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ORIGINAL ARTICLE

Evaluation of Human Damage in Tsunami Evacuation Considered the Variance of Walking and Tsunami Run-up Speeds

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Abstract**:** The huge tsunami generated by the Great East Japan Earthquake on Marth 11, 2011, caused especially extensive human and structural damages along the coast of the northeast part of Japan. More than 90% of 20,000 peoples are damaged by the tsunami. From the lesson learns of the tsunami disaster, damage estimation, disaster prevention and evacuation planning for the Nankai Megathrust Earthquakes which occurrence in future is assumed have been revised. To reduce the number of human damage for tsunami disaster, two methods are considered. One is the structural measures such as newly construction and/or designated of tsunami evacuation facilities, the other is the non-structural measures such as improvement of disaster awareness. Usually, the following considerations are used in the evaluation of the human damages. The area-wide mesh is used from the viewpoint of easiness of understanding the number and distribution of the damage. The fragility function represented by tsunami inundation height and the damage ratio is used. And the average walking speed is assumed and the tsunami run-up speed obtained by simulation is used. However, to evaluate distribution and scale of the damage, considering the variance of the walking speed is preferable because population composition and geographic condition are difference in every mesh.

In this study, an evaluation method of the number of the human damage in tsunami evacuation considered the variance of the walking and the tsunami run-up speed is proposed. The walking speed and the tsunami run-up speed are assumed to follow a normal distribution. The structural reliability method is applied to evaluate the number of the damage. Using the proposed method, numbers and distributions of the damage in model area are evaluated. Also, reduction of the damage by newly construction and designated of tsunami evacuation facilities is discussed.

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

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1. Introduction

The huge tsunami generated by the Great East Japan Earthquake on Marth 11, 2011, caused especially extensive human and structural damages along the coast of the northeast part of Japan. More than 90% of 20,000 peoples are damaged by the tsunami occurred after the earthquake. In response to enormous human damage of the great earthquake, cabinet office in Japan has published the maximum cases of damage estimation for the maximum class seismic intensity and tsunami height caused by a Nankai Trough earthquake which occurrence to be assumed in the future (Central Disaster Management Council, 2012 and 2013).

Usually, to evaluate both the human damage and the development of evacuation planning for tsunami, an area-wide mesh has been used (Central Disaster Management Council, 2012, Yashiro and Fujita, 2014). In evaluating the number of the human damages, utilization of the area-wide mesh seems to preferable because of the following merits; (1) damage reduction can be observed by structural measures such as newly construction and/or designated of tsunami evacuation facilities, (2) damage reduction can be understood easily by non-structural measures such as improvement of evacuation awareness, experience of evacuation training and education for disaster prevention. In the estimation of the human damage for tsunami, average walking speed in evacuation action and tsunami run-up speed obtained by tsunami simulation analysis have been used. Fragility functions represented by relation between tsunami inundation depth and human damage ratio have been used to evaluate the human damage (Kawata, 1997, Takeuchi, *et al*., 2008, Koshimura, *et al*., 2009, Shishido *et al*., 2010). Usually, in estimating of buildings damage for earthquake, fragility functions have been used because of uncertainness by variability of structural strength and seismic intensity. To evaluate the building damage caused by an earthquake and the human damage caused by tsunami in the whole area, a risk assessment method combined seismic risk and tsunami risk seems to be reasonable.

In this study, an evaluation method of the number of the human damage in tsunami evacuation considered the variabilities of walking and tsunami run-up speed is presented. The walking speed and the tsunami run-up speed are assumed to follow a normal distribution (Fujita and Yashiro, 2016), and applying the evaluating method for structural reliability (Hoshiya, *et al*. 1986) to evaluate the number of the human damage. Using the proposed method, variation of the number and distributions of the human damage by the difference in the evacuation awareness are evaluated for a model area. Also, variation of the human damage by newly construction and/or designated of tsunami evacuation facilities is discussed.

2. Evaluation method of human damage

The area-wide mesh have been used to the evaluation of the human damage. For each mesh, population composition, height above sea level, tsunami inundation depth and evacuation awareness are set up based on a real area data.

