Human Vulnerability Index for Evaluating Tsunami Evacuation Capability of Communities

Y. Goto[1] and T. Nakasu[2]

[1] *Senior Engineering Adviser, KAIHATSU-TORANOMON CONSULTANT CO., LTD, gotoyozo@mti.biglobe.ne,jp*
[2] *Academic Researcher, Chulalongkom University, Tadashi.N@chula.ac.th*

Abstract

Mortality rates caused by tsunamis vary from community to community, depending on geographical and social features peculiar to each. If the relation between mortality rate on the one hand and geographical and social features on the other can be quantitatively formulated, it can be a means to concretely evaluate the community's vulnerability with regard to evacuation (hereafter, evacuation vulnerability) and to adopt measures that effectively reduce loss of human life.

Therefore, the authors proposed to apply an HVI (Human Vulnerability Index), defined as the rate of mortality divided by the rate of incidence of damaged buildings, to evaluate the evacuation vulnerability of a municipality. Factors associated with a tsunami hazard, such as tsunami height, should be omitted from the HVI when evaluating the vulnerability of a community. Therefore, as the most appropriate parameters in the formula, the authors selected the incidence of washed-away buildings as that of damaged buildings.

Then, using reliable public databases, the authors evaluated the HVIs of the twenty municipalities that were heavily damaged by the tsunami of the 2011 Great East Japan Earthquake. Through comparison of these twenty HVIs with geographical and social factors of the corresponding municipalities, the following quantitative relation between HVI and specific factors were observed:

1) Tsunami arrival time after earthquake divided by length of evacuation route lowered HVI, which meant the allowance of safe evacuation increased.
2) Rate of car evacuees multiplied by car speed, which meant the capacity of evacuation road, pushed down HVI.
3) People's cognition rate regarding the large tsunami warning issued by JMA soon after the earthquake and the forecast tsunami heights initially broadcast to the municipalities' areas were sensitive to HVI. HVI of the 3 meter area was higher than that of the 6 meter area.
4) Disaster education such as letting people prepare emergency bags was always effective in lowering HVI

A simple regression analysis applied to the above factor-HVI relations did not show enough correlation. However, a multiple-regression analysis using the above four factors as explanatory variables extracted a balanced and reliable formula, which enables us to evaluate the HVI of a municipality before it suffers a large tsunami, although some municipalities may need to improve their databases to express the explanatory variables numerically.

HVI and the formula for its prediction provide an effective tool for a municipality to assess its evacuation vulnerability specifically, to set a numerical goal for which its effort and resources should be concentrated and to judge its attainment of vulnerability lowering.

Keywords: Human Vulnerability Index; Tsunami evacuation; 2011 Great East Japan Earthquake; Geographical and Social factors; Multiple Regression analysis

1. Introduction

Over 18,000 people were killed or went missing in East Japan Pacific coast municipalities during the March 11, 2011 Great East Japan Earthquake and Tsunami Disaster. But, the mortality rates were uneven. They seemed to vary from municipality to municipality, depending on geographical and social features peculiar to each.

If the relation between mortality rate and geographical and social features can be quantitatively formulated, it can be a means to numerically evaluate the community's vulnerability with regard to evacuation (hereafter, evacuation vulnerability) and to develop measures that effectively reduce loss of human life. Here, the meaning of evacuation vulnerability is conceptually denoted by Eq. (1).

$$\text{Mortality rate} = \underset{\underset{\boxed{\text{Geographical and Social features}}}{\Uparrow}}{\boxed{\text{Evacuation vulnerability}}} \times \boxed{\text{Tsunamis hazard}} \qquad (1)$$

The concept of dividing the number of deaths by the number of damaged buildings was initially applied, to evaluate mainly the vulnerability of buildings to earthquakes, by Imamura in 1913 [1]. Later, Kawasumi [2], Ohta [3], Coburn [4], Miyano [5], Murakami [6], Matsuda [7], Moroi [8] and Takemura [9] used the same kind of formula to evaluate vulnerability.

While these studies analyzed the mortality rates caused by damage to buildings due to earthquake, Nakasu [10] newly proposed a Human Vulnerability Index (HVI, hereafter) which was defined as mortality rate divided by damage rate of buildings due to tsunamis. Nakasu, one of the co-authors, applied HVI to three historical tsunamis: the 1896 Meiji-sanriku Tsunami, the 1933 Showa-sanriku Tsunami and the 2011 Great East Japan Tsunami and analyzed the variation of evacuation vulnerability according to age.

On the other hand, Goto [11] also considered the number of damaged buildings as a general index of tsunami hazard and proposed a Victim Index (VI), which is defined as the number of deaths divided by the number of damaged buildings. He applied this index to 6 villages in Yamada-town of Iwate prefecture and showed that it could be related to the evacuation vulnerabilities of those villages.

In this study, the authors used HVI, because it is non-dimensional and possibly versatile, and analyzed its relation to geographical features and social features of the twenty heavily-damaged municipalities along the coast of Iwate, Miyagi and Fukushima prefectures. Fig.1, in the next page, shows the twenty municipalities analyzed in this study. As it was clear that many factors of geological and social features affected the HVIs, a multiple regression analysis was applied to extract a formula that correlated HVI and some dominant factors. The authors then verified the reliability of the formula and discussed a way to utilize HVI in disaster mitigation planning and management of municipalities.

