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ORIGINAL ARTICLE

Evaluation of Human Damage in Tsunami Evacuation Considered Street-Blockades Caused by Destroy of Buildings

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***Abstract*:** Damage estimation and disaster prevention planning for a Nankai megathrust earthquake which occurrence is assumed in the future have been carried out by cabinet office of Japan learned from the huge human damage caused by the tsunami generated by The Great East Japan Earthquake in 2011. In damage estimation, human damage for earthquake and tsunami disasters have been usually evaluated separately. However, to evaluate total damage in whole area, unified treatment of the human damage by the both disasters seems to be significant. The human damage for a large earthquake is generally evaluated by using complete or partial destroy ratios of buildings. Street-blockades caused by destroy of buildings along the street have been usually investigated in pass ability of emergency vehicles for lifesaving and fire-fighting. In the human damage estimation for tsunami, the damage in evacuation from a tsunami has been considered. The effect of the street-blockades in evacuation from a tsunami has been considered in some studies. However, 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, an evaluation method of human damage in evacuation from a tsunami considering street-blockades caused by destroy of buildings is by a large earthquake is presented. The human damage and the street-blockade are evaluated by using area-wide mesh. The street-blockades of evacuation routes is evaluated by using fragility curves of buildings. The author’s proposed method which evaluates the human damage taking account of variances of tsunami run-up speed and walking speed is extended to evaluation method of the human damage including the effect of the street-blockades. Using the evaluation method, the difference in configuration of the human damage by the street-blockades caused by destroy of buildings is discussed.

Keywords: tsunami evacuation, human damage, street-blockade, human damage probability, area-wide mesh

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1. Introduction

In disaster prevention planning for large scaled natural disasters such as mega-class earthquake, tsunami and eruption, estimation of buildings and human damages is extremely important. Damage estimation for the natural disaster in cabinet office and local governments of Japan has been evaluated independently for each disaster (Cabinet office, 2012 and Kanagawa Prefecture, 2012). Using the damage estimation results, disaster prevention planning for both structural measures and non-structural measures has been projected.

The disaster prevention planning for tsunami are as follows: construction of tide embankment, relocation to higher ground of town, education on evacuation and so on. Evacuation planning from tsunami is especially important item for tsunami disaster prevention. Evaluation of human damage for tsunami is carried out for evacuation action to safety area. In evaluation of the human damage, difference between evacuation time and tsunami arriving time to evacuation facilities is usually used. In evaluating of the human damage in evacuation from tsunami, the effect of damage of buildings and street-blockades by earthquake before arriving tsunami has not been considered in many studies and damage estimation. In evacuation planning from tsunami, to consider street-blockade by destroy of buildings, fallen down of street walls and fire caused by large earthquakes seems to be important. In the disaster estimation for large earthquakes, the street-blockades caused by destroy of buildings along the street have been usually studied pass ability of emergency vehicles for lifesaving and fire-fighting (Cabinet office, 2013). When the street-blockades are caused a change of evacuation routes, configuration of the human damage in evacuation from a tsunami may be different from no street-blockades.

This study presents an evaluation method of human damage in evacuation from tsunami considering the street-blockades by destroy of buildings. Area-wide mesh is used to evaluate an overview of the human damage in tsunami evacuation under the street-blockades from a view point of macro-perspective. The author's method (Yashiro and Fujita, 2014 and Fujita and Yashiro, 2016 and 2017) for the human damage taking account of variances of tsunami run-up speed and walking speed is extended to the evaluation method including the effect of the street-blockades caused by destroy of buildings by a large earthquake. Using the proposed method, the difference in configuration of the human damage between no street-blockades and the street-blockades is discussed. Moreover, the reduction effect of the human damage by new construction and/or designation of evacuation facilities is studied.

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, seismic intensity, street-blockade ratio, and evacuation awareness are set up for each mesh based on a real area data. The population composition and the height above sea level of GIS (Geographic Information System) data are used to the area-wide mesh.

