ANALYSIS ON THE TSUNAMI FLOW VELOCITY DURING THE PACIFIC COAST OF TOHOKU EARTHQUAKE AND TSUNAMI

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The March 11, 2011 tsunami caused serious damage to many buildings, bridges and lifelines, and 18,771 people were killed and missing in Japan (data on 2012, July 25). From this event, the digital videos on the damage of structures and the tsunami flows were recorded and uploaded to open web sites. The tsunami flow velocity on land is estimated by using image processing of videos and estimating the dimension of the moving and reference objects. The analyzed tsunami flow velocities range about 2.9 - 4.9 m/s in Kamaishi town, 2.1 - 2.8 m/s in Ofunato town, 2.6 - 5.4 m/s in Kesennuma town, 1.4 m/s in Iwaki town and 2.6 m/s in Oarai town. Finally, the analyzed tsunami flow velocities are used to validate the tsunami velocity from the tsunami inundation simulation for this event. The tsunami flow velocities from the simulation results have the similar trend with the tsunami flow velocities by image processing of videos; however, most of them are less than the results by image processing of videos.

Key Words **:** *Tsunami, tsunami wave velocity, tsunami videos, tsunami simulation*

1. INTRODUCTION

The March 11, 2011 tsunami caused serious damage to many buildings, bridges and lifelines, and 18,771 people were killed and missing in Japan (data on 2012, July 25). From this event, the digital videos on the damage of structures and the tsunami flows were recorded and uploaded to open web sites. To analyze the structural damage due to the tsunami, the tsunami flow velocity and the tsunami inundation height are needed to estimate the hydrodynamic force acting on the structures (CCH, 2000; FEMA55, 2000; Yeh, 2007; Lukkunaprasit et al., 2009).

Many researches proposed the way to estimate the tsunami inundation flow velocity. Fritz et al. (2006) analyzed the tsunami velocities from the 2004 Indian Ocean tsunami by using recorded videos by the survivors in Banda Aceh, Indonesia. The particle image velocimetry analysis was applied to rectify the video images. The tsunami velocities in Banda Aceh were about 2 - 5 m/s. Matsutomi et al. (2006) reported the results of field surveys in Southern Thailand and Northern Sumatra from the 2004 tsunami. The approximated tsunami velocities were about 3 - 4 m/s in Patong beach area, Thailand, 6 - 8 m/s in Khao Lak area, Thailand and 5 - 16 m/s in Northern Sumatra, Indonesia. Matsutomi and Okamoto (2010) proposed the relationship of the inundation flow velocity and inundation depth. The inundation flow velocity was estimated by using Bernoulli's theorem and the inundation depth, and examined with the experiments. Koshimura and Hayashi (2012) analyzed the tsunami flow velocity and estimated the tsunami force of the 2011 tsunami in Miyagi Prefecture, Tohoku, Japan by using image processing of recorded videos. The proposed tsunami flow velocity of the tsunami front was faster than 6 m/s. The tsunami hydrodynamic force was roughly estimated as 100 kN/m.

In this research, the tsunami flow velocities on land are analyzed by using image processing of recorded videos and estimating the dimension of the moving objects and reference distances in Kamaishi town, Ofunato town, Kesennuma town, Iwaki town and Oarai town. The analyzed tsunami flow velocities are used to validate the tsunami velocities from the tsunami inundation simulation for this event in Kamaishi town, Ofunato town and Kesennuma town.

2. TSUNAMI FLOW VELOCITY FROM VIDEOS

(1) Location of recorded videos

The videos were recorded with handheld amateur video cameras by survivors. Among 9 recorded videos, 3 datasets were recorded in Kamaishi town, 3 datasets in Kesennuma town, 1 dataset in Ofunato town, 1 dataset in Iwaki town and 1 dataset in Oarai town. 15 points are considered as shown in **Table 1**(Video No.1-15). The recorded videos locations are specified by comparing the building landmarks in the videos with the Google Street View (Street View for Google Maps, 2011). The criteria for selecting video frames are that 1) the location of the considered objects should be perpendicular with the video camera angle, 2) the moving object should be parallel to the reference distance and 3) the moving object should flow with the same speed as the tsunami.

