Development of Traffic Simulation for Tsunami Evacuation
- Case Study for Kesennuma city -

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Abstract: During the 2011 off the Pacific coast of Tohoku Earthquake, many residents living coastal area used car for their evacuation from mega Tsunami. Due to the rapidly increased traffic demand in road network and also trouble of traffic signals, heavy traffic congestions occurred in the road network. At first, this research investigated the condition of car evacuation in Kesennuma city. Secondly, tsunami evacuation simulation system was developed. Thirdly, several counter-measures for safer tsunami evacuation were developed and proposed. Finally, the scenario of roads widening proposed by Kesennuma city was evaluated using the simulation system. As a result, it was clarified that road widening is an effective countermeasure to modify the road traffic flow and that it could not solve the problems in car evacuation perfectly.

Keywords: the 2011 off the Pacific coast of Tohoku Earthquake, tsunami, traffic simulation, stochastic user equilibrium assignment model

1. INTRODUCTION

At 14:46 JST (5:46 UTC) on March 11th, 2011, an earthquake with a moment magnitude of 9.0 struck off the shore of the Sanriku area in the Tohoku Region. This earthquake was later named “The 2011 off the Pacific coast of Tohoku Earthquake” by the Japan Meteorological Agency.

Following mega tsunami hit deeply indented coastal areas and brought extensive and devastating damage to many cities and villages. Damage of the tsunami was not restricted to buildings and structures. Resulting fires destroyed many communities. Furthermore, nuclear power plant facilities have suffered complicated and serious damage due to this mega tsunami. The total number of fatalities and missing were 15,694 and 4,669 respectively and that of completely damaged buildings was 112,962.

Several big earthquakes with tsunami are expected to occur in near future in Japan. As seen in many cities in the Tohoku region, it is expected that heavy traffic congestion will occur on the road network due to the trouble of traffic signal and rapid increase of traffic demand. Such situation will be very dangerous evacuation from tsunami. Central Disaster Prevention Council, which is the supreme organization of disaster affairs in Japan, has warned about them in published reports.

According to our previous studies, it became clear that about 60% of residents evacuated used vehicles and that about 30% of residents using vehicles were involved in traffic congestion. It indicates that car evacuation is not safer than walking evacuation.

Local government is considering the countermeasures such as road widening to accomplish safer evacuation. Then, it is necessary to evaluate the countermeasures planned by local government.

The purpose of this study is to make a traffic micro-simulation and to evaluate the effectiveness of the proposed countermeasures for safer car evacuation. This study analyzed car evacuation of the resident suffered from the 2011 off the Pacific coast of Tohoku Earthquake in Kesennuma city using micro-simulation system. Moreover, authors developed concept of car evacuation methodology against tsunami to solve the problems which occurred in tsunami disaster, and evaluate the developed methodology using micro simulation system. As a result of developed car evacuation methodology is effective to reduce the evacuation time and road traffic congestions under the same conditions as the 2011 off the Pacific coast of Tohoku Earthquake.

This paper is organized as follows. In chapter 2, the previous studies regarding tsunami evacuation is reviewed. In chapter 3, the condition of car evacuation in Kesennuma city is investigated. In chapter 4, micro-simulation system regarding tsunami evacuation is developed. In chapter 5, concept of the countermeasures for safer tsunami evacuation is described. In chapter 6, the scenario of roads widening proposed by Kesennuma city is evaluated using the simulation system. In chapter 7, the result of this study and is remarked.

2. PREVIOUS STUDIES

Over the past few decades, a considerable number of studies have been conducted concerning the Tsunami evacuation in Japan (almost Japanese paper). For example, Katada *et al.* (2005), Tamagawa *et al.* (2006), Saito *et al.* (2006), Endo *et al.* (2011) and Onomura *et al.* (2012) are examined. These studies have focused on education of disaster prevention, survey for Tsunami evacuation of past Tsunami disasters and so on. Little attention has been given to conduct efficiency Tsunami evacuation during earthquake disasters using car. There is no study to evaluate countermeasure of Tsunami evacuation using car. Therefore, we will concentrate on following issues: Tsunami evacuation analysis and tsunami evacuation behavior.