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 to

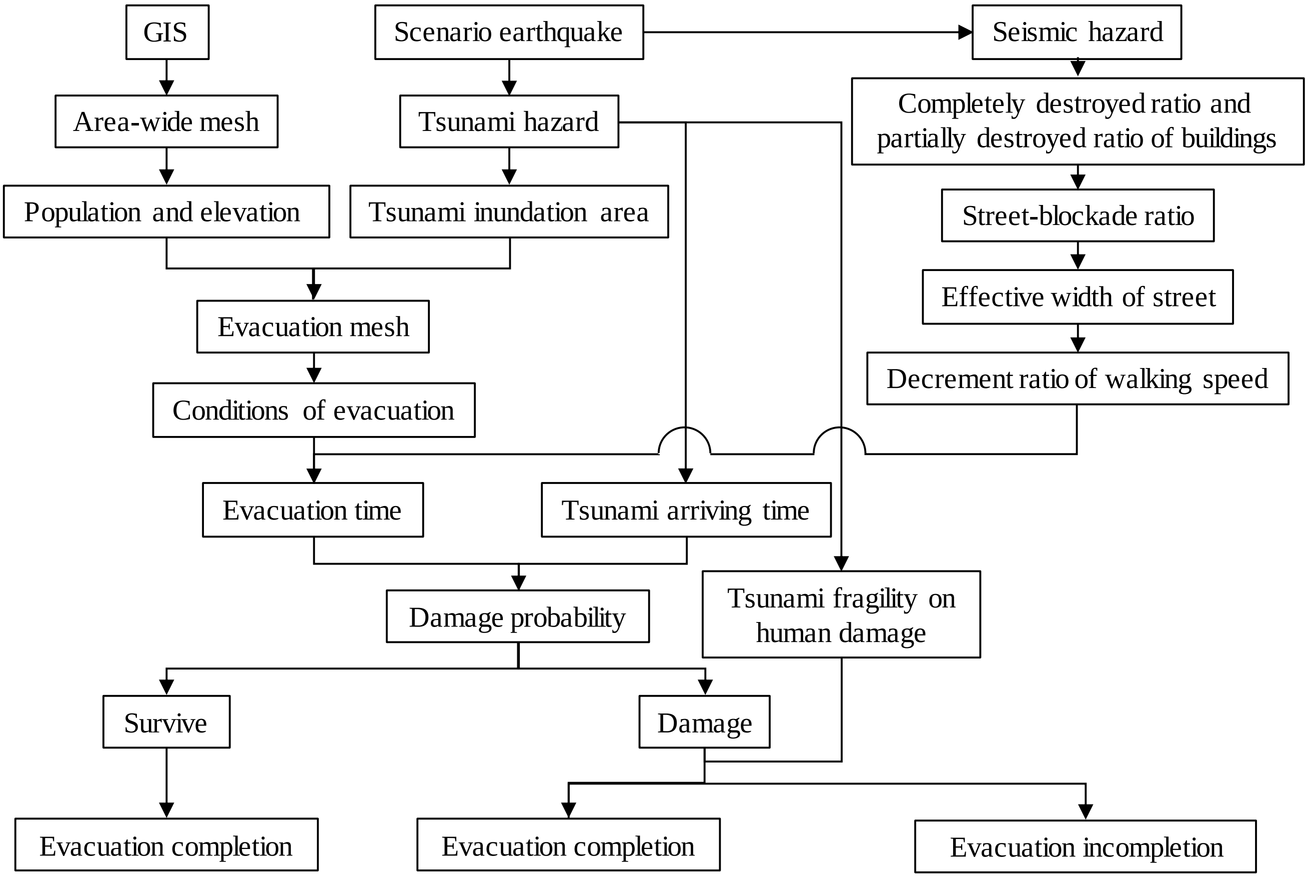


Fig.2.1 Evaluation flow of human damage in evacuation from tsunami

tsunami inundation depth in each mesh can be obtained from the tsunami fragility curve (Koshimura, *et al*., 2009). The street-blockade is evaluated by using the fragility of buildings for earthquakes (Midorikawa, *et al*., 2011). Decrement of the walking speed is determined by effective sidewalk width which passing is possible. From the above, the evaluation flow on the human damage can be shown in Fig.2.1.

2.2 Assumptions in evaluation

The assumptions to be used in this study are as follows:

1) The human damage is counted when a person is caught up with tsunami.
2) The evacuation is only walk. The walking is only permitted on sidewalk.
3) The evacuation facility is designated for each evacuation mesh. The facilities have no damage from earthquakes.
4) The street-blockades are occurred by destroy of buildings by a large earthquake.
5) The evacuation direction is not toward to coast.
6) In emergency, to across any railroad crossing is prohibited because crossing gates keeps down.

3. Human damage probability

3.1 Damage probability of Human in Evacuation

The human damage probability is evaluated by the author’s method (Fujita and Yashiro, 2016 and 2017). The probability is defined by a function of evacuation time and tsunami arriving time after earthquake occurrence. The evacuation time and the tsunami run-up time from coast to evacuation facilities are assumed to follow the normal distribution. The tsunami arriving time is divided into the time of tsunami propagation and run-up. The evacuation time and the tsunami run-up time can be evaluated from walking speed and tsunami run-up