The authors used human and building damage data collected from Fukko-Shien-Chosa archives [12] (hereafter, FSC archives) operated by the Center for Spatial Information Science, the University of Tokyo and the City Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan. These archives contain interview data of the emergency actions of 10,600 refugees as well as building and infrastructure damage to 65 municipalities along the Pacific coast of East Japan. They are GIS-based archives and are open for public and academic use. The municipalities N, Q and U in Fig.1 were omitted from the HVI evaluation in this study, because the data of the interview survey in these areas seemed to deviate to some extent.

The second section of this paper describes the formulation of HVI and discusses its features. The third section discusses the relation between HVI and several important geographical and social features. The fourth section describes a multiple linear regression analysis and its application. Selection of explanatory variables, verification of regression formula and utilization for municipalities are discussed. The fifth section provides conclusions.

2. Formulation of HVI

HVI is defined as follows:

$$\mathrm{HVI} = \frac{\dfrac{\boxed{\text{Number of deaths}}}{\boxed{\text{Population}} \times \boxed{\text{Ratio of persons who were at home or coming back home}}}}{\dfrac{\boxed{\text{Number of washed-away buildings}}}{\boxed{\text{Total number of buildings}}}} \times \boxed{100} \tag{2}$$

Both the mortality rate (Number of deaths / Population) and the damaged building rate (Number of washed-away buildings / Total number of buildings) due to tsunamis increase monotonically with increase in tsunami height. Therefore, the effect of tsunami height was canceled out by taking the ratio of these two rates and hence comparing HVI of communities would become possible without considering tsunami height. The effect of vacant buildings is also decreased by dividing the number of damaged houses by the number of the houses in the area in the denominator. On the other hand, in order to compensate for the number of persons who were out of their homes at the time of the tsunami, the numerator is divided by the ratio of persons who were at home (including coming home soon after the earthquake). The formula is multiplied by 100 for ease of understanding.

The following describes the characterization and quantification of the four components in Eq. (2).

2.1 Mortality rate

The number of deaths is rather easily evaluated by counting the number of dead and missing from the public data source. However, it is not easy to identify their locations when they were struck by the tsunami.

Concerning people's locations, the questionnaire investigation showed that 50-80% of people whose houses were washed-away or heavily damaged by the tsunami were at home or returning home just after the 2011 Great East Japan Earthquake. And the mortality rate seemed to increase linearly with increase in the ratio of persons who were at home at least one time before the tsunami. Therefore, the mortality rate was divided by the ratio of persons who were at home or coming back home before the tsunami. This ratio is discussed in section 2.4 later.

2.2 Damaged building rate

The number of damaged buildings in each municipality area was listed in the FSC archives. But, some trial studies were needed to set the threshold level of damage for counting the number of damaged buildings. In this study, the washed-away damage level was selected from the view-point of HVI's independence from tsunami inundation height and for simplicity. This independence is discussed in section 2.5.

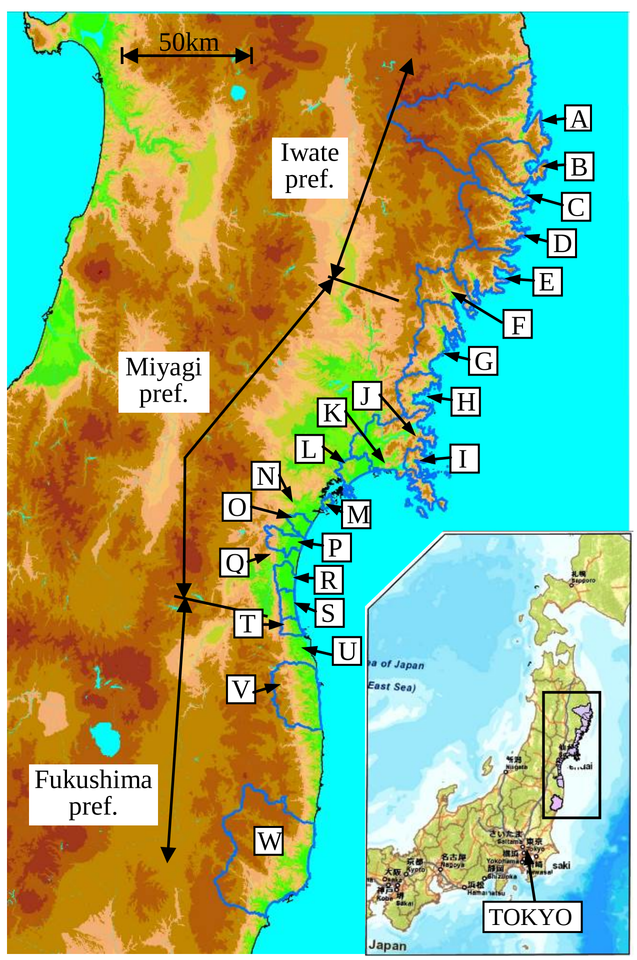

Fig. 1 – Analized municipalities

2.3 Area for counting population and buildings

For the population and the number of buildings, it was thought to be more accurate to use the data inside the tsunami inundation area. However, it was not always easy to identify the tsunami inundation area and to count the population and the number of buildings. Although the population and buildings data by municipality unit are easy to get from census data on the web or from municipality publications, the tsunami inundation area was only a part of the total municipal area and it was not easy to extract the relevant data from the whole. HVI should be calculated by using an easily attainable database, so the data by municipality unit were used.