From the view point of Tsunami evacuation analysis, Limanond *et al.* (2011) investigated the tsunami evacuation route decision among sample groups of Thai and foreigners in Patong area. The majorities of Thais were local residents or stayed in the Patong Beach area for more than a year, while most foreigner respondents were tourists and spend less than a month in the area. The evacuation route decisions among these two groups were rather distinctive. Almost 70 percent of Thai samples preferred to choose their own evacuation routes, and another 23 percent would follow the ‘evacuation route’ guide signs. The foreigner respondents mostly relied on the evacuating crowd (38 percent) and, to a lesser extent, on the ‘evacuation route’ guide sign. Only 19 percent confidently decided their own evacuation route, while 12.6 percent would seek assistance from the officers.

From the view point of Tsunami evacuation analysis, Charnkol *et al.* (2007) developed emergency trip destination (emergency shelter) choice model using logistic regression model and neural network model. It has demonstrated the feasibility of using logistic regression and artificial neural networks in predicting a respondents’ decision to select emergency trip destination. It is therefore concluded that the same specification among the logistic regression and the neural network models could be used to compare the performance of the models.

Logistic regression and neural network models appear, overall, to perform with similar accuracy on the data used in this study.

The research of Tsunami evacuation analysis and Tsunami evacuation behavior has been reviewed. However, there is no research which examined the analysis of Tsunami evacuation using car and evaluation of Tsunami evaluation countermeasures.

3. CONDITION OF CAR EVACUATION IN KESENNUMA CITY

3.1 Description of Investigated Area

Kesennuma city located in the northeast of Miyagi prefecture was selected as investigated area because the large sections of the city were destroyed by the tsunami. Figure 1 shows a map indicating the level of damage. As seen in the figure, completely destroyed area spread in coastal area. Some damaged area and only inundation area are few regions. Moreover, damaged houses which is completely destroyed in this area is about 30%, and damaged houses which is partially destroyed houses is about 17% in this area.

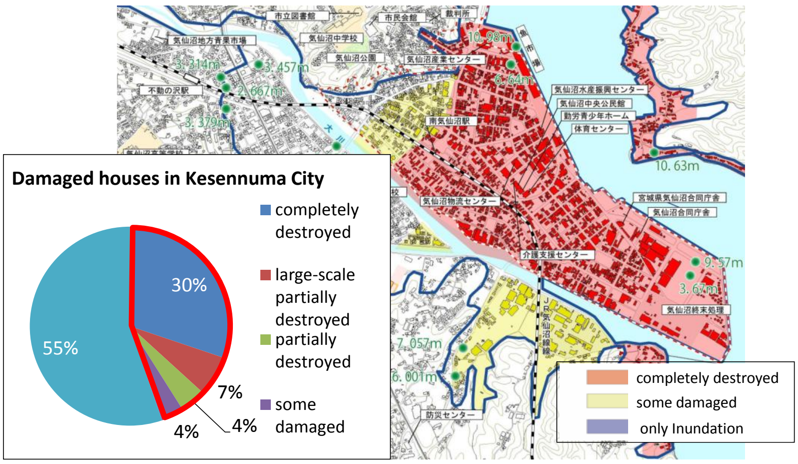

Figure 1. Inundation area & damaged houses

3.2 Situation of Tsunami Evacuation in Kessennuma City

This study investigated the tsunami evacuation mode in Kesennuma city for evacuation person which live in a temporary dwelling. Figure 2 shows the ratio of safety evacuation by car and walk. As a result of that survey, about 90% of walking evacuation people answered that they can evacuate smoothly to evacuation center. On the other hand, about 50% of car evacuation people answered that they cannot evacuate smoothly to evacuation center. Furthermore, this study analyzes relation of starting point and evacuation situation as shown in figure 3. Red point indicates that they can evacuate smoothly, blue point indicates that they cannot evacuate smoothly, and purple line indicates that congestion road in damaged area. And, yellow line indicates that inundation area. As a result of this analysis, traffic congestions occurred on main road in damaged area. Then, evacuation person cannot evacuate smoothly. On the other hand, evacuation person which started in coastal area have difficulty for evacuate to evacuation center.