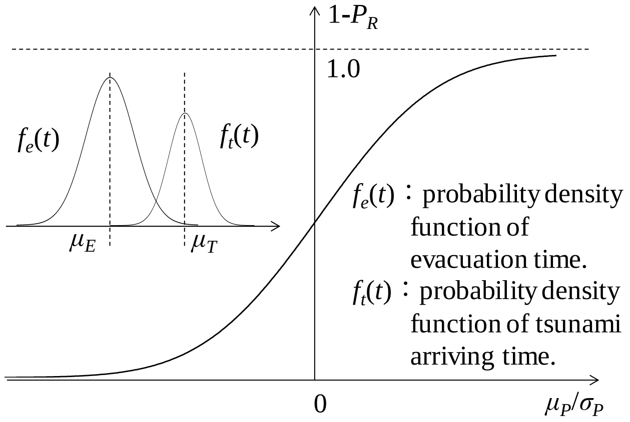


Fig.3.1 Human damage probability function

speed, respectively. The variation of the tsunami run-up speed is considered for evaluation of the tsunami arriving time. The tsunami run-up time can be obtained by the relation of the run-up speed and the minimum distance between coast and evacuation facilities. The mean value of the run-up speed can be determined by the tsunami inundation depth (Shuto *et al.*, 2007). Average tsunami inundation depth from the coast to the evacuation facilities is considered in this study. The run-up speed υ_L of tsunami is given by the following equation:

$$\upsilon_L = 1.1\sqrt{gh_I} \tag{3.1}$$

where g is the gravitational acceleration and h_I is the tsunami inundation depth.

The standard deviation of the run-up speed is evaluated by the geometric standard deviation (Aida, 2009) which indicates the adaptation between tsunami height marks on land and tsunami simulation results.

In this study, the reliability evaluation method for structures (Hoshiya and Ishii, 1986) applied to the evaluation of the human damage. The evaluation equation of the human damage probability can be provided the following equation:

$$P_R = 1 - \Phi\left(\frac{\mu_P}{\sigma_P}\right) \tag{3.2}$$

where, Φ is the standard normal distribution function with the mean value 0 and the standard deviation 1. The function P_R is shown in Fig.3.1. Also, μ_P and σ_P are provided by the following equations, respectively:

$$\mu_P = \mu_T - \mu_E \tag{3.3}$$

$$\sigma_P = \sqrt{\sigma_T^2 + \sigma_E^2} \tag{3.4}$$

where, μ_E and μ_T are the mean value of total evacuation time and the tsunami arriving time to evacuation facilities after earthquake, respectively, σ_E and σ_T are the standard deviation of μ_E and μ_T, respectively. In addition, μ_E is expressed by summation of the time t_I from earthquake occurrence to start time of evacuation and the time t_W from the evacuation start to evacuation complete. Deterioration ratio of walking speed by the street-blockade is considered in t_W. Also, μ_T is evaluated by summation of the time tsunami arriving time t_S from earthquake occurrence to propagation to coast and the tsunami run-up time t_L from coast to an evacuation facility.

3.2 Deterioration 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 shown in Fig.3.2 (Midorikawa, *et al.*, 2011). 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

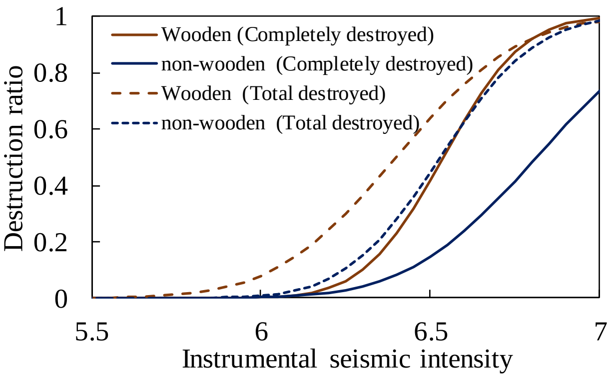


Fig.3.2 Fragility curves of buildings for earthquake

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:

$$W_{es} = (1 - R_d) W_s \qquad (3.5)$$

where, W_s is the sidewalk width in normal period, R_d is the street-blockade ratio which given for range of W_s represented by the following equation:

$$R_d = \begin{cases} 1.28 D_{rb} & (W_s < 3m) \\ 0.604 D_{rb} & (3m \le W_s < 5.5m) \\ 0.194 D_{rb} & (5.5m < W_s \le 13m) \end{cases} \qquad (3.6)$$

where, D_{rb} is the destruction ratio represented by the following equation (Cabinet office, 2013):

$$D_{rb} = D_c + D_p / 2 \qquad (3.7)$$

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

Deterioration of the walking speed is assumed to be proportional to the effective width. The deterioration ratio of the speed may be expressed by using consideration of the decrement ratio of walking speed of crowded with people (Cabinet office, 2007). In this study, the sidewalk width is assumed to be proportional to the deterioration ratio of the degree of crowded people per area. In evacuation, no deterioration of the walking speed is 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 deterioration ratio R_w may be evaluated by the following equation:

$$R_w = \begin{cases} 1.0 & (1.5m < W_{es}) \\ 0.8 W_{es} - 0.2 & (0.5m \le W_{es} < 1.5m) \\ 0 & (W_{es} < 0.5m) \end{cases} \qquad (3.8)$$

The walking speed in evacuation is 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 tsunami using the proposed method is discussed under the following conditions: no street-blockade, street-blockade and new construction and/or designation of evacuation facilities.