2.4 Ratio of persons who were at home including coming home before the tsunami

The location of people at the time of the earthquake and their movement before the tsunami were extracted from FSC archives. But, the data concerning people's behavior was based on a questionnaire to a limited number of evacuees, and inevitably deviated to some extent from the census data in sex and age distribution of the corresponding area. Therefore, weighting factors for three age groups, namely, ages of 20-49, 50-69 and 70-over, were calculated in order to adjust the age distribution to that of census data, and a weighted average was applied.

2.5 Calculation of HVI and verification of independence from tsunami height

Table 1 is a list of the parameters discussed in sections 2.1 to 2.4.

Table 1 – Statistical data for HIV evaluation

Municipality	Number of deaths *1	Population of municipality *2	Rate of persons who were at home *3	Washed-away houses *4	Residential houses in municipality *2	HVI	Average inundation depth around washed away houses*4	Tsunami arrival time after earthquake
A	514	59,430	0.718	1,628	25,010	18.5	5.43 meters	35 minutes
B	752	18,617	0.729	2,182	7,950	20.2	5.42	35
C	1229	15,276	0.658	3,323	6,130	22.6	7.98	35
D	1040	39,574	0.724	2,608	18,420	25.6	7.46	35
E	419	40,737	0.698	2,908	16,580	8.4	6.9	35
F	1,763	23,300	0.803	3,726	8,550	21.6	10.9	35
G	1,326	73,489	0.741	5,922	25,670	10.6	7.05	35
H	812	17,429	0.752	4,564	5,540	7.5	10.73	35
I	850	10,051	0.762	1,815	3,981	24.3	13.48	35
J	985	23,611	0.881	4,384	9,524	10.3	8.14	35
K	2,292	112,683	0.823	5,109	45,451	22.0	4.52	60
L	1,086	42,903	0.835	2,823	15,450	16.6	3.61	60
M	78	20,416	0.895	1,053	6,650	2.7	4.52	65
O	297	132,306	0.561	1,307	70,640	21.6	4.26	65
P	950	73,134	0.623	1,571	25,820	34.3	4.75	65
R	270	34,845	0.819	968	11,520	11.3	3.41	65
S	698	16,704	0.756	2,380	5,310	12.3	5.78	60
T	110	8,218	0.827	497	2,760	9.0	7.60	65
V	636	70,895	0.631	1136	25,050	31.4	5.24	65
W	330	342,198	0.733	930	147,740	20.9	3.31	53

*1 Extracted from damage data reported by Iwate, Miyagi and Fukushima prefecture
*2 2010 census data. The number includes vacant house.
*3 Extracted from FSC archives and corrected by the process descrived in the secssion 2.4
*4 Extracted from FSC archives

Fig.2 shows plots of HVI taking the average inundation depth around the washed-away houses on the horizontal axis. The dotted line in the figure is a regression line through the least-square method. The gradient of the line is small enough, so the HVI is almost independent of the inundation depth and satisfies necessary conditions to be a vulnerability index. As shown in Table 1 and Fig.2, the HVIs spread between 2.7 to 34.3, which indicates that the municipality evacuation vulnerabilities vary widely.

3. Vulnerability Analysis using HVI

3.1 Warnings and their transmission

JMA (Japan Meteorological Agency) issued a large tsunami warning 4 minutes after the Great East Japan Earthquake, which was immediately broadcast all over Japan by NHK (Japan Broadcasting Corporation). However, this first warning underestimated the tsunami heights as 3 meters in Iwate and Fukushima, and 6 meters in Miyagi. JMA amended the warnings twice (28 minutes and 44 minutes after the earthquake), and in the final warning, the tsunami heights were raised to more than 10 meters. But, because of the delay and confusion, these upgraded warning did not reach the people near the sea effectively.

Fig.3 denotes the relation between HVI and the possible tsunami heights of the first warning. The dotted line in the figures is the result of a single regression analysis taking HVI as the explanatory variable. The p value is the significance level (probability of rejection of null hypothesis which is true).

The HVIs of the municipalities that received the 3-meter warning tended to be higher than those that received the 6-meter warning. The warnings were transmitted to the people mainly by wireless loudspeaker systems of each municipality and by NHK radio or other broadcasters, although TVs in private houses were useless because of the electricity outage just after the earthquake. People in the area seemed to have perceived 3 meters as a moderate tsunami. The 3-meter warning would have been a sign of safety to people in areas protected by a seawall or at some distance from the coastline.

Fig.4 shows HVI and people's cognition rate regarding the large tsunami warning issued by JMA soon after the earthquake. In Fig.4, municipality P failed to broadcast the warning because of a malfunction of the wireless loudspeaker system. But people there were able to get the large tsunami warning from radio news of NHK or other broadcasters. Municipalities V is located in Fukushima prefecture, where the tsunami awareness level of municipalities and people there might have been low compared to those of Iwate and Miyagi prefectures.

Fig.5 shows "impact of warning" which was defined as the broadcasted tsunami height in the first warning multiplied by the people's cognition rate of the warning. The value of impact of warning might express one of the switch that makes people start evacuation.

