Measurement of The Flow Velocity for Tsunami Wave Propagation

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The flow velocity of tsunami wave was estimated by using Particle Image Velocimetry(PIV) and Particle Tracking Velocimetry(PTV). These methods have many advantages that can be used to measure velocity under limited data such as the 2011 off the Pacific Coast of Tohoku Tsunami. The results of video image analysis are evaluated by comparing with theoretical approach. The collected video image is stabilized and rectified in the pre-processing to enhance the accuracy of PIV method, whereas the proposed theoretical method is based on conservation equation. It is found that the estimated flow velocity range is consistent regardless of the method. The method is expected to perform well for analyzing videos and providing information in tsunami cases where there is no adequate measurement data.

Key Words : *Particle Image Velocimetry(PIV), Particle Tracking Velocimetry(PTV), The 2011 off the Pacific Coast of Tohoku Tsunami, tsunami propagation into a river, flow velocity*

1. INTRODUCTION

The 2011 off the Pacific Coast of Tohoku Earthquake generated huge tsunami waves. Tsunami wave caused severe damages to the eastern coastal area in Tohoku District. Houses, buildings, and infrastructures were destroyed, as well as hydraulic measurement stations in coastal areas and rivers. Thus, data availability is limited. On the other hand, these data are crucial in the recoveries as well as future disaster prevention in coastal area, estuary and rivers.

There were several videos, recorded at the damaged areas due to the 2011 tsunami event. These videos may provide various information regarding physical parameters of tsunami wave. The flow velocity is considered as an important physical parameter for understanding the mechanism of tsunami propagation. In general, PIV method is widely used to measure the flow velocity from recorded video images. The method is widely used in various engineering fields. Furthermore, measurement devices and technics have been developed to further enhance

PIV. It is expected that the method will perform well in practical application.

PIV measurement technics have been studied in various flow condition such as swash flow, river flood flow and so on^{1),2)}. The flow velocity was estimated by laboratory experiments and using PIV method based on image analysis, and to improve its availability for real field^{3),4)}. Recently, the video image recording of the last tsunami event was analyzed and compared with past tsunami event on the island of Hokkaido⁵⁾. However, it required expensive measurement devices and large scale laboratory experiment. Moreover, the images were obtained from the fixed camera angle like CCTV. Nevertheless, PIV analysis can be applied to the collected image. PIV analysis was used to assess the characteristics of The Great Indian Tsunami 2004 in Banda Aceh from survivor videos⁶⁾. Unfortunately, it was not verified due to the lack of tsunami data and information. Therefore, verification of PIV is crucial to allow this method for further application in assessing tsunami characteristic based on collected videos of a tsunami event.

In this study, PIV method is used and verified by comparing the estimated velocity with theoretical approach, and tracking debris method. The methods are applied in the case of tsunami propagation due to the 2011 off the Pacific Coast of Tohoku Earthquake.

2. STUDY AREA

Study area is the Sunaoshi River in Miyagi Prefecture as shown in **Fig.1**. This area is chosen based on the data availability in order to verify PIV method for assessing the flow velocity in a real case tsunami. It was severely damaged during the 2011 off the Pacific Coast of Tohoku Earthquake. Nevertheless, the Sunaoshi River has sufficient data for this study, i.e. water level data and videos.

The collected video was recorded by a digital personal camera at 3.3 km from the river mouth. Water level data was obtained from five measurement stations. The location of the video recording and the water level measurement stations are shown in **Fig.2**.

Fig.1 Location of study area

Fig.2 Location of video recording and water level measurement stations

3. METHODOLOGY

(1) Pre-processing for image analysis

Pre-processing covering image stabilization and image rectification is crucial in video image analysis. These processes correct errors that may arise due to the camera movement and camera viewpoint.