4.1.1 Area-wide mesh and population

The area-wide mesh and population distribution of target area (Zushi city) is shown in Fig.4.1. The mesh size is 250m x 250m and the population is 23,345.

4.1.2 Tsunami inundation depth and seismic intensity

Tsunami inundation depth and seismic intensity used in this study are based on a Meio type scenario earthquake (moment magnitude scale, Mw 8.4) and a scenario earthquake along the Miura peninsula faults (Mw7.0), respectively. To investigate the maximum case of the human damages considered the effect of the street-blockade, two types scenario earthquakes

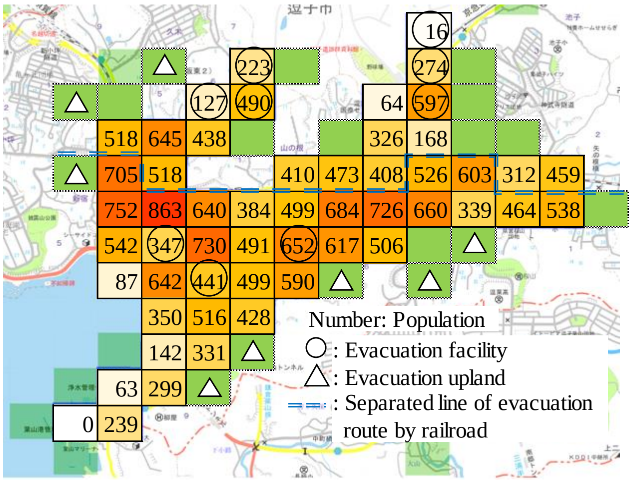


Fig.4.1 Area-wide mesh and population distribution

Table 4.1 Population ratio for evacuation awareness

Evacuation awareness	Percentage of evacuation awareness (%)			
	Evacuation immediately after earthquake (Strong awareness)	Evacuation immediately after work (Weak awareness)	Urgency evacuation (Weak awareness)	No evacuation (Weak awareness)
Strong	80%	10%	5%	5%
Average	50%	25%	15%	10%
Weak	15%	35%	30%	20%

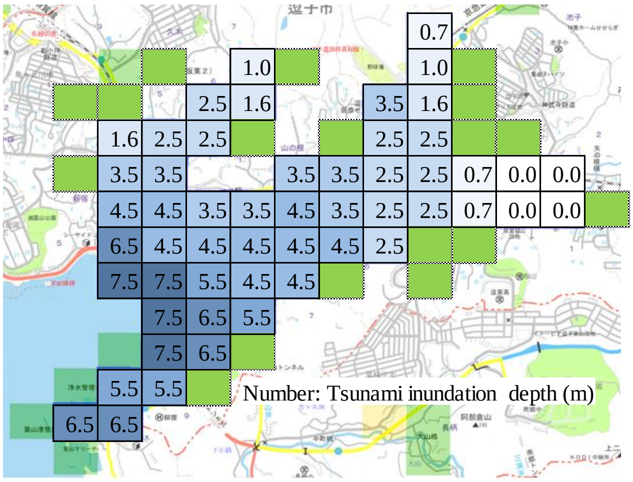


Fig.4.2 Tsunami inundation depth

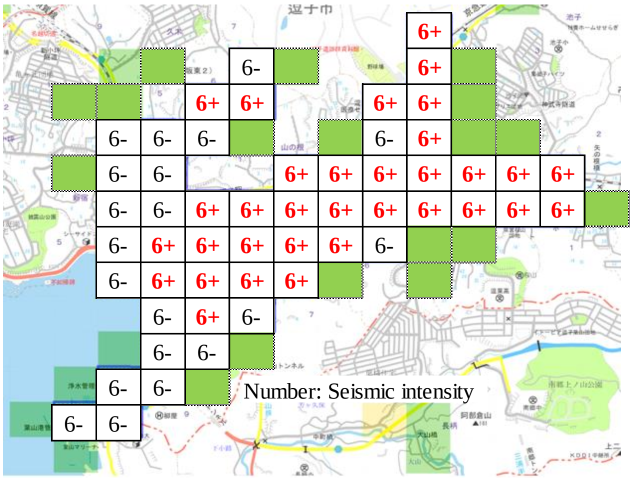


Fig.4.3 Seismic intensity

which are the maximum case of the damage estimation in the target area (Zushi city) is selected.