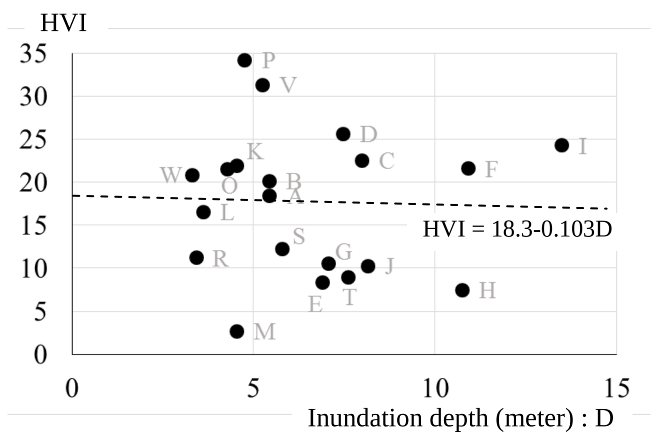

Fig. 2 – HVI vs. Average Inundation depth around washed away houses

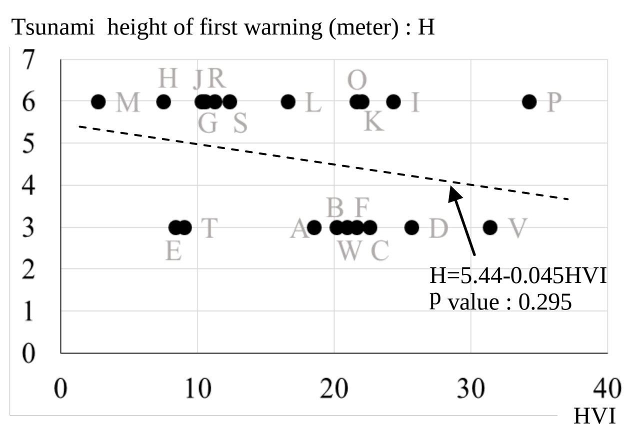

Fig. 3 – Tunami height of first waning vs. HVI

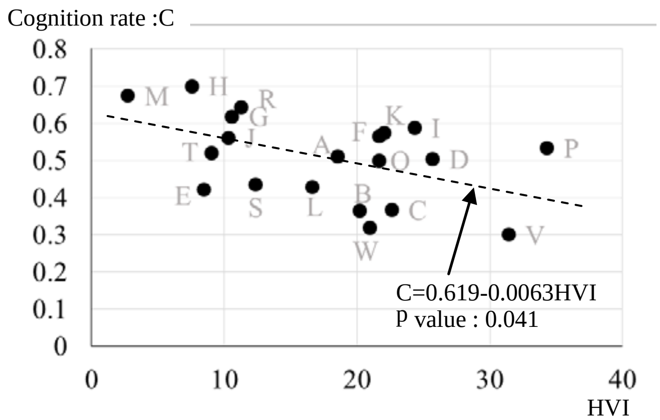

Fig. 4 – People's cognition rate concerning large tsunami warning vs. HVI

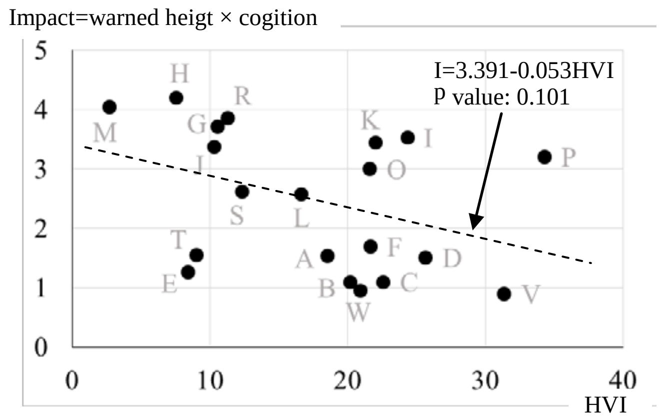

Fig. 5 – Impact of warning (Tsunami height of first warning × congnition rate) vs. HVI

3.2 Evacuation distance, tsunami arrival time and allowance for evacuees

Walking distance to get away from the tsunami inundation area was expected to be a good parameter to express the topographical difficulty for evacuation. But, in the plain region (K-W of Fig.1), over half of the evacuees drove cars and there were only a few data of pedestrian evacuees in some municipalities, so a modified distance was introduced adding the average distance of car-driven evacuation. Fig.6 shows HVI and the modified distance.

Namely,

$$M(i) = W(i) * RW(i) + D(i) * RD(i) * 0.234 \tag{3}$$

where, M(i) : Modified distance of i municipality
W(i) : Average walking evacuation distance to get out of tsunami inundation area
RW(i) : Rate of walking evacuating persons of i municipality
D(i) : Average car-driving evacuation distance to get out of tsunami inundation area
RD(i) : Rate of car-driving evacuating persons of i municipality
$0.234 = \Sigma W(i) / \Sigma D(i)$

Tsunami arrival time from earthquake incidence was also an influential parameter for safe evacuation as well as evacuation distance. Therefore, the following allowance for evacuees was defined.

$$\text{Allowance(i)} = \frac{\text{Tsunami arrival time (i)}}{\text{Modified distance (i)}} \tag{4}$$

Allowances are shown in Fig.7 with HVI on the horizontal axis. Tsunami arrival times to municipalities are listed in the rightmost column of Table 1.

3.3 Preparedness

"Looking at and checking the hazard map", "Participating in disaster drill", "Talking evacuation method with family" and "Preparing emergency bag" can be index values of evacuation preparedness level. However, the hazard maps of some municipalities greatly underestimated tsunami risk, and/or their disaster drills did not include evacuation from tsunamis. So, these two were not effective indexes in the case of the Great East Japan Earthquake.

"Talking evacuation method with family" seemed to be effective, but it did not have a clear relation with HVI. This index was difficult to evaluate through questionnaire survey, which inevitably included interviewer and interviewee personal judgements. Additionarily, talking with family did not demand any action by itself.

