Estimation of tsunami arrival time on the north-eastern coast of Japan

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ABSTRACT

Estimation of tsunami arrival time is crucial in tsunami disaster research. An estimated tsunami arrival time is useful to improve the preparation of an evacuation plan. However, the data collection is not sufficient to estimate the arrival time of the 2011 Tohoku tsunami because most of the measurement stations were destroyed by the massive tsunami. In this study, available video data and measured water level data have been used to estimate the tsunami arrival time. Estimation of the arrival time by video analysis and water level analysis was evaluated by comparison with a numerical simulation result and observation data reported by reliable organizations. The earliest tsunami arrival time was assessed at the place facing and close to the epicenter. The geographical position and relative distance from the epicenter are one of the important characteristics of the tsunami propagation. The analysis of video and water level can be used to assess the tsunami propagation.

1. INTRODUCTION

On March 11, 2011, magnitude of 9.0, off the Pacific Coast of Tohoku Earthquake occurred in the eastern coast of Japan. The earthquake generated a huge tsunami. The massive tsunami waves were observed in the eastern Pacific Coast. Buildings, houses, and infrastructures were destroyed and washed away, as well as most of the hydraulic measurement stations. Thus, data collection has been difficult in research. In addition data quality should be improved to obtain an accurate result. Fortunately, many videos and few of the available water level data can be used to assess the effect of the tsunami propagation and inundation. These data give real-time information of the tsunami event. It is useful for assessing the tsunami behaviors where the data availability is limited.

Many researchers have studied the 2011 tsunami event to understand the tsunami physical factors such as tsunami height, tsunami celerity and tsunami flow velocity by using various methods, such as field survey, numerical calculation and image analysis. Extreme tsunami heights were observed in the eastern Pacific Coast. Mori et al. (2012) and Kakinuma et al. (2012) surveyed the tsunami height, inundation height and run-up height by using various instruments. The measured maximum run-up height attained at approximately 40 m. Furthermore, the tsunami impacts can be assessed by a numerical model. Muhari et al. (2012) and Shimozono et al. (2012) simulated the the tsunami propagation and inundation characteristics using the 2D tsunami model. Image analysis is an also a useful and practical method to obtain the tsunami characteristics. Adityawan et al. (2012) conducted video image analysis, recorded at the Sendai Plain, to estimate the tsunami celerity and velocity as well as tsunami arrival time. Ushiyama et al. (2012) suggested the tsunami arrival time by using the video and pictures in the Rikuzentakata City, which is one of the severely damaged areas due to the tsunami. Previous studies may well explain the 2011 Tohoku tsunami characteristics. Especially, the tsunami arrival time is available to develop the evacuation plan, hazard map and so on. An accurate tsunami arrival time is crucial to the response of tsunami disaster.

In this study, video data and available water level data are used to estimate the tsunami arrival time. The uncertain arrival time in videos has been adjusted by good record data, and the validity of the revised data has been verified by the cross checking with other video sources, numerical simulation result, and observation data. The improved tsunami arrival time has been obtained from the comparison results.

2. STUDY AREA

The study area is located in the Tohoku District along the eastern Pacific Coast as seen in **Fig.1**. Main rivers and tidal measurement stations are indicated on the map. The blue square is the location of river mouth, and the green square is the location of the tide stations. The coast area in the Miyagi Prefecture was enlarged to show the location of main rivers that are concentrated in that area.