The population composition and the height above sea level in GIS (Geographic Information System) data are used to the area-wide mesh. The minimum height above sea level is used for each mesh. Population ratio of the evacuation activity is divided into four type; evacuation immediately, evacuation after finished work, urgency evacuation and no evacuation.

The evacuation awareness is classified into three types; strong awareness, average awareness and weak awareness. Using these awareness, the four type population ratio is composed.

The 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 longer than the evacuation route on plane. The human damage probability is evaluated by using relation between tsunami arriving time from earthquake occurrence and evacuation time. The human damage in each mesh can be obtained by multiplying the population in each mesh to the tsunami fragility function (Koshimura *et al*., 2009). Total number of the human damage in area can be evaluated by summation of the damage in each mesh.

The above evaluation flow of the human damage in the tsunami evacuation can be shown in Figure.2.1

The following assumptions are considered in the evaluation of the human damage.

1) The human damage is counted when a person is catch up with a tsunami.
2) The evacuation is the only walk.
3) The evacuation facility is designated for each evacuation mesh.
4) The direction from the evacuation mesh to the evacuation facility is not toward to coast.
5) In emergency, to across any railroad crossing is prohibited because crossing gates keeps down.

3. The Human damage probability

The human damage probability proposed 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 time of tsunami in sea area and 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 arriving