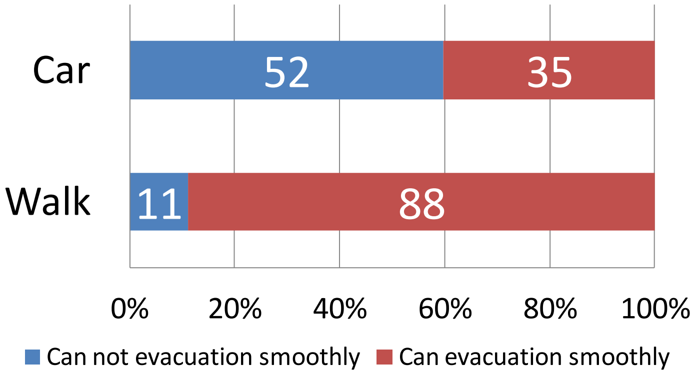

Figure 2. Ratio of safety evacuation by Car and walk

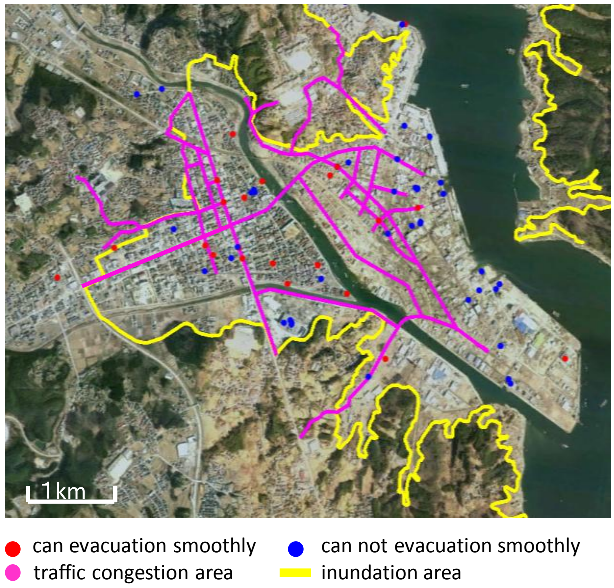

Figure 3. Traffic conditions during the evacuation period

4. DEVELOPMENT OF TSUNAMI EVACUATION SIMULATION

4.1 Zoning

In this study, the tsunami evacuation around the Kesennuma district in Kesennuma city was examined. To conduct micro-simulation of car evacuation, it was necessary to make Origin-Destination matrix regarding of the car evacuation. Therefore, this district was divided by 24 zones as shown in the figure 4. Seventeen zones were considered as the zones for origins and seven zones were for destinations. In the figure 4, origin zones are framed by red line with zone code in black ink and destination zones are framed by pink line with the zone code in pink ink.

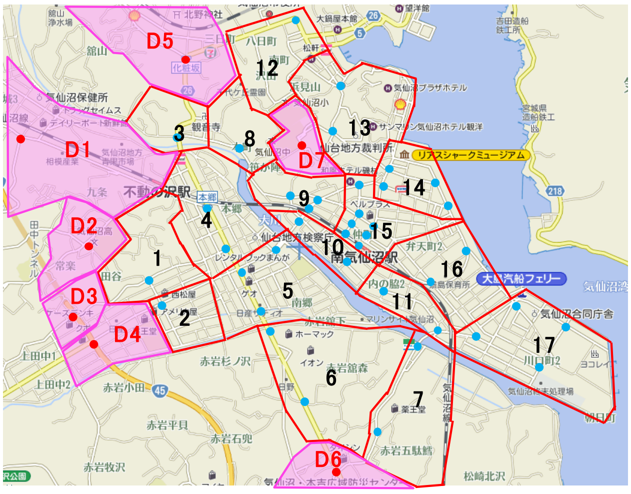

Figure 4. Zoning for micro-simulation

4.2 Road Network

Road network used for micro-simulation was configured according to OpenStreetMap. The road network indicated by grey lines in figure 5 is the network considered in micro-simulation. Meanwhile, Kesennuma city government has reported the congested road links during tsunami evacuation and the configured road network includes the whole congested links in this district.

Moreover, the blue dots in figure 5 indicate the origin nodes and also red dots indicate the destination nodes.