(2) Estimation of tsunami flow velocity

The examples of the moving object and the reference distance are shown in **Fig.1** to **Fig.3**. **Fig.1** shows the moving object, the wave front, and the reference distance, car parking channel, of the point No. 3 in Kamaishi town. **Fig.2** shows the moving car and the reference distance between 2 poles of the point No. 7 in Ofunato town. **Fig.3** shows the moving car and the reference distance on the building of the point No. 10 in Kesennuma town. The reference distance is estimated by the size of the car and drain cover. For the point No. 3, the width of the car parking channel is general size that can be measured from other places. For the point No. 7, the distance between 2 poles can be estimated by the size of the moving car. As shown in **Fig.4**, the width of the building for the point No. 10 can be estimated by using the photo from the Google Street View.

The number of frames and the lengths of the reference distance of each point are shown in **Table 1**. The frame rate of all videos is 30 frames per second. Therefore, the tsunami flow velocity v_e can be computed by Eq.(1). The tsunami flow velocities from the video analysis of all points are also shown in **Table 1**. The tsunami flow velocities are ranging about 2.9 - 4.9 m/s in Kamaishi town, 2.1 - 2.8 m/s in Ofunato town, 2.6 - 5.4 m/s in Kesennuma town, 1.4 m/s in Iwaki town and 2.6 m/s in Oarai town.

$$v_e = \frac{\text{Reference distance}}{\text{No. of frame} / \text{Frame rate}} \qquad (1)$$

Fig.1 Frame of the point No. 3 in Kamaishi town.

Fig.2 Frame of the point No. 7 in Ofunato town.

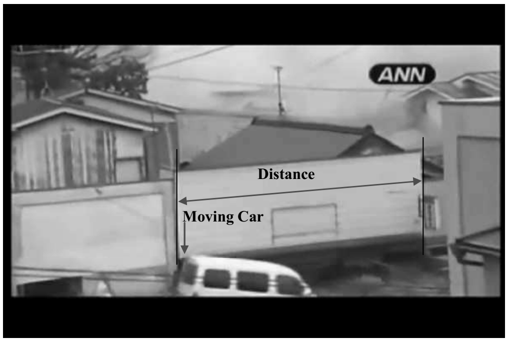

Fig.3 Frame of the point No. 10 in Kesennuma town.

Fig.4 The estimation of the building width of the point No. 10 from the Google Street View.

Table 1 The locations and the tsunami flow velocities by image processing of videos.

No.	Location	Coordinates		Object		No. of Frame	Distance (m)	Velocity (m/s)
		Latitude	Longitude	Moving	Reference			
1	Kamaishi, Iwate	-	-	White Car	Building	29	4.38	4.53
2		39.27454	141.88876	3 Cars	Building	38	5.30	4.18
3		39.27498	141.88818	Front Wave	Parking Channel	24	2.30	2.88
4		39.27486	141.88825	Wood Debris	ATM Building	18	2.50	4.17
5		39.27512	141.88961	Black Debris	Side of Building	108	17.46	4.85
6	Ofunato, Iwate	39.05632	141.72293	White Container	House	90	8.26	2.75
7		39.05628	141.72298	White Car	2 Poles	46	3.16	2.06
8	Kesennuma, Miyagi	38.89893	141.57822	White Truck	Building	37	6.64	5.38
9		38.89893	141.57822	White Car	Building Roof	49	5.96	3.65
10		38.89876	141.57815	White Car	House	40	6.50	4.88
11		38.89893	141.57822	White Debris	Building	44	6.64	4.52
12		38.90754	141.58001	Debris	Building Span	57	5.00	2.63
13		38.89893	141.57822	White Bag	Building	42	6.64	4.74
14	Iwaki, Fuku-shima	36.91204	140.79252	Debris	2 Bridges	131	6.20	1.42
15	Oarai, Ibaraki	36.31314	140.57533	Red Car	2 Poles	167	14.20	2.55

3. TSUNAMI FLOW VELOCITY FROM TSUNAMI SIMULATION

(1) Computation boundary and calculation of the tsunami simulation

The tsunami flow is computed by using TUNAMI model (Tohoku University's Numerical Analysis Model for Investigation of Tsunami) (DCRC, Tohoku University). The governing equations of the non-linear shallow water theory as shown in Eq.(2)-(4) are discretized using the finite difference method with a staggered leap-frog scheme.

