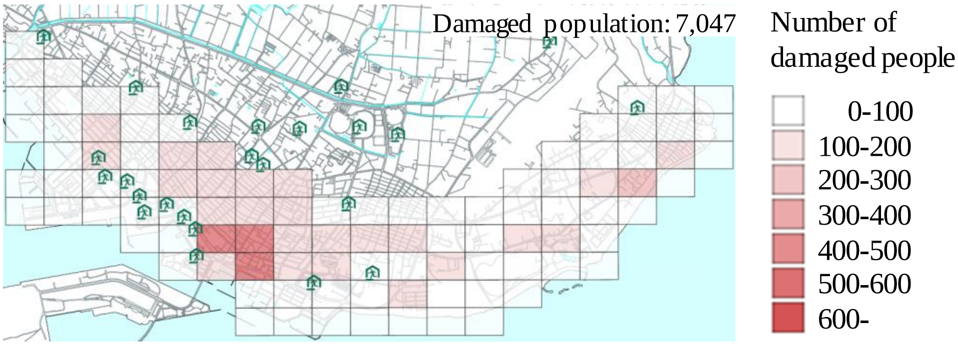
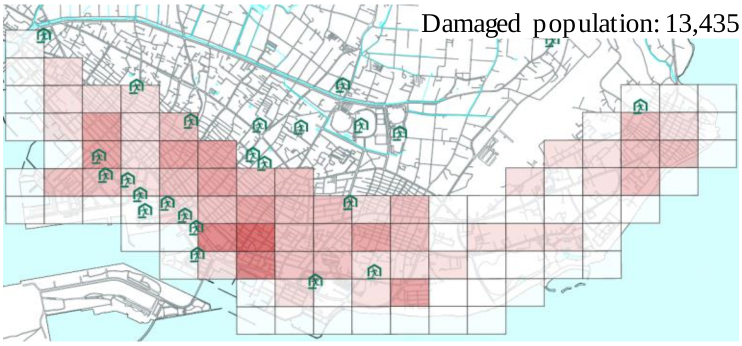
Table 3 – Evaluation result of human damage in evacuation from tsunami

Evacuation awareness	No blockade	Blockade	Blockade and N.D
Strong	7,047	10,611	5,911
Middle	13,435	15,672	12,734
Weak	20,908	21,593	20,712

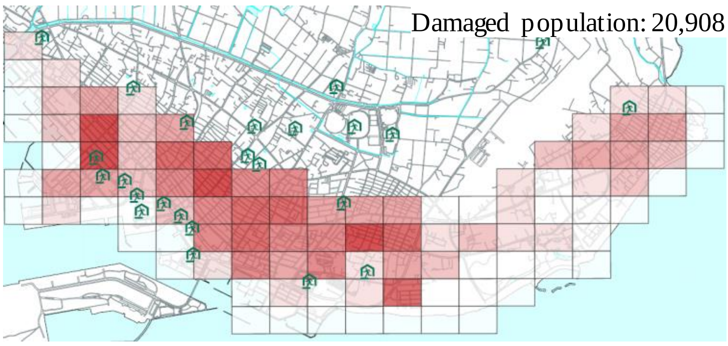
N.D: New designated of evacuation facilities



(a) Strong awareness



(b) Middle awareness



(c) Weak awareness

Fig.5 – Human damage distributions in evacuation from tsunami without street-blockades

The street-blockade ratio distribution is shown in Fig.7. The range of the ratio is 0.02 to 0.43. The blockade ratio becomes relatively small because the destruction number of buildings was small.