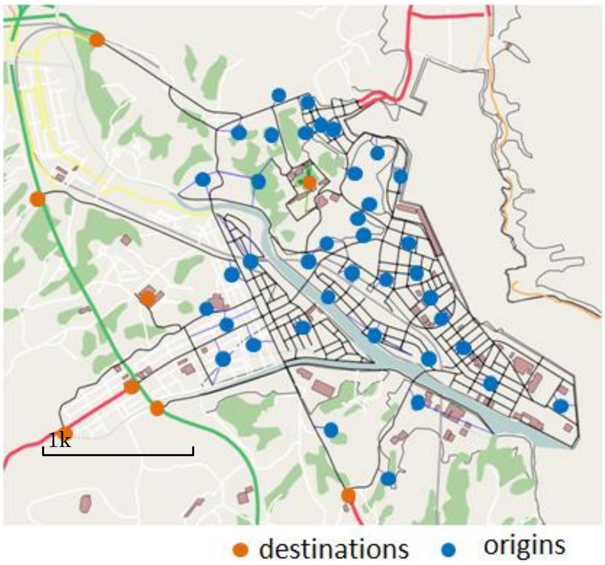

Figure 5. Road network used for micro-simulation

4.3 Evacuation Place Choice Behavior

An evacuation place choice model was estimated by multinomial logit model. As the results of our interviewed survey to the tsunami victims in Kesennuma city, several places were used as evacuation destinations. Therefore, 7 places which are indicated in red dots in figure 5 are set as the evacuation destinations. However, choice probability of one destination was relatively lower than other destinations. Consequently, this destination was excluded in the choice set for discrete choice model.

Distance to evacuation places and dummy variables are considered as explanatory variables of the model. The result of parameter estimation is shown in Table 1.

As shown in the table, distance to evacuation place is statistically significant variable. Both McFadden's Rho-squared and hitting ratio are not enough large to demonstrate explanatory power of the estimated model. Refining of the model would be done in our continued study.

Table 1. Estimation result of evacuation place choice model

Explanatory Variables	Model	
	Parameter	t score
Distance to evacuation place	-1.078**	-4.57
Dummy variable regarding evacuation place 1	-0.022	0.04
Dummy variable regarding evacuation place 2	-2.588*	-2.49
Dummy variable regarding evacuation place 3	-1.133**	-2.67
Dummy variable regarding evacuation place 4	-2.085**	-3.93
Dummy variable regarding evacuation place 5	-1.832**	-3.95
Observations	60	
McFadden's Rho-squared $\bar{\rho}^2$	0.106	
Hitting ratio	53.3%	

** Significant at 1% level; * Significant at 5% level.

4.4 Generation of Evacuation Traffic Volume and Origin-Destination Traffic

Actual volume of origin-destination traffic during tsunami evacuation should be set for simulation. However, the statistics of the volume is not available. Therefore, in this study, the traffic volume was derived by using several statistics. Because the earthquake occurred at 14:46, the O-D traffic was determined based on daytime population in Kesennuma city. Therefore, distribution of work place population, elderly population and students are used for the determination. The daytime population is totally 17,007 in the investigated district. Japanese government has reported that almost 60% of the tsunami evacuation was executed by car. Therefore, in this study, the traffic volume was set of the 60% of daytime population. Traffic volume generated in the simulation was set as 10,204 which is the 60 percent of 17,007.

Using the determined traffic generation volume in each origin zone and the choice probability of evacuation places, origin-destination traffic volume was determined as shown in table 2.

Table 2. Origin-Destination traffic (vehicles/30min.)

Destination / Origin	D1	D2	D3	D4	D5	D6	D7	Total
1	333	224	213	456	147	371	168	1912
2	62	19	34	133	23	106	45	420
3	43	5	3	13	25	11	48	147
4	267	82	83	352	137	283	165	1369
5	86	29	42	245	44	203	77	726
6	10	3	5	54	5	115	7	200
7	36	13	20	171	14	1323	99	1675
8	48	15	9	39	189	32	756	1088
9	43	13	19	91	21	85	201	473
10	57	18	26	121	21	198	177	618
11	15	5	8	23	7	149	63	270
12	82	27	18	61	459	71	1637	2355
13	80	25	36	151	156	138	1114	1700
14	49	17	24	115	74	94	472	844
15	78	24	35	164	64	173	411	949
16	74	23	33	145	56	449	412	1192
17	51	15	23	81	40	604	255	1069
total	1414	557	630	2414	1483	4402	6106	17007