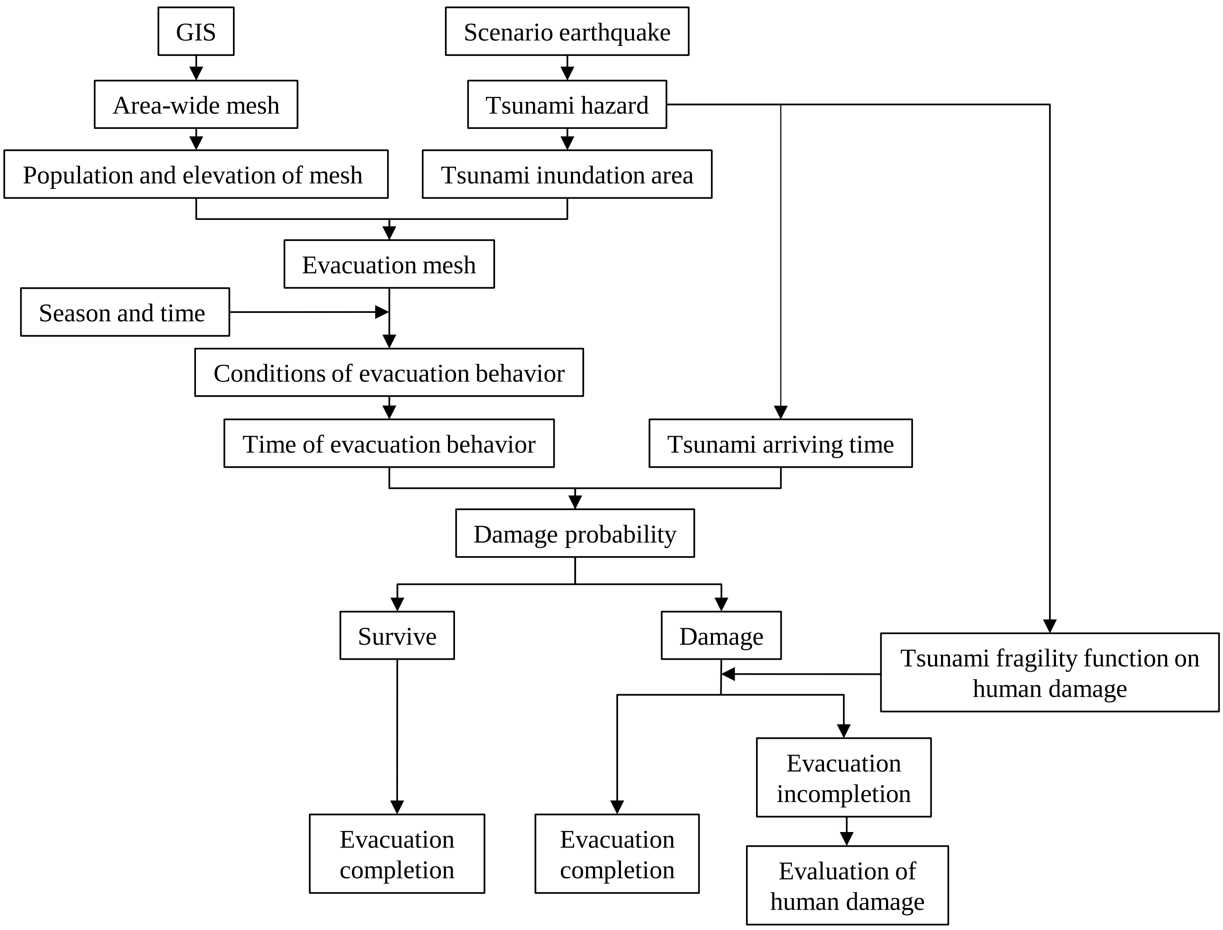

Figure 2.1 Evaluation flow of human damage

time, the variation of the tsunami run-up speed is considered. For evaluation of evacuation time, the variation of walking speed is considered.

The evaluation method of the human damage probability proposed in this study is shown in the following. Define a tsunami influence function is represented by using relation between the tsunami arriving time F_T and the evacuation time F_E. The function can be represented by the following equation.

$$F_I = F_T - F_E \tag{3.1}$$

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 the completed evacuation. The mean value can be represented by the following equation.

$$\mu_E = t_I + t_W \tag{3.2}$$

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 arriving 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 arriving time t_S from earthquake occurrence to reach on coast and tsunami run-up time t_L from coast to an evacuation facility. The mean value μ_T can be provided as the following equation.

$$\mu_T = t_S + t_L \tag{3.3}$$

where, the tsunami arriving time t_L is the normal distribution with the mean value μ_L and the standard deviation σ_L. The arriving time can be obtained by the relation of tsunami run-up speed and the minimum distance between shore and evacuation facility. The mean value of the tsunami run-up speed is evaluated by using the equation of the fluid speed

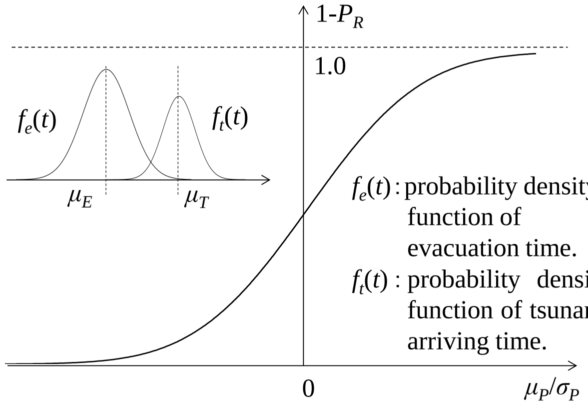

Figure 3.1 Human damage probability function

defined by the tsunami inundation depth (Shuto, *et al*. 2007). In this study, average tsunami inundation depth from the coast to the evacuation facilities is considered. The standard deviation of the run-up speed is used by the geometric standard deviation (*Aida*, 1977) which indicates the adaptation between tsunami height marks on land and tsunami simulation results.

In this study, the reliability evaluation method for structures is applied to the evaluation of the human damage. The evaluation equation of the human damage can be provided the following equation.

$$P_R = 1 - \Phi\left(\frac{\mu_P}{\sigma_P}\right) \tag{3.4}$$

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

$$\mu_P = \mu_T - \mu_E \tag{3.5}$$

$$\sigma_P = \sqrt{\sigma_T{}^2 + \sigma_E{}^2} \tag{3.6}$$

4. Evaluation of human damage

The human damages using the proposed method in this study are investigated under the conditions of difference of evacuation awareness, the number of evacuation facilities and location of the facilities. The evaluations of human damage are carried out in