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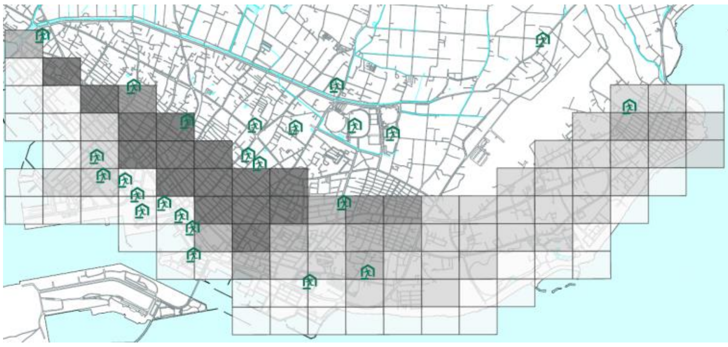

Fig.6 – Destruction distribution of buildings for earthquake

Fig.7 – Street-blockade ratio distribution by destruction of buildings

Fig.8 – Decrement ratio distibution of walking speed by street-blockade

The decrement ratio distribution of the walking speed by the blockade is shown in Fig.8. The range of the ratio is 0.51 to 0.75. The ratio is relatively large for the small ratio of the street-blockades because the width of sidewalk in this study is narrow.

The human damages for several evacuation awareness in the evacuation from tsunami under the street-blockade condition are shown in Fig.9. The numbers of the human damage for the blockades are shown in Table 3. The human damages under the blockade condition are increased to 1.51, 1.17 and 1.03 times for the strong, middle and weak awareness compared the results with the no street-blockades. The difference between the both results in no-blockade and blockade is significant. To consider the decrement of the walking speed by the blockades is important for the evaluation of human damage in the evacuation from tsunami.

4.2.3 Evaluation results with street-blockade and new designation of evacuation facilities

The human damage in evacuation from tsunami by new designation of tsunami evacuation facilities is discussed under the street-blockades condition. The new evacuation facilities are allocated on the mesh with

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Fig.9 – Human damage distributions in evacuation from tsunami with street-blockades

human damage more than 300 persons. The locations of the facilities are shown in Fig.10. The facilities are marked with circle in the figure. The number of the new facilities is 13.

The human damages for several evacuation awareness in the evacuation from tsunami under the street-blockades and the new designation of evacuation facilities are shown in Fig.10. The overall human damages become the minimum compared with the results for the other cases in this study. It can be seen that the shortening of the evacuation distance by the new designation of evacuation facilities leads to decrease the human damage.

The numbers of the human damage are shown in Table 3. The human damage is decreased to 0.84, 0.95 and 0.99 times for the strong, middle and weak awareness in the results of the no street-blockades, respectively. It is considered that the new designation of the evacuation facilities becomes one of the effective way to reduce the human damage.