4.5 Route Choice Behavior and Traffic Assignment Method

In this study, traffic simulation package software by the name of “Aimsun6” was utilized. This package has route choice function and the C-Logit model proposed by Cascetta(2001) is adopted.

$$P_k = \frac{e^{\theta(V_k - CF_k)}}{\sum_{l \in K_i} e^{\theta(V_l - CF_l)}} \qquad (1)$$

$$CF_k = \beta \ln \sum_{l \in K_i} \left(\left(\frac{L_{lk}}{\sqrt{L_l L_k}} \right)^{\gamma} \right) \qquad (2)$$

where,

- P_k : the choice probability of each alternative path *k*,
- V_i : the perceived utility for alternative path *i*,
- θ : scale parameter,
- CF_k : the commonality factor of path *k*.
- L_{lk} : the cost of links common to paths *l* and *k*,
- L_l, L_k : the cost of paths *l* and *k* respectively,
- β, λ : parameters.

The parameters of the C-logit model were set such as $\theta = 1$, $\beta = 0.15$, and $\lambda = 1$ in this study. Furthermore, stochastic traffic assignment model was adopted in this study.

4.6 Validation of Reproducibility of Traffic Condition during Tsunami Evacuation

Figure 6 is a result of simulation and it shows the level of traffic congestion at each road link. Red line indicates the congested road link where the average speeds is less than 5km per hour. The other hand, green line is not congested road link where the average speeds is among 25km and 30km per hour.

By comparing with figure 3 showing traffic condition during tsunami evacuation, it is demonstrated, the congested road link was reproduced by the simulation.

Figure 6. Reproductively of traffic flow

5. COUNTERMEASURES FOR SAFER CAR EVACUATION

In this chapter, the concept to accomplish safer car evacuation is explained. There are two kinds of countermeasures to control traffic flow during tsunami evacuations. One is the countermeasure to decrease the car use and the other is the countermeasure not to occur traffic congestion. Meanwhile, these countermeasures are achieved by the different approaches. One is hard which means physical approach and the other is soft which means psychological approach.

As the results, there are four categories according to the type of countermeasures and type of approaches as shown in figure 7. In each category, several methods to accomplish safer evacuation are listed. It is necessary to confirm the effectiveness of all method by using micro-simulation. In this paper, only the effectiveness of road widening proposed by Kesennuma city was verified in the following chapter.

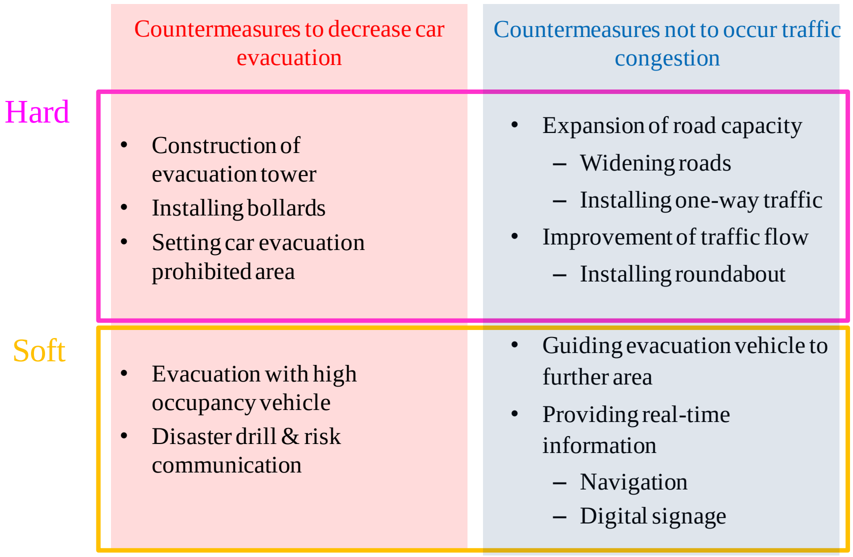

Figure 7. Countermeasures for safer car evacuation

6. EVALUATION OF ROAD WIDENING

6.1 Road Widening in Kesennuma City for Increase the Road Capacity

Kesennuma city have a new road planning for disaster prevention which is road widening for increasing the road capacity. Figure 8 shows that new road planning in Kesennuma city which indicates yellow line. Main road which indicates yellow line occurred traffic congestion during that earthquake. Then, local government decided road widening to increase the road capacity. This study evaluates the effects of road widening in Kesennuma city using Micro simulation.