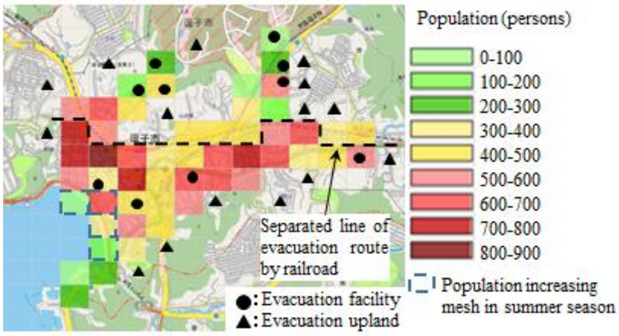

Figure 4.1.1 Area-wide mesh and population

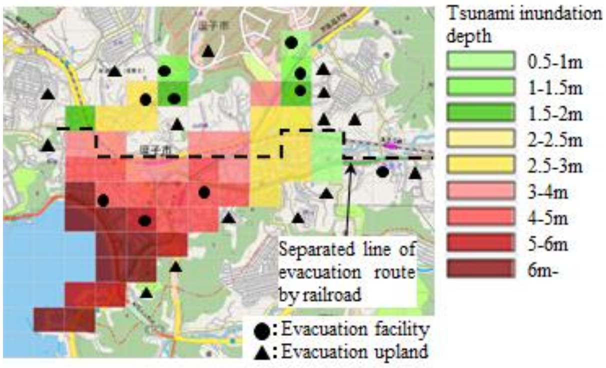

Figure 4.1.2 Tsunami inundation depth

two seasons; one is the summer season with increment of population becomes large by beach-gores and the other is seasons (spring, autumn and winter) without increment of population.

4.1 Evaluation conditions

The evaluations of the human damage is carried out for a real model area. In this study, Zushi city,

Table 4.1.1 Mesh population in each season

Mesh population (persons)	
Summer	Spring, autumn and winter
30,595	23,361

Kanagawa prefecture in Japan is selected (Kanaga pref., 2012). A Meio type earthquake tsunami data for the estimation of earthquake damage is used. The tsunami height is 8.94m and the tsunami arriving time to the coast is 59 minutes. The tsunami inundation depth and the location of evacuation facilities are used the data on the tsunami hazard map. To clear the variation of the number of the human damage due to the difference of evacuation awareness, tsunami arriving time is shorten to 20 minutes.

The area-wide mesh and population distribution are shown in Figure.4.1.1. The mesh size is 250m x 250m. In this figure, circle and triangle marls with black are the evacuation facility and the evacuation upland, respectively. These facilities and uplands are set up based on the hazard map. The broken line shows the no across by railroad crossing gate keeps down in an earthquake disaster. Total number for seasons of the population are sown in Table.4.1.1. Beach-gores in the summer season considered the

Table 4.1.2 Population ratio for evacuation awareness

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

Table 4.1.3 Start time of evacuation from an 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 4.1.4 Walking speed in evacuation

	Mean and Standard deviation of walking speed (m/s)		
	Summer		Spring, autumn and winter
	Coast mesh	Inland mesh	All mesh
Mean	0.566	1.34	1.34
Standard deviation	0.167	0.167	0.167

Table 4.2.2 Total number of human damage

Evacuation awareness	Damaged population (persons)			
	Summer season		Spring, autumn and winter seasons	
	Designated of E.F.	No designated of E.F.	Designated of E.F.	No designated of E.F.
Strong	4,144	3,463	2,572	1,917
Middle	10,187	8,617	6,394	4,756
Weak	18,072	15,862	11,720	9,370

E.F. : evacuation facilities

average during in 2005 to 2014 yrs. The average of the beach-gores in the 10 years is about 434,000 peoples (Zushi city, 2013) and the beach-gores per day is 7,236 peoples. The beach-gores is allocated equally in four coast mesh indicated by the broken line. The distribution of tsunami inundation depth is shown in Figure.4.1.2.

The population ratio for the evacuation awareness is shown in Table 4.1.2. The awareness is divided into three classes, strong, average and weak. Population ratio is classified for evacuation immediately, evacuation after finished works, urgency evacuation and no evacuation (MLITT, 2011). The start time of evacuation from an earthquake occurrence is shown in Table 4.1.3.

The walking speed to be used in this study is shown in Table 4.1.4. The mean value and the standard deviation of the walking speed is used measured data in streets (Matsumoto, *et al*., 2009). The population compositions in each mesh are assumed middle-aged people. The walking speed on the coast mesh in the summer season is assumed to be 0.556m/s (four-persons/m^2) in congestion.