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \tag{2}$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right) = -gD\frac{\partial \eta}{\partial x}-\frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2} \tag{3}$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) = -gD\frac{\partial \eta}{\partial y}-\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2} \tag{4}$$

where D is the total water depth (η+h), η is the tsunami wave height, h is the water depth, g is the gravitational acceleration, M is the discharge flux of x direction and N is the discharge flux of y direction.

In this research, 3 areas are considered in Kamaishi area, Ofunato area and Kesennuma area. Six computational nested-grid regions are used in the nested grid system. Region 1, region 2 and region 3 are the same for all 3 areas. Region 4, region 5 and region 6 are generated for each area separately. Region 1 and region 2 are generated by using GEBCO 30-arcsecond-grid data (2009) for both topography and bathymetry with a grid size of 1,350 m and 450 m, respectively. Region 3 is generated by using GEBCO 30-arcsecond-grid data for topography and JHA data for bathymetry with a grid size of 150 m. Region 4, region 5 and region 6 are generated by using GSI data for topography and JHA data for bathymetry with grid sizes of 50 m, 50/3 m and 50/9 m, respectively. The time step of the computation is 0.1 second for all areas, and the tsunami inundation and propagation on dry land is considered in all regions.

(2) Tsunami source model

The tsunami fault model proposed by Imamura et al. (2011) is used to simulate the 2011 tsunami that is consisted of 10 faults. The fault parameters are shown in **Table 2**. For all fault segments, the length and the width are 100 km, the strike angle is 193.0 degree, the dip angle is 14 degree and the rake angle is 81 degree.

(3) Validation of tsunami simulation

The tsunami simulation results are validated with observed data which are tidal data, tsunami inundation heights and inundation area. The data from 3 coastal wave gauge stations along the shore line of Iwate, which are Iwate-Chubu-Oki coastal wave gauge, Iwate-Nanbu-Oki coastal wave gauge and Miyagi-Hokubu-Oki coastal wave gauge (PARI, 2011), are used to compare with the tsunami simulation. **Fig.5** shows the comparison of the inundation heights of the tsunami simulation results with the observed tsunami inundation heights that corrected by the astronomical tide at the time of the event with reliability level A (The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011) at the same points. There are 34 data points in

Kamaishi area, 15 data points in Ofunato area and 57 data points in Kesennuma area. The simulation results at the points in Ofunato area and Kesennuma area agree well with the observed data; however, for Kamaishi area, the simulation results are larger than the observed data by about 50%.

Table 2 Fault parameter for the 2011 off the Pacific coast of Tohoku tsunami (Imamura et al., 2011).

Fault No.	Latitude (°N)	Longitude (°E)	Depth (km)	Slip (m)
1	40.168	144.507	1.0	20.0
2	39.300	144.200	1.0	10.0
3	38.424	143.939	1.0	35.0
4	37.547	143.682	1.0	10.0
5	36.730	143.070	1.0	7.5
6	40.367	143.394	24.2	1.0
7	39.496	143.100	24.2	3.0
8	38.620	142.853	24.2	4.0
9	37.744	142.609	24.2	2.0
10	36.926	142.009	24.2	2.0

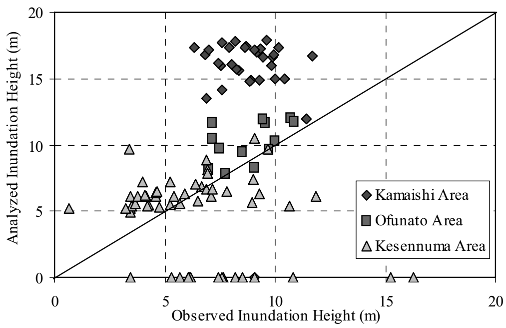

Fig.5 The comparison of the tsunami inundation heights.