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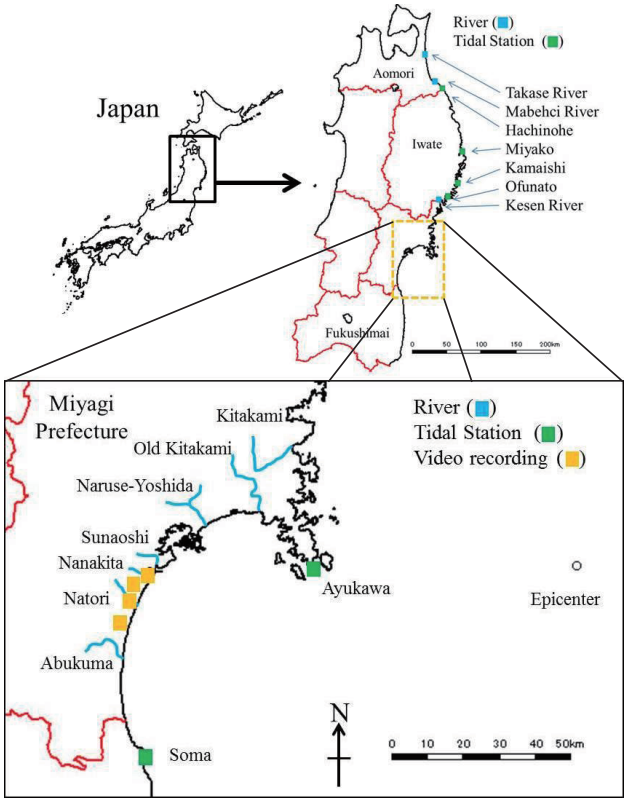
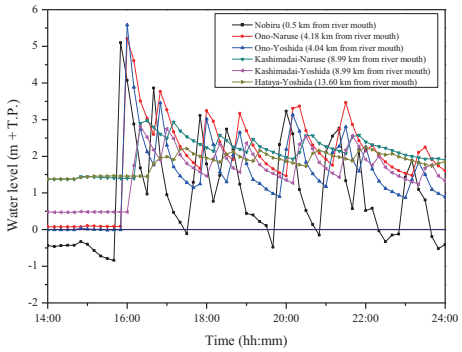


Fig.1 : *Location of Study area*

This study covers the area starting from the Takase River in the Aomori Prefecture (approximately 300 km from the epicenter) to the Soma in the Fukushima Prefecture (approximately 130 km from the epicenter). The tsunami caused severe devastating damages to this region where is considered as the first priority for research. Water level data and video data are available. Water level data is from the measurement stations located along the river. Video data was recorded in several places at the Sendai Airport, upstream and downstream in the Natori River, and the Nanakita River. The available data is used to estimate the tsunami arrival time. The differences of tsunami arrival time from the earthquake occurrence in the study area can be shown in this paper.

3. DATA COLLECTION

The data were collected from helicopter videos, CCTV for river management, personal video, and measured water level. **Fig.2-(a)** shows the water level of the Naruse-Yoshida Rivers observed at intervals of 10 minutes. The snapshot image from the video is shown in **Fig.2-(b)**. These data provide the time information and the tsunami travel distance according to the tsunami arrivals. Furthermore, the observed arrival times of the first tsunami wave and maximum tsunami wave on the tidal stations has been released by Japan Meteorological Agency. Various arrival time data for the 2011 Tohoku tsunami event were suggested by Muhari et al. (2012). The observation data and numerical simulation result can be used to compare with the video and water level analyses results. Those results are combined to complement the lack of data and uncertainty of the time data. The information of data collection is summarized in Table 1.



(a) Naruse-Yoshida Rivers *(b) Nanakita River*

Fig.2 : *Water level data and snapshot image from video recorded by helicopter (Source : Ministry of Land, Infrastructure, Transport and Tourism)*