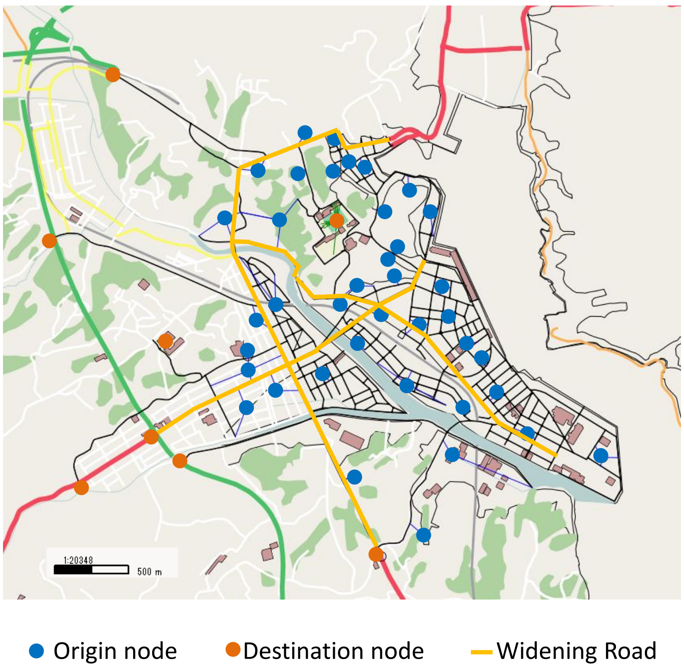

Figure 8. New road planning for disaster prevention in Kesennuma city

6.2 Result of the Simulation

This study evaluates the effects of road widening in Kesennuma city using Micro simulation as show in figure 9. Road widening has some effects which some road network can decrease in congestion level. On the other hand, some road network increases congestion level because of concentrate of traffic flow in main road in center of the city. In this study, road widening for increasing road capacity evaluates two indexes which is “total travel distance” and “vehicle inside”. “total travel distance” and “vehicle inside” means total amount distance of evacuation cars reached for evacuation center or evacuate further place and evacuation vehicle remain of inundated area respectively. As a result of evaluation shown in figure 10, “total travelled distance” is increasing. On the other hand, “vehicles inside” is decreasing. Road widening is an effective countermeasure to modify the road traffic flow; however, it could not solve the problem in car evacuation perfectly. Therefore, it is necessary to take structural countermeasures in combination with non-structural countermeasures.