Fig.8 is a plot of the rate of persons who always prepared an emergency bag, with HVI on the horizontal axis. The emergency bag usually contained a flashlight, a radio, some food, paper, some clothing, some medicines, etc., and was hooked near the door for easy access in an emergency. Preparing the emergency bag seemed to require a high level of awareness against disaster.

3.4 Mitigation facilities

Disaster mitigation by hardwares, such as road serviceability, must also be an appropriate explanatory variable. Road serviceability level for tsunami evacuation (hereafter RS) was assumed to be evaluated by multiplying car speed by the rate of car evacuees.

$$\text{Road serviceability level: } RS = S \times R \qquad (5)$$

where, S: Average car speed driving from house to outside tsunami inundation area, shown in Fig.9
R: Rate of car users among evacuees , shown in Fig.10
S and R were extracted from FSC archives.

Fig.11 is a plot of road serviceability level. Municipalities O, S and V were outside the trend and pushed up the p value. Rates of car users were more than 90%, and car speeds were rather higher than others. Their HVIs seemed affected by other factors.

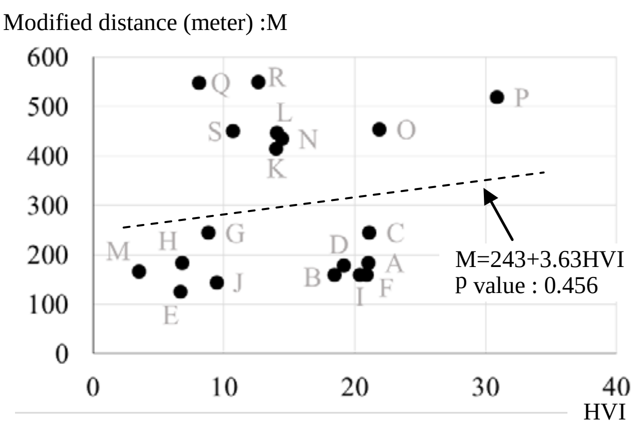

Fig. 6 – Modified distance to safe area vs. HVI

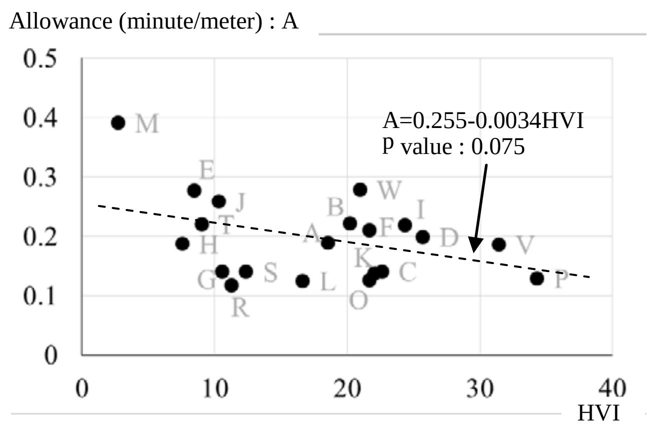

Fig. 7 – Allowance for safe evacuation vs. HVI

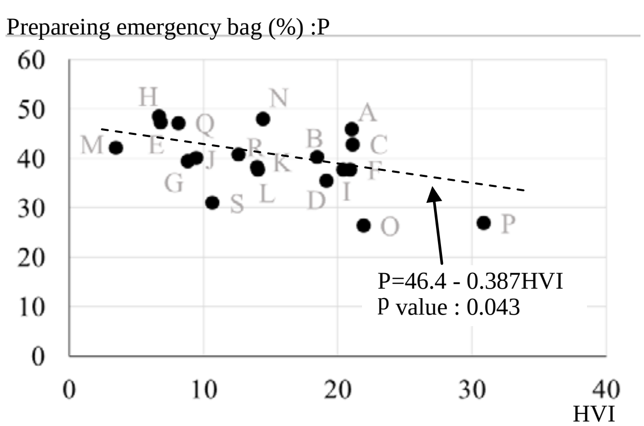

Fig. 8 – Rate of persons always preparing an emergency bag vs. HVI

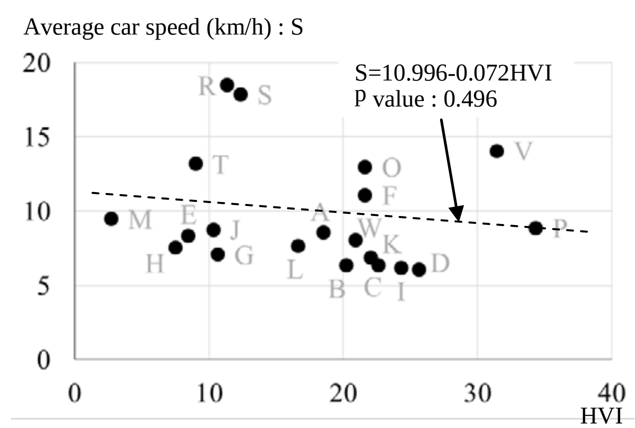

Fig. 9 – Average car speed on evacuation vs. HVI

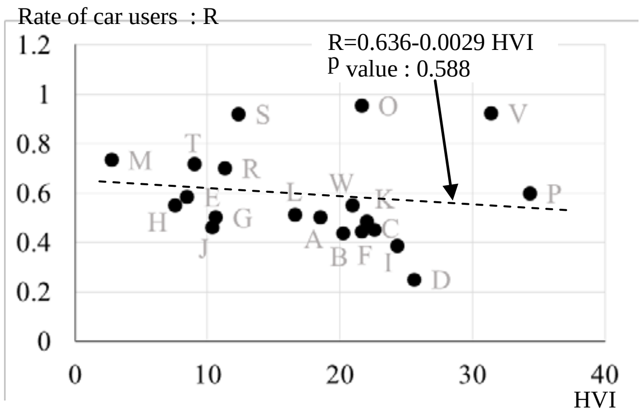

Fig. 10 – Rate of car users among evacuees vs. HVI

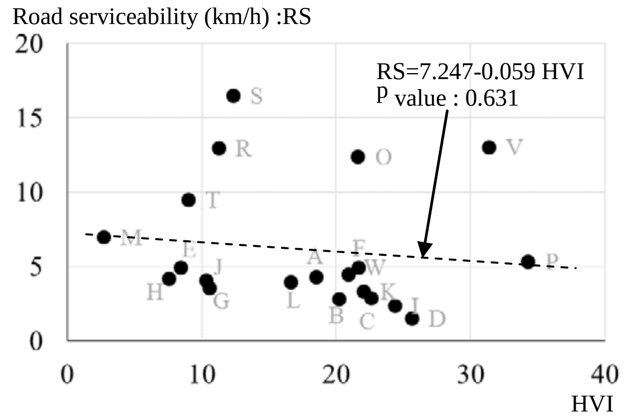

Fig. 11 – Road serviceability level vs. HVI

4. Multiple Regression Analysis

Many of the results of the simple linear regression analyses applied in section 3 did not extract clear correlation between the candidate explanatory variables and HVI. The p values exceeded 0.05 except for the cases shown in Fig.4 and Fig.8. Therefore, a multiple regression analysis was applied for further study.

4.1 Selection of explanatory variables

Through a lot of trial-and-error, four explanatory variables were selected according to four items as shown in Table 2. The more explanatory variables included, the larger the coefficient of determination R2. But, the regression formula, which is the outcome of the multiple regression analysis, must be simple for easier understanding and for better use in municipal disaster mitigation planning.

The following four items were set in consideration of clear meaning and orthogonality.

Impact: The variable should express the switch that makes people aware of the emergency and start evacuation. Impact of warning (tsunami height broadcast in the first warning × people's cognition rate of the warning, shown in Fig.5) was applied in this study.

Allowance: The variable should express the natural environment that affects the ease of evacuation. The longer the tsunami arrival time and the shorter the evacuation route length, the greater the allowance for safe evacuation. Allowance was already discussed in section 3.2 and defined as the arrival time of the first big tsunami divided by the evacuation distance along which the evacuees actually moved.