Table 1. Data information

Name	Data type	Data source	Remarks	Adjustment
Takase	Water level	MLIT	Arrival time of peak water level at 0.20 km and 5.45 km from river mouth	On time
Oirase	Simulation	Muhari et al.*	Primary crest arrival time – 15:54:00	-
Mabechi	Water level	MLIT	Arrival time of peak water level at 1.20 km and 4.00 km from river mouth	On time
Hachinohe	Tide level	JMA	Maximum wave height arrival time – 16:51:00	On time
	Simulation	Muhari et al.*	Primary crest arrival time – 15:53:00	-
Miyako	Tide level	JMA	Maximum wave height arrival time – 15:21:00	On time
Kamaishi	Tide level	JMA	Maximum wave height arrival time – 15:21:00	On time
	Simulation	Muhari et al.*	Primary crest arrival time – 15:19:00	-
Ofunato	Tide level	JMA	Maximum wave height arrival time – 15:15:00	On time
Kesen	Video	Ushiyama et al.**	Arrival times of the Kesen River and the Rikuzentakata City were adjusted by the cross-checking.	On time
Rikuzentakata				
	Simulation	Muhari et al.*	Primary crest arrival time – 15:30:00	-
Kitakami	Water level	MLIT	Arrival time of peak water level at 8.5 km and 17.2 km from river mouth	On time
Onagawa	Simulation	Muhari et al.*	Primary crest arrival time – 15:28:00	-
Ayukawa	Tide level	JMA	Maximum wave height arrival time – 15:20:00	On time
Old Kitakami	Water level	MLIT	Arrival time of peak water level at 1.2 km and 21.7 km from river mouth	On time
Naruse-Yoshida	Water level	MLIT	Arrival time of peak water level at 0.5 km and 4.0 km from river mouth	On time
Ishinomaki	Simulation	Muhari et al.*	Primary crest arrival time – 15:45:00	-
Sunaoshi	Water level	MLIT	Arrival time of peak water level at 2.9 km and 5.5 km from river mouth	On time
Tagajo	Simulation	Muhari et al.*	Primary crest arrival time – 15:53:00	-
Nanakita	Video	MLIT	Arrival time of wave front at 4.3 km from river mouth	On time
		Personal video	At 4.4 km from river mouth. The arrival time is estimated from the MLIT video.	No record
		FDMA	At the river mouth. It is adjusted by the comparison with MLIT and SDF video.	Approx. 10 min
Arahama	Video	MLIT	Inundation time of wave front on land at 2.0 km from coastal line.	On time
	Simulation	Muhari et al.*	Primary crest arrival time – 15:53:00	-
Natori	Video	NHK	Arrival time of wave front at 1.5 km from river mouth	On time
		SDF	Arrival time of wave front at 4.5 km from river mouth	On time
	Simulation	Muhari et al.*	Primary crest arrival time – 15:53:00	-
	Video	NHK	Natori River downstream areas (approximately 0.7 ~ 1.8 km from coastal line)	On time
Sendai Airport	Video	CCTV	The arrival time is estimated from the TBC video.	No record
		TBC	Inundation time of wave front at approx. 1.3 km from coastal line	On time
Abukuma	Water level	MLIT	Arrival time of peak water level at 1.0 km and 8.0 km from river mouth	On time
Iwanuma	Simulation	Muhari et al.*	Primary crest arrival time – 15:54:00	-
Soma	Tide level	JMA	Maximum wave height arrival time – 15:50:00	On time
	Simulation	Muhari et al.*	Primary crest arrival time – 15:48:00	-

MLIT : Ministry of Land Infrastructure, Transport and Tourism
JMA : Japan Meteorological Agency
FDMA : Fire and Disaster Management Agency
SDF : Japan Self-Defense Forces
NHK : Japan Broadcasting Corporation
TBC : Tohoku Broadcasting Company
* : Muhari et al., 2012
** : Ushiyama et al., 2012

4. ANALYSIS RESULTS

4.1 Tsunami travel distance and arrival time

Fig.3 shows the relationship between the tsunami travel distance and the arrival time that was estimated by the analyses of videos and water level data. The tsunami arrival time and travel distance were assessed by using the peak water level at the water level measurement stations. In case of video analysis, the wave front in rivers and on land was used to estimate the arrival time and the travel distance. In order to calculate the tsunami arrival time at the river mouths and coasts, the linear regression analysis was applied to the estimated arrival time and travel distance. The calculated arrival time at the river mouth is shown in this figure as the solid line. The result can be used to compare the observation data and numerical simulation result.