The raw video data should be stabilized because it may have distortion due to oblique view and camera motion during the recording process. In this process, several fixed points such as building, structures were used to make a stable video frame. Thus, each video frame will be analyzed and adjusted to ensure that the stable video frame remains in constant position. A stable video may be recorded using fix axis such as tripod or other means. However, video recordings from amateur or news are mostly recorded by hands such as the video used in this study. Therefore, this process is crucial for analyzing video images. The level of stabilization has significant effect to the overall accuracy of the video image analysis. Four fixed points were chosen and used in this study as shown in **Fig.3** (a).

The stabilized video does not contain any information of coordinate system. Therefore, image rectification in pre-processing is required to give local coordinate system to the video image. The process plays an important role in determining the accurate distance which is crucial for analyzing flow velocity and direction from images. The rectification results for the selected red dot area in **Fig.3** (a) is shown in **Fig.3** (b).

Fig.3 Pre-processing for PIV method

(2) Velocity assessment by PIV and PTV

The pre-processed video images were analyzed by PIV method and tracking debris method. Recently, various techniques are being developed to obtain stable and exact result in this field. Also, advanced analysis method have been tried to estimate the characteristics of flow behaviors. Performance and capabilities of various PIV analysis were summarized and given in the reference⁷⁾.

In this study, PIV method based on the background of Large-Scale Particle Image Velocimetry(LSPIV) is used to trace the difference of luminance for a period of time. Tracking debris method focuses on the object in the video image. It was assumed that the debris was regarded as one particle on water surface. The method concept is based on Particle Tracking Velocimetry(PTV).

First of all, two areas in the video were selected. They are location A (river downstream) and location B (river upstream) as shown in **Fig.4**. Therefore, flow velocity changes along the river can be observed. Moreover, PTV method was applied to location B.

Furthermore, the theoretical approach based on conservation equation is applied to the measured water level data for evaluating the flow velocity variation due to tsunami propagation in this river.

Fig.4 Locations for image analysis
(Sunaoshi River)

4. RESULTS

The tsunami flow velocity were estimated using three different methods in this study. They are the PIV method, PTV method, and the theoretical approach. The results from these methods were compared.

(1) Velocity estimation using PIV

The tsunami flow velocity can be determined by the time interval and displacements. The mean velocity at a specific zone was calculated by averaging vector fields over a 1 sec time interval. PIV method was utilized to Location A and Location B that are composed of 225 and 100 estimation points, respectively.

Fig.5 shows the averaging flow velocity vectors during 1 sec in Location A. The standard deviation was used to measure the error during a 1 sec interval in the estimation field. According to the time, the

mean tsunami flow velocity including the standard deviation value is shown in **Fig.6**. The calculated mean velocity and standard deviation value of Location A mean that various flow patterns were obtained throughout Location A by the difference of range between mean velocity and standard deviation value.

Fig.5 Velocity vectors at 16:03:42 (Location A)

Fig.6 Mean and standard deviation of velocity
(Location A)

As seen in **Fig.7** (a), (b) and (c), the change of velocity vectors in Location B is shown according to the time. White line is streamline, and contour line is velocity magnitude during 1 sec time interval. There is shown the velocity vectors at three different time because Location B provides the point of comparison between different methods as well as the effect of river topography. The effect can be confirmed by streamlines that is shown along the curvature of river channel from river downstream to river upstream.

In **Fig.8**, mean velocity and standard deviation value of Location B provide that smaller target area of measurement lead to reliable result compared with Location A. However, tsunami wave fluctuates every

time in a real field as well as the flow velocity is changed according to the place and time. It can be obtained spurious vectors that wrong direction vectors or extremely high velocities may be released due to distorted video images in pre-processing stage. It is that the accuracy of analysis method is rely on the stabilization and rectification process. From the measurement result, the pre-processing step for image analysis in this paper is able to overcome the conventional problems of PIV method.

Fig.7 Velocity vector (Location B)

Fig.8 Mean and standard deviation of velocity (Location B)

(2) Velocity estimation using PTV

Tracking debris method was applied to Location B. The red object can be found floating in the raw video as shown in **Fig.9**. Thus, the displacement of this object can be detected. This object is chosen as the target for PTV analysis.