Preparedness: This study focused on people's awareness level concerning tsunami risk in order to identify their preparedness. Many variables were examined. And the rate of prior emergency bag preparation remained as the best fit, as discussed in section 3.3.

Facilities: This variable should express the improvement level of evacuation facilities. This study applied the road serviceability level, which was evaluated by the evacuating car speed multiplied by the rate of car users among evacuees, as described in section 3.4. The higher the road serviceability, the greater the car speed and rate of car users. If many evacuees use cars and the road serviceability is low, traffic jams occur, which lowers car speed.

Table 2 – Explanatory variables for multiple regression analysis

Sign	Item	Explanatory variable
I	Impact	Tsunami height of first warning × congnition rate (Fig.5)
A	Allowance	Tsunami arrival time / Equivalent distance to safe place (Eq. (4), Fig.7)
P	Preparedness	Rate of persons who always prepared emergency bag (Fig.8)
F	Facilities	Road serviceability level evaluated by Eq. (5) and Fig.11

The extent and height of seawalls could be an effective variable in the facilities item. But, in the case of the 2011 Great East Japan Earthquake, the tsunami overflowed and destroyed most of the seawalls. Moreover, their existence seemed to give people a virtual sense of security and to hinder them from looking at the tsunami coming. More data and survey were needed to evaluate the efficacy of seawalls.

4.2 Regression formula and recurrent HVI

The input values for the variables are listed in Table 3. They were computed from the FSC archive data, on a municipality-to-municipality basis. As already mentioned in section 2.4, weighting factors for three age groups and a weighted average were applied in order to adjust the age distribution of the data to that of census data of the corresponding area.

The multiple regression analysis program released by IBM-SPSS was used, and the calculated regression coefficients as well as their approval data, p values and VIF, are listed in Table 4. The indicators that denote the fitness of the regression formula are listed in Table 5. The correlations between variables are listed in Table 6.

The formula for recurrent HVI, the outcome of the multiple regression analysis, is denoted by Eq. (6). The recurrent HVI for each municipality is listed in the rightmost column of Table 3.

$$\text{Recurrent HVI} = 55.98 - 1.348\times I - 50.85\times A - 0.684\times P - 0.798\times F \tag{6}$$

In order to approve the regression formula Eq. (6), HVI and recurrent HVI are plotted in Fig.12. The deviation of the plots from a one-to-one straight line indicates the error from the ideal value. However, using the recurrent HVI, recurrent number of deaths was calculated using Eq (7) denoted in section 4.3. The total deviation of the number of deaths is 5.3% as listed in Table 7 and it can be concluded that the deviation is not serious for practical use.