Tsunami inundation depth distribution of the area in the damage estimation for a Meio type scenario earthquake is shown in Fig.4.2. The maximum tsunami height is 8.94m. Though tsunami arriving time to coast is 59 minute (Zushi city), to clear the difference of evacuation awareness, tsunami arriving time in this study is set to 20 minute.

Seismic intensity distribution of the area in the damage estimation for a scenario earthquake along the Miura peninsula faults is shown in Fig.4.3 The seismic intensity 6- indicates in the range of greater or equal 5.5 and less than 6.0 of measured seismic intensity defined by Japan Meteorological Agency. Also, the intensity 6+ indicates in the range of greater or equal 6.0 and less than 6.5 of the measured seismic intensity. In the evaluation of the destroy of buildings, the upper value of the measured seismic intensity is used.

4.1.3 Buildings and streets

Buildings and roads are uniformly allocated to each mesh because of the evaluation to be simplification. Total number of buildings in the target area is 9,256 (wooden: 6,664, non-wooden: 2,592). Street area including sidewalk per mesh is 7,375m^2 which is 11.8% of one mesh area.

4.1.4 Evacuation behavior

Population ratio for the evacuation behavior is divided into four type: evacuation immediately, evacuation after work, urgency evacuation and no evacuation (Ministry of Land, Infrastructure, Transport and Tourism, 2011). The population ratio is set up by combining the following three types evacuation awareness: strong awareness, average awareness and weak awareness. The evacuation

Table 4.2 Start time of evacuation after earthquake occurrence

Start time of evacuation (min.)		
Evacuation immediately after an earthquake	Evacuation immediately after finished the work	Urgency evacuation
5	15	tsunami arriving time

Table 4.3 Total number of human damage

Evacuation awareness	Damaged population (persons)		
	No blockade	Blockade	Blockade and N.D
Strong	2,631	4,181	2,403
Middle	6,543	8,401	5,972
Weak	11,997	13,857	11,191

N.D: New designated of evacuation facilities

awareness ratio for the population are shown in Table 4.1. The start time of evacuation after earthquake occurrence for evacuation awareness are shown in Table 4.2.

4.1.5 Walking speed and tsunami inundation speed

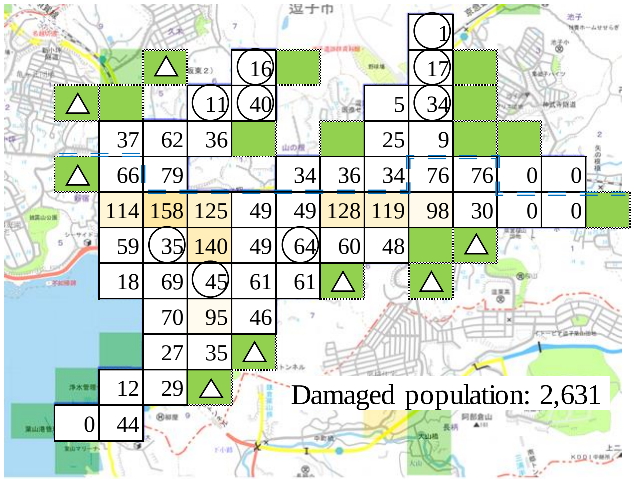
The mean value and standard deviation of walking speed is 1.34m/s and 0.167m/s in normal period (Matsuno *et al*., 2009). In addition, the mean value is deteriorated by the effect of the street-blockade and the standard deviation is assumed to be not variable for the blockade in this study.

The mean value and the standard deviation of tsunami run-up speed can be evaluated by using equation (3.1) and the geometric standard deviation (Aida, 2009), respectively.