4.2 Evaluation results for summer season

4.2.1 Human damage by difference of evacuation awareness

The human damage of the mesh in the summer season is shown in Figure.4.2.1. The evacuation area is the same with in Figure.4.1.1. The damage is shown by the classification and the number of the damages. In the classification, the large number of the damage shown with deep color. The damage with the strong evacuation awareness is decreased in the global area. The damage near the evacuation area mesh is less than that of the other mesh. However, the damage on mesh of the coast and the railroad crossing is large.

The number of the human damage is shown in Table 4.2.1. The human damage with the strong awareness decreased to 23% of the damage with the

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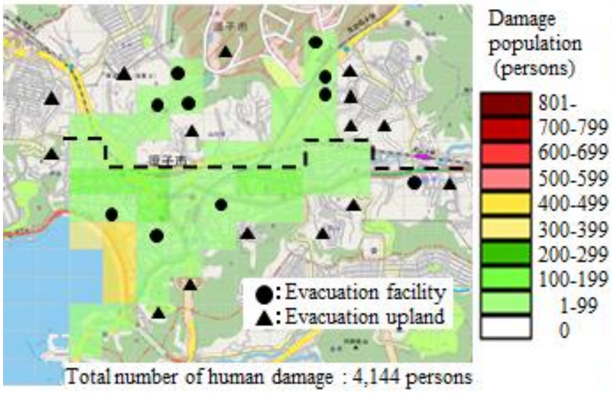
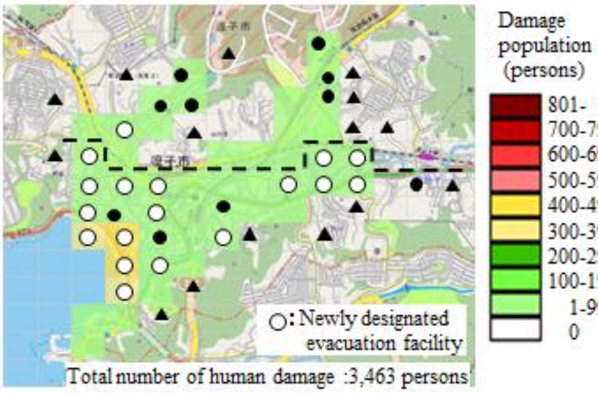
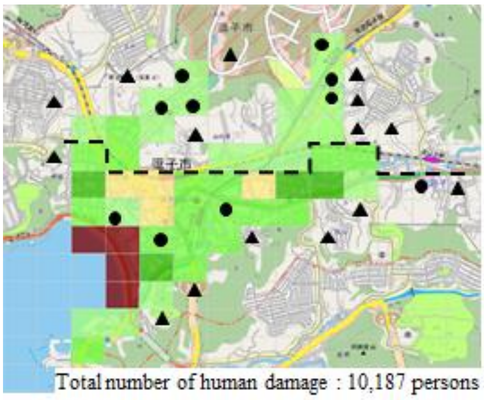