Table 3 – Input values for explanatory variable and recurrent HVI

Municipality	HVI	I (Impact)	A (Allowance)	P (Preparedness)	F (Facilities)	Recurrent HVI
		(meter)	(minute/meter)	(%)	(Kirometer/hour)	
A	18.5	1.536	0.190	37.9	4.34	14.9
B	20.2	1.098	0.222	31.1	2.81	19.7
C	22.6	1.104	0.142	30	2.9	24.4
D	25.6	1.515	0.200	27	1.54	24.1
E	8.4	1.266	0.278	35.6	4.92	11.9
F	21.6	1.698	0.211	30	4.94	18.5
G	10.6	3.72	0.141	31.1	3.57	19.7
H	7.5	4.212	0.188	36.6	4.19	12.4
I	24.3	3.534	0.220	28.5	2.4	18.6
J	10.3	3.378	0.259	33.2	4.09	12.3
K	22.0	3.456	0.139	34.9	3.36	17.7
L	16.6	2.58	0.126	37.6	3.97	17.2
M	2.7	4.05	0.392	36.5	6.99	0.04
O	21.6	3.006	0.127	13.1	12.43	26.6
P	34.3	3.21	0.130	20	5.35	27.1
R	11.3	3.864	0.118	35.4	13.01	10.2
S	12.3	2.622	0.141	29.9	16.51	11.6
T	9.0	1.56	0.221	36	9.52	10.4
V	31.4	0.903	0.187	9.4	13.04	28.4
W	20.9	0.96	0.279	16.1	4.47	25.9

Table 4 – Regression coefficients

	Constant	I (Impact)	A (Allowance)	P (Preparedness)	F (Facilities)
Regression coefficient	55.98	-1.348	-50.85	-0.684	-0.798
*p value	0.000	0.189	0.006	0.000	0.010
Standard regression coefficient		-0.189	-0.420	-0.689	-0.408
**VIF (variance inflaction factor)		1.151	1.074	1.265	1.172

*p value should be less than 0.05. **VIF should be less than 10.

Table 5 – Fitness indicators

Coefficient of determination R2	0.756
R2* adjusted for degrees of freedom	0.691
Standard error SE	4.65
Significance probability p	0.000

Table 6 – Correlation between variabls

	I	A	P	F
I	1	-0.105	0.300	0.063
A	-0.105	1	0.139	-0.218
P	0.300	0.139	1	-0.310
F	0.063	-0.218	-0.310	1

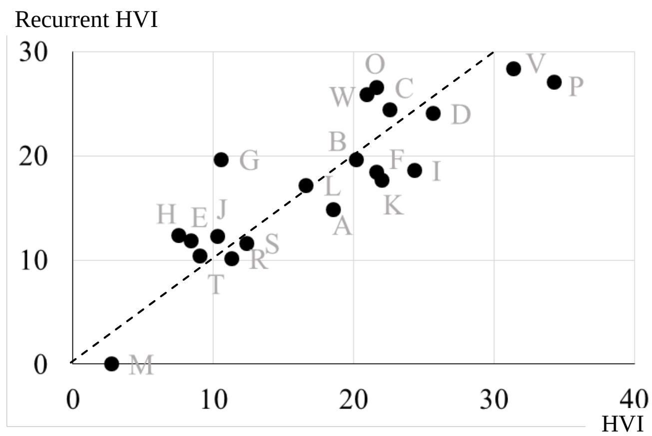

Fig. 12 – Recurrent HVI vs. HVI

Table 7 – Fitness about total number of deaths

	Number of deaths
Acutual number	16,437
Recurent number	17,300
Error	5.3%

4.3 Discussion of HVI application to assess loss of human life beforehand

Recurrent HVI must be an effective tool to assess loss of human life and to assess the impact of each explanatory variable. This assessment will help municipalities to plan countermeasures and to evaluate the progress of its improvement.

In order to evaluate loss of human life using the recurrent HVI, Eq. (2) was transformed to Eq. (7).

$$\text{Number of deaths} = \frac{\text{Recurrent HVI} \times \text{Total population} \times \text{Number of washed-away buildings}}{\text{Total number of buildings} \times 100} \quad (7)$$

The total number of deaths in the twenty municipalities was evaluated by Eq. (7) using the sets of explanatory variables of which values were improved or decreased with 1σ (standard deviation) of their dispersion. Seven cases including the original case are listed in Table 8. If all sets of variables were improved with 1σ, shown in the last line of the table, the number of deaths became less than three thousand, which was about 7 times smaller than that of the original set case. For all variables degraded case, shown in the sixth line, the number of deaths was over thirty thousand.

The second to fifth lines of Table 8 show the cases that one of the explanatory variables was set to the improved values by 1σ and the other three variables were set to their original values. The preparedness level was most effective among the four variables for reducing the number of deaths.

In order to assess HVI and the number of tsunami victims of a municipality that has not yet suffered a tsunami, the four explanatory variables and the number of washed-away buildings must be evaluated.

Variable I should be evaluated in accordance with people's perception of tsunami height. In the case of the Great East Japan Earthquake, people along the coast of Iwate and Miyagi prefectures seemed to perceive the tsunami height of 3 meters as a moderate tsunami, and to perceive the height of 6 meters as a large tsunami. Tsunami warning height and people's cognition rate of it can be reflected to this variable.

Variable A is easy to evaluate from road network data and scenario tsunami data of the region. Variable P can be evaluated from the questionnaire survey on people's risk awareness level.

Variable F needs data on car speed during evacuation and the rate of car evacuees. The speed may be evaluated by analyzing the road network capacity and the traffic demand. Multi-agent simulation or network simulation will be effective tools for this evaluation.