Fig.9 Movement of tsunami debris(Location B)

The velocity magnitude and vector of debris are shown in **Fig.10** (a) and (b) respectively. The flow velocity of debris was steadily increasing during around 15 seconds, and then the peak velocity is attained as 1.03 m/s. The direction of debris can be confirmed by vector analysis.

(3) Velocity estimation using a conservation equation

The calculation method is based on the conservation equation⁸⁾. The flow velocity in the river will be calculated using Eq.(1a).

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (1a)$$

where, A is river cross-section area, Q is river discharge, t is time, and x is an arbitrary point along river upstream direction.

(a) Velocity magnitude

(b) Vector components

Fig.10 Velocity measurement of tsunami debris

This equation can be rewritten as,

$$\int_{x_1}^{x_2} B \frac{\partial \eta}{\partial t} dx + Q_2 = Q_1 \quad (1b)$$

where B is river width, η is water level, Q_1 and Q_2 are discharge at x_1 and x_2 , respectively. If water level variation is given due to tsunami wave propagation into river, tsunami flow velocity can be estimated using Eq.(1b).

It was assumed that the river cross section is rectangular and water surface motion due to tsunami wave between measurement stations moved linearly at the same time. In addition, end of river upstream discharge is ignored. The reasons are that the season was dry season when the earthquake occurred, and the selected river is commonly classified as second class river. Thus, the upstream end boundary is zero.

The calculation result of river discharge(Q) and flow velocity(V) in Sunaoshi River are depicted in **Fig.11** and **Fig.12** respectively. From these figures,

the positive value means flow direction from river downstream to river upstream. It can be observed that the peak velocity becomes slower in the function of distance from the river mouth. These figures also informs how far the effect of tsunami wave propagation into Sunaoshi River.

It was found that the maximum river discharge and flow velocity attained to 150 m^3/s and 1.4 m/s at the measurement station of 2.9 km from river mouth. The calculation result of conservation equation depends on the measurement time interval, river topographical characteristics and the distance which is between two water level measurement stations.

Fig.11 Calculated river discharge⁸⁾

Fig.12 Calculated tsunami flow velocity⁸⁾

(4) Comparison results

To verify the methods, the calculation and image analysis results were replotted in **Fig.13** according to the real time. The flow velocity of tsunami was estimated to be ranging from 0.6 m/s to 1.0 m/s by PIV and tracking debris method. Meanwhile, the calculated flow velocity were attained to the range of 1.0 m/s to 1.2 m/s by conservation equation at the blue arrow in **Fig.12**. It was found that the measured flow velocity from PIV and tracking debris analysis is closer to the calculated flow velocity by using conservation equation at Point 1 (2.9 km from the river mouth) than Point 2 (5.5 km from the river mouth).

Fig.13 Comparison calculation result and image analysis result

The results are dependable and consistent between PIV analysis, PTV analysis and conservation equation results although the comparison analysis was limited. The result of conservation equation was obtained from 10 minutes time interval data. On the other hand, video image analyses were conducted for a very short period of time (25 seconds). Nevertheless, it seems not only to have the similar tendency of flow velocity variation but also these methods are able to estimate the flow velocity from the distorted video images including moving camera motion and oblique viewpoint.

5. CONCLUSIONS

PIV method was applied to analyze flow velocity at Sunaoshi River due to tsunami in 2011. The application of PIV method has been verified by various approaches in this paper. The PIV results were compared to the results from PTV and theoretical approach.

Overall, the results from all of the methods suggested similar trend and behavior. Thus, this measurement process and analysis method can be proposed to overcome the conventional limitations such as moving camera motion and oblique viewpoint. Therefore, the accuracy of the results can be improved regardless of the video source.

In conclusion, the presented methods can be useful to achieve the estimation of tsunami flow velocity, especially in the area where there are no adequate measurement data. Furthermore, image analysis methods (PIV and PTV) can be applied to assess

tsunami characteristic in other regions based on various video sources. It is hoped that more detail analyses based on the presented methods in this study may provide a better understanding of the mechanism of the tsunami propagation.

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