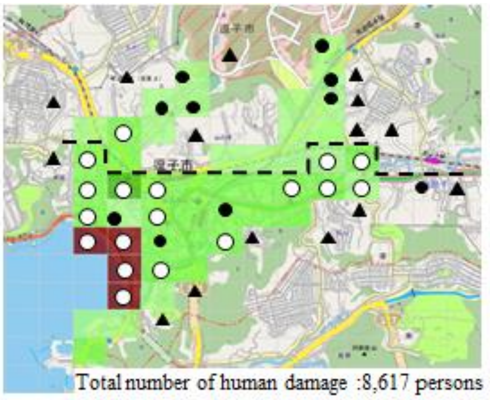
(a) Strong awareness for evacuation



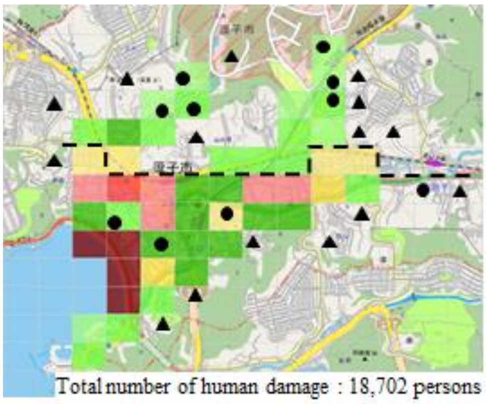
(a) Strong awareness for evacuation



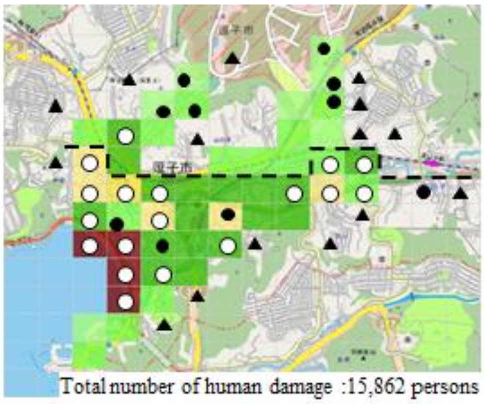
(b) Average awareness for evacuation



(b) Average awareness for evacuation



(c) Weak awareness for evacuation



(c) Weak awareness for evacuation

Figure 4.2.1 Human damage distribution in summer season

Figure 4.2.2 Human damage distribution in summer season with newly designed evacuation facilities

weak one. The evacuation awareness has a large influence to decrease the human damage.

4.2.2 Human damage by newly construction and/or designation of tsunami evacuation facilities

The human damage by newly construction and/or designation of tsunami evacuation facilities is discussed. The new designation of the facilities are plotted with white color circle in Figure.4.2.2. The new facilities are located on the coast, near the railroad crossings and the large number of human damage with evacuation awareness. The numbers of the designation are four mesh on sea-side and 14 mesh on inland. The evacuation destinations for some of mesh are changed to shorten the evacuation route.

The human damage is shown in Figure.4.2.2. The damage for all mesh is decreased remarkably by newly construction and/or designation of the facilities. The damages on mesh with the railroad crossing and the long evacuation route are reduced remarkably. The effect of the newly construction and/or the designation can be seen. However, the decrement of the damage is relatively small because the evacuation route is congestion by a lot of beach-gores and the tsunami arriving is fast. To show the human damage in each mesh becomes useful to formulate of evacuation panning because the distribution of the human damage can be understood easily.

The number of the human damage is shown in Table 4.2.1. To construction and/or the newly designate of the facilities, the human damage is more decrement than that with improvement of the evacuation awareness. The human damage is decreased to 19% for the case of the weak awareness without the new designate. To reduce the human damage in the tsunami evacuation, necessity of improvement of the evacuation awareness, the new designate of the facilities and re-planning of the evacuation route is clear.

4.3 Evaluation results for spring, autumn and winter seasons

4.3.1 Human damage by difference of evacuation awareness

The human damage with variation of the evacuation awareness in spring, fall and autumn seasons is shown in Figure.4.3.1. The evacuation area is the same with shown in Figure.4.1.1. The damage with the strong evacuation awareness is decreased in the global area. The damage near the coast is less than that in the summer season. However, the damage on mesh with railroad crossing is large. The total number of the human damage is shown in Table 4.2.1. The damage with the strong awareness is decreased to 22% of the damage with week the weak awareness.

4.3.2 Human damage by newly construction and/or designated of tsunami evacuation facilities

The human damage by the newly construction and/or designation of evacuation facilities is shown in Figure.4.3.2. The designation is the same with Fig.4.2.2. The damage for all mesh is decreased remarkably by the newly construction and/or the designation of the facilities. The number of the human damage except for the coast is the same with the summer season. The decrement of the damage in the coast by the newly construction and/or the designation of the evacuation facilities can be seen. The total number of the human damage is shown in table 4.2.1. The human damage by the designation of the facilities is decreased to 16% of the case of no designation with the weak awareness. The human damage is less than that in the summer season because of no beach-gores.

5. Conclusions

The evaluation method of the human damage in tsunami evacuation taking account of the variances of walking speed and tsunami run-up speed is proposed. The knowledges obtained in this study are shown in the following.