Number of washed-away buildings can be evaluated by mapping the tsunami inundation simulation data to the location data of houses of the municipality and counting the houses that dipped more than the threshold depth. The threshold depth for washed-away damage can be evaluated using the tsunami fragility formula of existing studies.

Table 8 – Recurrent estimation of number of deaths using regression formula

	Average Recurrent HVI	Factors to multily to the coresponding values of Table 3				Number of deaths
		I (impact)	A (Allowance)	P (Preparedness)	F (Facilities)	
Original	17.6*	1.0	1.0	1.0	1.0	17,300
I improves by 1σ	16.0*	(1.0+1σ)	1.0	1.0	1.0	15,500
A improves by 1σ	14.1*	1.0	(1.0+1σ)	1.0	1.0	13,800
P improves by 1σ	11.8*	1.0	1.0	(1.0+1σ)	1.0	10,900
F improves by 1σ	14.2*	1.0	1.0	1.0	(1.0+1σ)	14,400
All descend by 1σ	31.8*	(1.0-1σ)	(1.0-1σ)	(1.0-1σ)	(1.0-1σ)	31,800
All improve by 1σ	3.31*	(1.0+1σ)	(1.0+1σ)	(1.0+1σ)	(1.0+1σ)	2,700

* Simple average of twenty municipalities' HVIs

4. Conclusions

(1) HVI was defined as the ratio of the rate of deaths divided by the rate of washed-away houses. It was computed for twenty municipalities and was verified to express the evacuation vulnerability of each one.

(2) The multiple regression analysis for HVIs of the twenty municipalities defined the balanced regression formula to estimate HVI by introducing four explanatory variables, namely, impact, alllowanse, preparedness and facilities.

(3) The regression formula was verified to be reliable by comparing the original HVI with the recurrent HVI and by comparing the actual number of deaths with the number of deaths evaluated by the recurrent HVI.

(4) From cases where one of the explanatory variables was set to an improved value with 1σ of its dispersion, preparedness, emergency bag preparation, was found to be a most effective factor in reducing the number of deaths. HVI has a potential to compare the effectiveness of different kind of countermeasures.

(5) Municipalities facing tsunami risk can utilize this formula to evaluate specifically their vulnerability in people's evacuation management and to set up a goal for countermeasures numerically.

(6) Some technical improvements would be necessary to apply the HVI to municipalities that do not have enough data for the explanatory variables.

(7) This study was based on the data of people's evacuation actions during the Great East Japan Earthquake and Tsunami. The next step of this study is to apply the HVI to the data of other tsunami disasters, to improve the regression formula and to elevate its applicability.

Acknowledgements

The authors acknowledge the assistance of the City Bureau of the Land, Infrastructure and Transportation Ministry of Japan and the Center for Spatial Information Science of the University of Tokyo, for their efforts in collecting very many data concerning people's evacuation in the Great East Japan Earthquake tsunami, compiling them and uploading them on the web as the Fukkou Shien Chosa archive.

The authors also express much appreciation to Professor Hitomi Murakami of Yamaguchi University for her helpful discussions.

References

[1] Imamura A (1913): *Disaster prevention Committee Report 77*. Disaster prevention Committee (in Japanese)

[2] Kawasumi H (1954): Intensity and Magnitude of Shallow Earthquake, *Bureau Central Seism. Intern.*, Ser. A, Tray. Sc., 19, 99-114

[3] Ohta Y, Goto N and Ohashi H (1983): An Empirical Construction of Equations for Estimating Number of Victims at an Earthquake, *Zisin*, Vol. 36, No.6, pp. 463-466 (in Japanese)

[4] Coburn A and Spence R (1992): Earthquake protection.Wiley

[5] Miyano M and Lu H G (1995): The Effect of Fault Distance to the Relationship between Human Casualties and Housing Damage due to Earthquakes, *Jounal of Japan Society for Natural Disaster Science,* No.13-3, pp. 287-296 (in Japanese)

[6] Murakami H (1996): Chances of Occupant Survival and SAR Operation in the Buildings Collapsed by the 1995 Great Hanshin Earthquake, Japan. *Proceedings of Eleventh World Conference on Earthquake Engineering, Paper* No. 852

[7] Matsuda I (1996): Changes of Human Losses and Deaths due to the 1995 Hyogo-ken Nanbu Earthquake, *Comprehensive Urban Studies*, Vol. 61 pp.155-166 (in Japanese)

[8] Moroi T and Takemura M (1999): Comparison of Fatality Risk between the 1891 Nobi Earthquake, the 1948 Fukui Earthquake and the 1995 Hyogoken-Nanbu Earthquake, *Zisin*, Vol. 52, pp.189-197 (in Japanese)

[9] Takemura M (2008): Earthquake and Disaster Prevention ~from vibration to aseisemic design~. *Chukoshinsyo*, Chuokoron-Shinsha Inc. (in Japanese)

[10] Nakasu T and Kurahara M (2013): Disaster investigation and the Great East Japan Eathquake. *Social Research* Vol.10, pp. 64-69, Japanese Association for Social Research (in Japanese)

[11] Goto Y (2014): Index to Evaluate Tsunami Evacuation Potential and its Validation at Yamada, Iwate Prefecture. *Journal of Disaster Research*, Vol.9, No.7, pp.730-742.

[12] City Bureau of the Land, Infrastructure and Transportation Ministry of Japan and the Center for Spatial Information Science of the University of Tokyo: Fukkou Shien Chosa archive. http://fukkou.csis.u-tokyo.ac.jp/default/about (Browsed at March, 2014) (in Japanese)