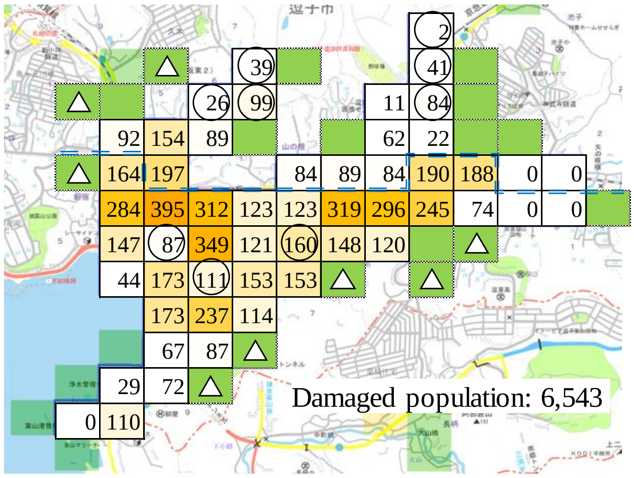
4.2 Evaluation results

4.2.1 Evaluation results with no street-blockade

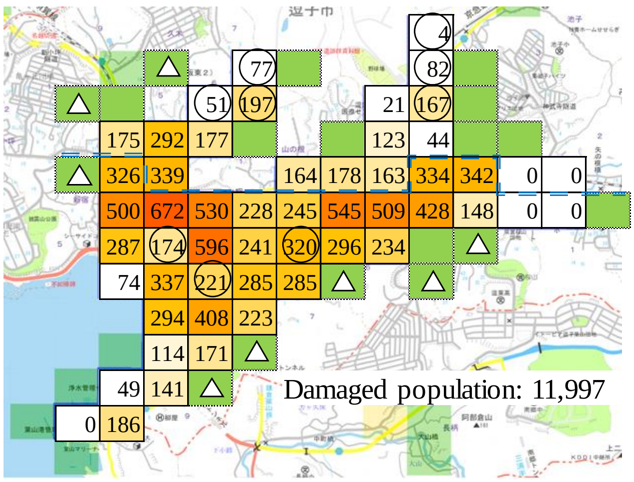
The human damage for several evacuation awareness under no street-blockade condition are shown in Fig.4.4. The large number of the damage is shown with deep color. The number of the damage with the strong awareness is the minimum. The



(a) Strong awareness



(b) Middle awareness



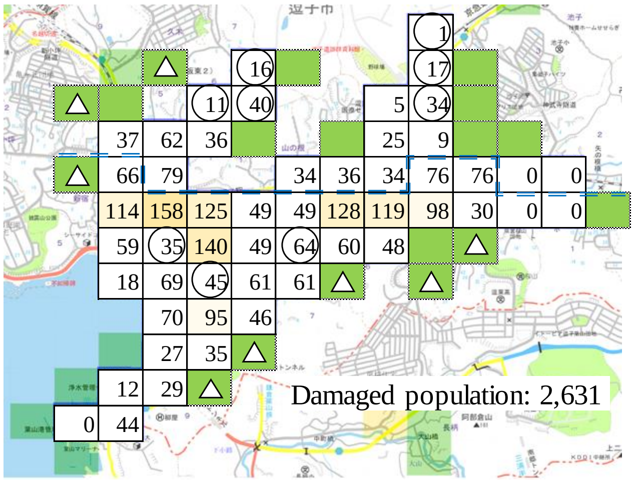
(c) Weak awareness

Fig.4.4 Human damage distribution with no street-blockade damage near the evacuation mesh is less than that of the other mesh. The damage on mesh of the coast and the railroad crossing becomes large.

The numbers of the human damage for several awareness are shown in Table 4.3. The human damage with the strong awareness decreased to 22% 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 street-blockade ratios by destroyed of buildings are shown in Fig.4.5. The ratio becomes large for strong seismic intensity. In addition, the numbers of destroyed buildings simulated in this study are 1,801 for completely destroyed and 1,114



(a) Strong awareness

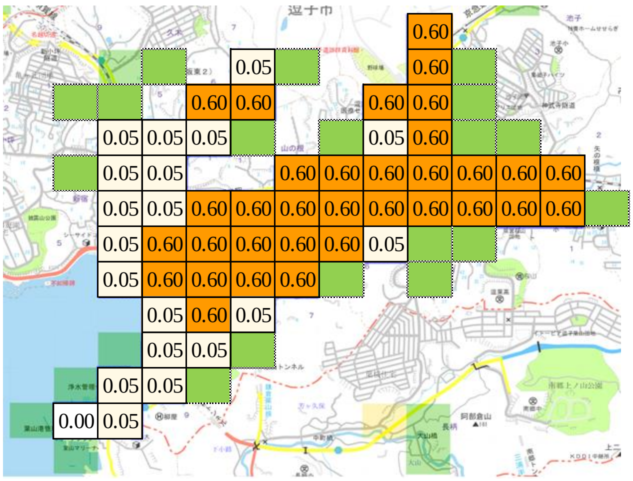
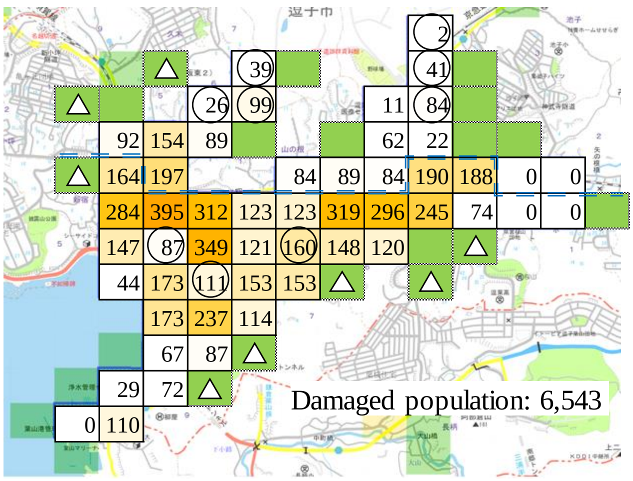