The tsunami travel in rivers and over land are affected by river characteristics, bottom conditions, and the geographical position from the epicenter. Analysis for the Kitakami River, Old Kitakami River, Natori River, Abukuma River and Naruse-Yoshida Rivers show that the tsunami waves were propagated constantly up to the river upstream as compared with Sunaoshi River and Takase River. The Sunaoshi River and the Takase River has a distinct trend, which is the significant decrease of the tsunami energy into the river channels. It may cause the different of the tsunami propagation features according to the river characteristics. The inundation flows were greatly influenced by tsunami debris and land covers such as residence area, bottom conditions covered with asphalt and so on. The difference of the tsunami arrival time is shown in this figure according to the geographic locations from the epicenter. The estimated tsunami arrival time at the river mouth and costal line can be divided into several groups. It is found that the tsunami wave arrived approximately 30 min early in the Kesen River and the Kitakami River compared with the second group such as Old Kitakami River, Naruse-Yoshida Rivers, Natori River, Nanakita River, and Sunaoshi River. The Takase River and the Mabechi River can be classified as the third group. The calculated arrival time at the coastal line from land data shows the similar to the result of rivers. The analysis result of video and water level can explain the effect of the geographic characteristics on the tsunami arrivals.

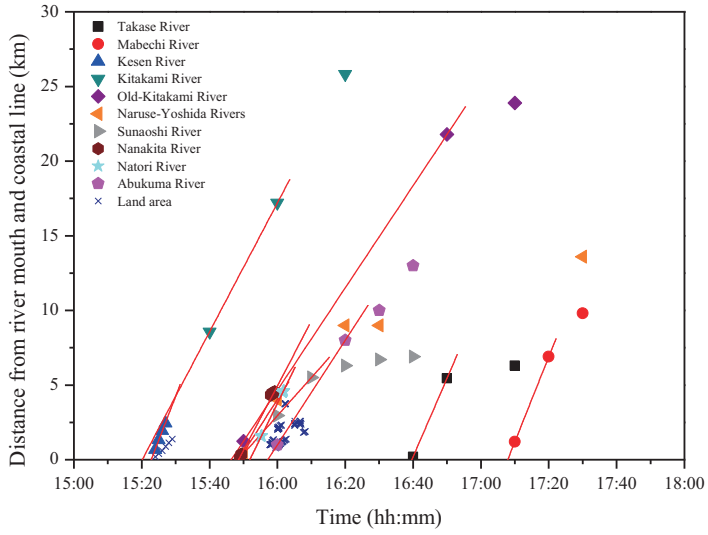


Fig.3 : *Estimated tsunami travel distance and arrival time*

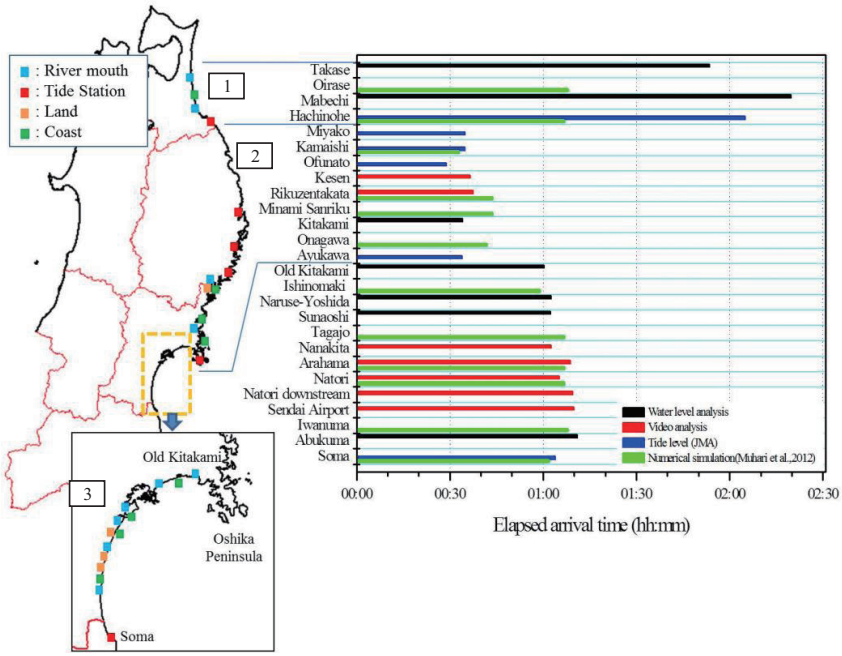


Fig.4 : *Elapsed tsunami arrival time on the north-eastern coast*

4.2 Elapsed tsunami arrival time along the north-eastern coast

The tsunami arrival time along the north-eastern coast can be obtained from the result of previous section. Based on the estimated time data at the river mouths and the coasts, the elapsed tsunami arrival time after the earthquake occurrence can be calculated. It can be combined with the tide observation data and the simulated tsunami arrival time. The elapsed tsunami arrival time from the Takase River to Soma tide station is shown in **Fig.4**. The earthquake occurrence time (14:46:00) is used to define the 00:00 time. The estimation result is classified by the type of data collection and the geographic location of data source.