1) The human damage in tsunami evacuation is decreased by the non-structural measurements such as enhance awareness for evacuation and education for disaster prevention.
2) To combine the structural measurement such as newly construction and/or designating of evacuation facilities and the non-structural measurement, the human damage is decreased

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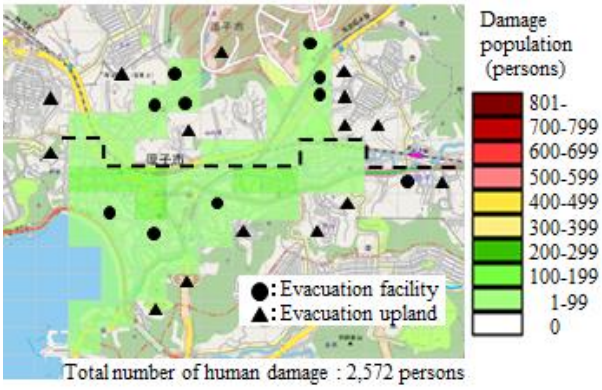
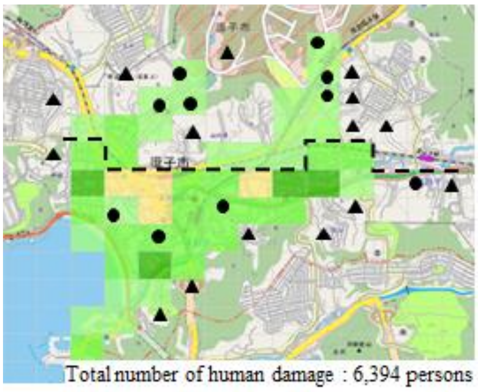
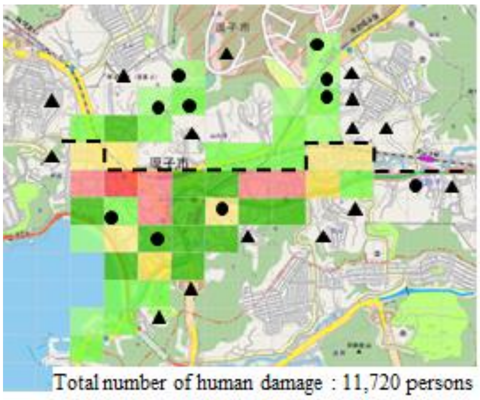


(a) Strong awareness for evacuation

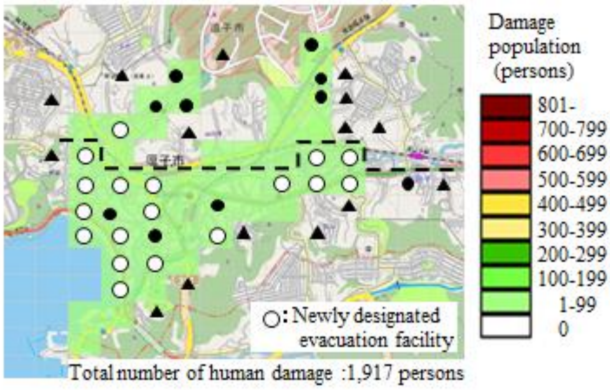


(b) Average awareness for evacuation

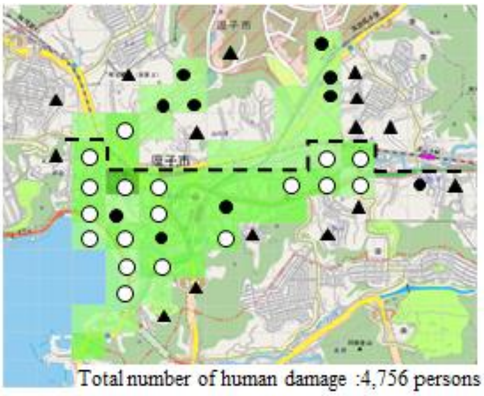


(c) Weak awareness for evacuation

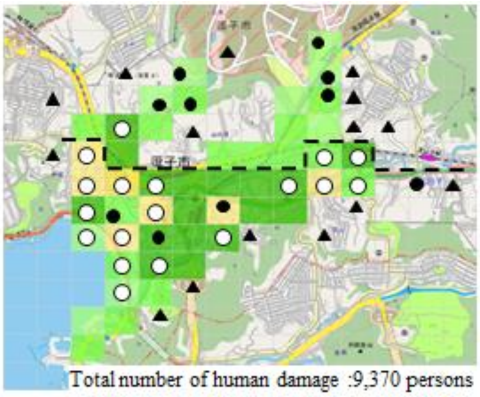
Figure 4.2.1 Human damage distribution in except for summer season



(a) Strong awareness for evacuation



(b) Average awareness for evacuation



(c) Weak awareness for evacuation

Figure 4.2.2 Human damage distribution in except for summer season with newly designed evacuation facilities

remarkably.