Fig.4.5 Street-blockades ratio by destroy of buildings



(b) Middle awareness

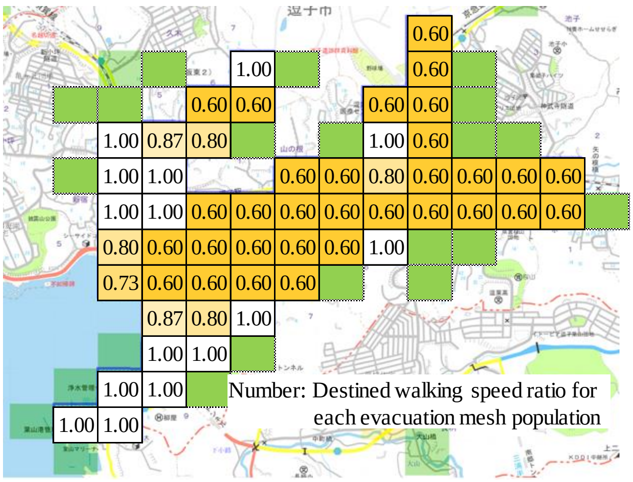
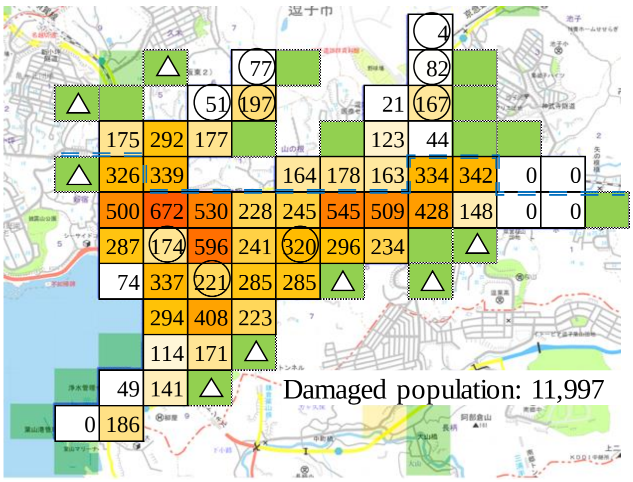


Fig.4.6 Decrement ratio of walking speed by street-blockade



(c) Weak awareness

Fig.4.7 Human damage distribution with street-blockade for partially destroyed. The decrement ratio of the walking speed by the blockade is shown in Fig.4.6. The number shown in the figure represents the destined ratio of the walking speed for each evacuation mesh population. The ratio is variable with the scale of the blockades.

The human damages for several evacuation awareness under the street-blockade condition are shown in Fig.4.7. The human damage becomes large in spite of the evacuation awareness compare to that of the no blockade. The number of the damage with the strong awareness is the minimum.

The numbers of the human damage for the blockades are shown in Table 4.3. The damages are increased to 1.59, 1.28 and 1.16 times for the strong, middle and weak awareness in the results of the no street-blockades, respectively. To consider the decrement of the walking speed by the blockades is important for the human damage estimation from tsunami. Enhancing of evacuation awareness as well as seismic strengthening of buildings become the one way to decrease the human damage in evacuation.

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

The human damage by newly construction and/or designation of tsunami evacuation facilities is discussed under the street-blockades condition. The new evacuation facilities are plotted with red color circle in Fig.4.8. The new facilities are located on the coast, near the railroad crossings and the large number of human damage. The numbers of the new facilities are four mesh on sea-side and 14 mesh on inland. The evacuation destinations of part of mesh are changed to shorten the evacuation route.

The human damages for several evacuation awareness under the street-blockades and the new construction and/or designation of evacuation

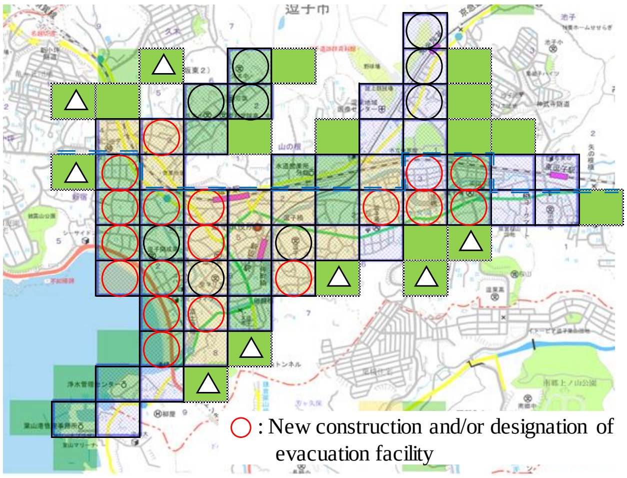


Fig.4.8 Distribution of new construction and/or designation of evacuation facilities

facilities are shown in Fig.4.9. The human damages become the minimum compared with the other cases in this study. It can be seen that the reduction of the evacuation distance by the new evacuation facilities leads to decrease the human damage.