The first group, covering the Takase River to Hachinohe tide station, which is relatively far from the epicenter. Thus, the estimated tsunami arrival time was approximately 2 hours from the water level analysis and the tide observation data, whereas the simulation result was 1 hour 10 min at the Oirase and the Hachinohe. The earliest arrival time of the tsunami was found on the second group. The tsunami wave arrived at approximately 30 min ~ 40 min after the earthquake occurrence. The estimated tsunami arrival time from each analysis has similar results. The third group is from the Old-Kitakami River to the Soma tide station. The elapsed arrival time for this group is approximately 1 hour ~ 1 hour 10 min. The third group has indicated the good agreement in all analysis results. Especially, the influence of the geographic location and feature has been confirmed in analyzing the results. The geographical effect can be found at the Oshika Peninsula between the second section and the third section. The tsunami wave arrivals have different behaviors based on the Oshika Peninsula. The arrival time difference was 30 min between the second section and the third section. The distance of the third section from the epicenter is closer than the first section. The relative location and the distance of the estimation point were also reflected in the tsunami arrival time. It is clearly shown that the geographical feature and location are related to the tsunami propagation, and it may cause the different tsunami arrival time. Furthermore, the definition of the arrival time in

the video is involved in the instant when the tsunami propagates into rivers and over land. There is a 10 min ~ 15 min difference between the video analysis result and the numerical simulation result.

The video image analysis and water level analysis are useful and effective, especially for the limited data availability. Based on this study result, the detailed tsunami arrival time can be obtained through the comparison of the reliable observation data and simulation result.

5. Conclusions

- Available data such as video and water level have been analyzed to assess the tsunami arrival time on the coastal line. The observed tide data and the numerical simulation result have been combined to evaluate the result of video analysis and water level analysis. The tsunami arrival time of the north-eastern coast of Japan has been successfully completed for the 2011 Tohoku tsunami event.
- The difference of the tsunami arrival time in rivers and on land can be explained from the relationship between the travel distance and the arrival time. The tsunami propagation and inundation are affected by the river characteristics, bottom conditions, and tsunami debris.
- The relative location and distance from the epicenter are one of the significant parameters to determine the tsunami arrival time. The earliest tsunami arrivals were estimated at the areas where is relatively close, and facing the epicenter. The arrival time of the maximum tsunami wave was estimated at approximately 30 min ~ 40 min after the earthquake occurrence up to the earliest arrival area.

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