3) The location of newly construction and/or designation of evacuation facilities should be selected adequately.

4) The human damage with increasing of beach-gores becomes increased. To construction of the tsunami evacuation facilities to be noticeable such as tsunami evacuation towers is important.

5) The evaluation of the human damage using the area-wide mesh can be easily understand the distribution of the damage in area. Also, the mesh becomes useful to development of evacuation planning.

Future tasks in this study are as follows; the evaluation of considering of scale and seating capacity of evacuation facilities, the evaluation of the variance of walking speed in congesting and the effect to the human damage by separated evacuation route such as railroad crossings.

References

1) Aida, I., 1997. Simulations of Large Tsunamis Occurring in the Past off the Coast of the Sanriku District, *Bulletin of the Earthquake Research Institute*, Univ. of Tokyo, Vol.52, No.1, pp.71-101. (in Japanese)

2) Central Disaster Management Council, 2007. Simulation Method of Homecoming action. (in Japanese)

3) Central Disaster Management Council: Damage, 2012. Estimation of Nankai Trough Earthquake (1st. Report). (in Japanese)

4) Central Disaster Management Council, 2013. Damage Estimation of Nankai Trough Earthquake (2nd. Report). (in Japanese)

5) Fujita, K., Yashiro, H., 2016. A Study on the Number of Installed and Installation Location of Tsunami Evacuation Facilities Using Area-wide Mesh, *Journal of Japan Society of Civil Engineers*, *Ser. F6* (*Safety Problem*), Vol. 72, No.2, p.I_151-I_156. (in Japanese)

6) Hoshiya, M., Ishii, K., 1986. *Reliability Based Design for Structures*, Kajima Institute Publishing Co., Ltd. (in Japanese)

7) Kanagawa prefectural Land Development Bureau, 2012. Manual of Tsunami Inundation Forecast. (in Japanese)

8) Kawata, K., 1997. Prediction of Loss of Human Lives Due to Catastrophic Earthquake Disaster, *Journal of Japan Society for Natural Disaster Science*, Vol.16, No.1, pp.3-13. (in Japanese)

9) Koshimura, S., Namegawa, Y., Yanagisawa, H., 2009. Fragility Functions for Tsunami Damage Estimation, *J. of Japan Society of Civil Engineers*, *ser. B*, Vol.65, No.4, pp.320-331. (in Japanese)

10) Matsumoto, N., Kiyota, S., Ito, M., 2009: Relationship between the Characteristics of Streetscape and Walking Speed, *Journal of architecture and planning* (Trans. of AIJ), Vol.74, No.640, pp.1371-1377. (in Japanese)

11) Ministry of Land, Infrastructure, Transport and Tourism, 2011. Present State Survey in Tsunami Affected Area of the Great East Japan Earthquake (3rd. Report), Results of Actual Survey on Tsunami Evacuation (Preliminary). (in Japanese)

12) Shishido, N., Ukawa, H., Imamura, F., 2010. Study on the Evaluation Method of Human Loss including Evacuation Process from Tsunami, *J. JSCE, ser. B2* (*Coastal engineering*), Vol.66, No.1, pp.1311-1315. (in Japanese)

13) Shuto, N., *et al*., eds., 2007. *Encyclopedia of Tsunami*, Asakura Publishing Co., Ltd. (in Japanese)

14) Takeuchi, M., Koshimura, S., Meguro, K., 2008. Initial Assessment on Capability of Multi-Purpose Buoy System for Tsunami Warning, *Proceedings of Coastal Engineering, JSCE*, Vol.55, pp.1416-1420. (in Japanese)

15) Yashiro H., Fujita K., 2014. Evaluation Method of Evacuation Safety Performance for Tsunami Using Area-wide Mesh, *15th European Conference on Earthquake Engineering & 34th General Assembly of European Seismological Commission*, CD-ROM.

16) Zushi City Homepage, http://www.city.zushi.kanagawa.jp/