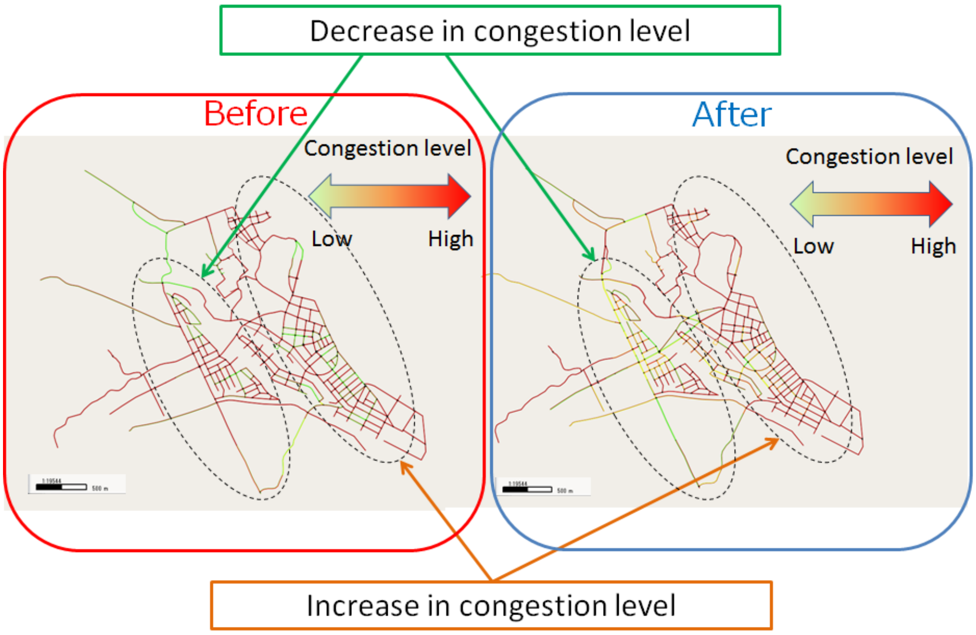

Figure 9. Simulation result of road widening

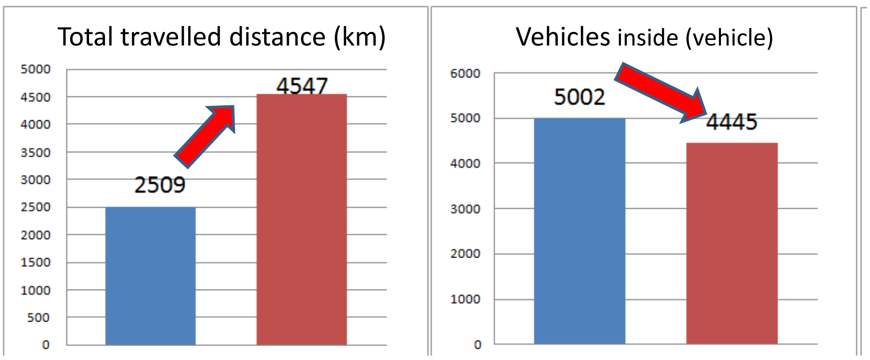

Figure 10. Simulation result of road widening

7. CONCLUSION

During The 2011 off the Pacific coast of Tohoku Earthquake, many residents which inhabit coastal area used the car for evacuation from mega Tsunami. Then, heavy traffic congestions occurred in the evacuation route for going forward evacuation site due to the trouble of traffic signal and rapid increase of traffic demand on the road. This situation is very dangerous to evacuate safely from Tsunami, and several big earthquakes with Tsunami is expected to occur in near future in Japan. Central Disaster Prevention Council which is the supreme organization of disaster affairs in Japan has warned about them in published reports. This paper analyzes the car evacuation of resident who suffered from the 2011 off the Pacific coast of Tohoku Earthquake in Kesennuma city using micro simulation system. Moreover, authors developed concept of car evacuation methodology against Tsunami to solve the problems which occurred in that Tsunami disaster, and evaluate the developed methodology using micro simulation system. As a result of developed car evacuation methodology is effective to reduce the evacuation time and road traffic congestions under the same conditions as the 2011 off the Pacific coast of Tohoku Earthquake.

REFERENCES

Toshitaka, K.(2005) Issues Of Resident's Consciousness And Evacuation From The Tsunami : From Questionnaire Survey In Kesennuma City, Miyagi Pref. After The Earthquake Of Miyagiken-Oki, 2003, Journal of JSCE, Vol.789, pp.93-104, 2005.

Natsuko, T.(2006) Multi Agent Simulation of Evacuation from Tsunami in the Central Part, Journal of architecture engineering, Vol.79, pp.175-178, 2006

Takashi, S. (2005) Simulation Of Evacuation Behavior From Tsunami Utilizing Multiagent System : A case study of Aonae, Okushiri island, Journal of architecture engineering, Vol.597, pp.229-234, 2005.11.30

Satoshi, E.(2011) Analysis of Tsunami evacuation in Kesennnuma city, proceedings of JNNDS, pp.149-150, 2011.

Kohei, O.(2012) Analysis of Tsunami evacuation using car in Kesennuma city, proceedings of JNNDS, pp.149-150, 2011.

Thirayoot, L. (2011) Decision on Tsunami Evacuation Route in Tourism Area: A Case Study of Had Patong, Phuket, Journal of the Eastern Asia Society for Transportation Studies, Vol.9, 2011.

Thai, C. (2007) Emergency Trip Destination Of Evacuation As Shelter Anslysis For Tsunami Disaster: A Case Study In Phuket, Thailand, Journal of the Eastern Asia Society for Transportation Studies, Vol. 7, 2007

Cascetta, E. (2001) Transportation systems engineering: theory and methods, Kluwer Academic Publishers.