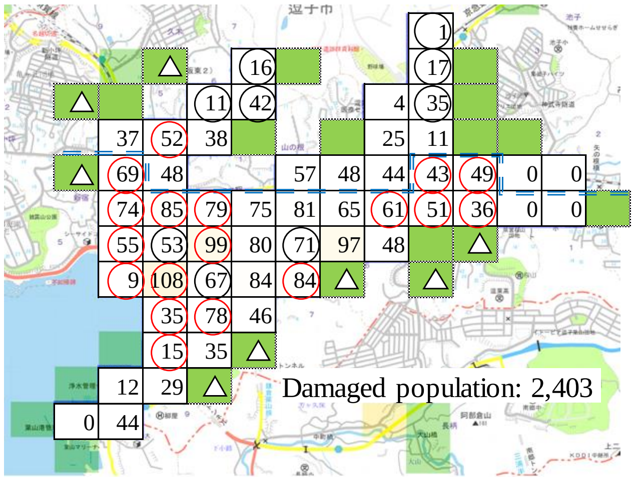
The numbers of human damage are shown in Table 4.3. The is decreased to 0.91, 0.91 and 0.93 times for the strong, middle and weak awareness in the results of the no street-blockades, respectively. New construction and/or designation of the evacuation facilities become one of the effective way to reduce the human damage.

From the results in these evaluations, combination the new evacuation facilities and the seismic strengthening of buildings in addition to increment of the evacuation awareness seem to be one of the most effective way to decrease the human damage in evacuation from tsunami.

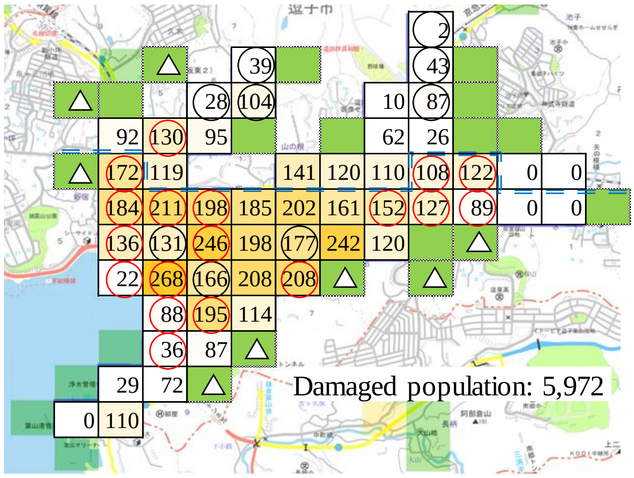
5. Conclusions

An evaluation method of the human damage considering the effect of the street-blockades by destroy of buildings is proposed. The human damage in evacuation from tsunami is discussed for the no street blockades, the street-blockades and the new facilities under the blockades conditions. The following conclusions can be drawn.

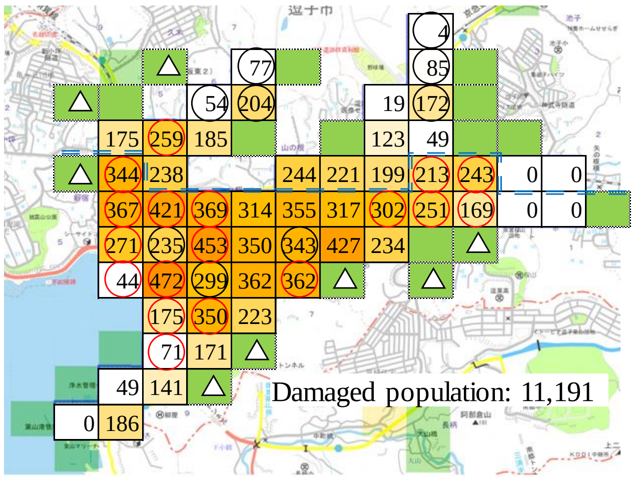
1) The human damage under the street-blockade becomes large compared to that of the no street-blockade because of decrement of the walking speed by the blockade.
2) To consider the effect of the street-blockade in evacuation planning is important.
3) The human damage in evacuation from tsunami can be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



(a) Strong awareness



(b) Middle awareness



(c) Weak awareness

Fig.4.9 Human damage distribution in street-blockades under new construction and/or designation of buildings

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