4. COMPARISON OF RESULTS

The tsunami flow velocities by the tsunami simulation are estimated at the same locations of the velocities by image processing of videos in the computational region 6 of each area. To analyze the tsunami flow velocities from the tsunami simulation, the inundation depths are needed, and estimated from the recorded videos. The inundation depths are estimated by two methods; visualized estimating from the recorded video (A), and measuring in the Google Street View (B). For the visualized estimating method, the tsunami inundation depths are estimated by the tsunami level on the building (A1) and on the submerged car (A2) with the assumption that, there is no buoyancy of the building and the car. The estimated method, the estimated inundation depths from the recorded videos and the tsunami flow velocities are shown in **Table 3**. The tsunami flow velocities are about 1.7-4.4 m/s in Kamaishi area, 2.0 m/s in Ofunato area and about 1.3-4.3 m/s in Kesennuma area. **Fig.6** shows the comparison of the tsunami flow velocities from image processing of videos with that from the tsunami simulation. The simulation results have the similar trend with the results by image processing of videos; however, most of them are less than the results by image processing of videos.

Table 3 The estimated inundation depth from the recorded videos and the tsunami flow velocities.

No.	Location	Estimated Inundation Depth		Velocity (m/s)		
		Method	Depth (m)	VDO	Simulation	Error (%)
1	Kamaishi, Iwate	A1	2.5	4.53	-	-
2		A2	1.0	4.18	3.96	5.5
3		A2	0.1	2.88	1.70	40.8
4		A1	0.8	4.17	4.35	4.4
5		A2	0.5	4.85	1.88	61.2
6	Ofunato, Iwate	A1	1.5	2.75	1.97	28.4
7		A1	1.5	2.06	1.99	3.3
8	Kesennuma, Miyagi	B	1.5	5.38	4.27	20.6
9		B	1.5	3.65	4.09	12.2
10		B	2.5	4.88	2.72	44.3
11		B	3.0	4.52	1.26	72.1
12		B	1.0	2.63	1.78	32.3
13		B	3.0	4.74	1.26	73.4

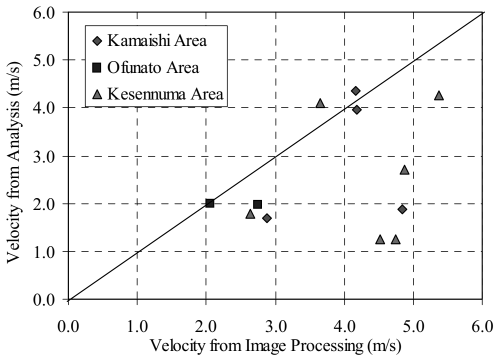

Fig.6 The comparison of the tsunami flow velocities from image processing of video with tsunami simulation.

5. CONCLUSIONS

The March 11, 2011 Pacific Coast of Tohoku tsunami caused serious damage to many buildings, bridges and lifelines and killed many people in Miyagi and Iwate prefectures, Tohoku, Japan. The tsunami flow velocities are analyzed from the recorded videos in Kamaishi town, Ofunato town, Kesennuma town Iwaki town and Oarai town. The analyzed tsunami flow velocities are used to validate the tsunami velocities from the tsunami inundation simulation for this event in Kamaishi town, Ofunato town and Kesennuma town. Findings can be summarized as follows:

1. The tsunami flow velocities are analyzed by using image processing of recorded videos and estimating the dimension of the moving objects and reference distances. The analyzed tsunami flow velocities are about 2.9-4.9 m/s in Kamaishi town, 2.1-2.8 m/s in Ofunato town, 2.6-5.4 m/s in Kesennuma town, 1.42 m/s in Iwaki town and 2.55 m/s in Oarai town.
2. The tsunami simulation is carried out in 3 areas to estimate the tsunami flow velocities and to compare with the observed data. The arrival times from tsunami simulation results are longer than the observed data from wave gauges for about 3 minutes for Iwate-Chubu-Oki coastal wave gauge and Iwate-Nanbu-Oki coastal wave gauge, and 4 minutes for Miyagi-Hokubu-Oki coastal wave gauge. The comparisons of the tsunami inundation heights at the same points are agreed well with the observed data in Ofunato area and Kesennuma area; however, for Kamaishi area, the simulation results are larger than the observed data by about 50%.
3. The tsunami flow velocities from the tsunami simulation are estimated at the same points of those from recorded videos by using the estimated inundation depths from the recorded videos. The tsunami flow velocities are about 1.7-4.4 m/s in Kamaishi area, 2.0 m/s in Ofunato area and about 1.3-4.3 m/s in Kesennuma area. The simulation results have the similar trend with the results by image processing of videos; however, most of them are less than the results by image processing of videos.

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