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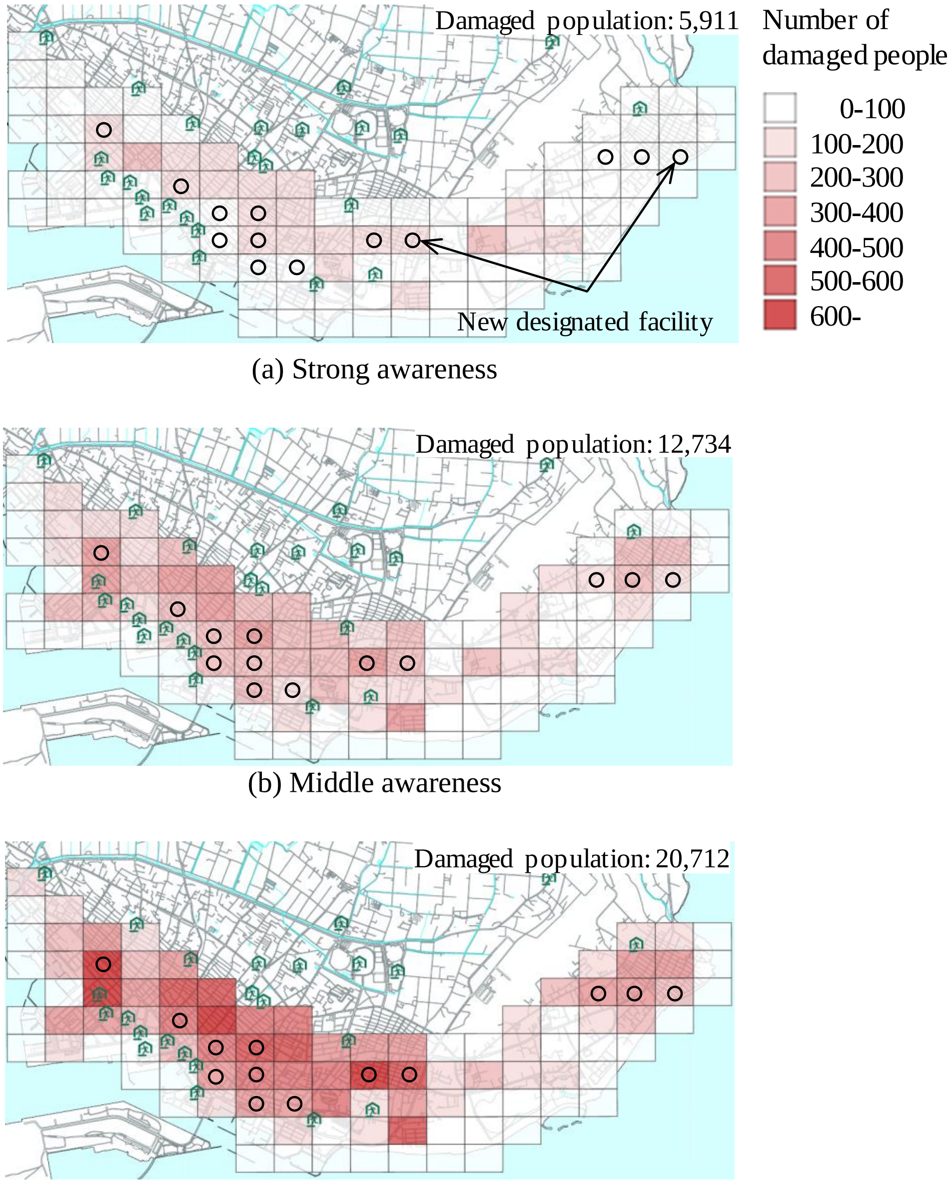

(a) Strong awareness
(b) Middle awareness
(c) Weak awareness

Fig.10 – Human damage distributions in evacuation from tsunami with street-blockades and new designation of evacuation facilities

From the above results, combination of the new designation of the evacuation facilities and increment of the evacuation awareness can be considered the one of the most effective way to decrease the human damage in evacuation from tsunami. However, the new designation of the evacuation facilities located in relatively high tsunami inundation depth and the evacuation method in the area where tsunami arriving in minutes, many problems are remained to be solved such as the evacuation to upward in evacuation facilities, water resistant of the facilities and the evacuation planning for vulnerable people.

5. Conclusions

An evaluation method of the human damage in the evacuation from a tsunami considering the effect of the street-blockades by destroy of buildings was shown in this study. Using the evaluation method, the human damage was discussed for a scenario earthquake. Also, the street-blockades occurred by destroy of buildings

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was evaluated by the common earthquake. Discussions were carried out to the following conditions: no street blockades, the street-blockades and the new designation of evacuation facilities with street-blockades. The following conclusions can be drawn.

1) The human damage under the street-blockade becomes large compared to that of the no street-blockade because of decrement of the walking speed.
2) To consider the effect of the street-blockade in evacuation planning is important.
3) The human damage in evacuation from tsunami can be decreased by enhancing evacuation awareness for evacuation and education on disaster prevention.
4) New designation of evacuation facilities is effective to decrease the human damage.
5) To decrease the human damage in evacuation from tsunami, combination of new designation of the evacuation facilities and increment of the evacuation awareness are effective.

To evaluate of human damage in evacuation from tsunami including vulnerable people is the future task.

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