Effect of river mouth morphology on tsunami propagation ascending rivers

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The tsunami wave, approaching to river entrance, is related with various river characteristics. In wave propagation process, river mouth morphology is one of the dominant factors because it is first the feature of the river when the tsunami wave arrived near rivers. At the tsunami wave generated by the 2010 Chilean Earthquake, the field observation data indicated a different aspect of wave propagation according to the river entrance structure. In this study, in order to evaluate the influence of tsunami wave due to river mouth morphology, a numerical experiment was conducted for hypothetical cases are based on the representative river mouth type. The results of numerical simulation and analysis of measurement applied to the effect of tsunami wave by the change of the river mouth.

Key Words: The 2010 Chilean Earthquake, Tsunami wave, River mouth morphology

1. Introduction

When tsunami is generated by an ocean earthquake, the long wave is propagated along the ocean to the coastal area. Generally, tsunami wave is accompanied with phenomenon such as the inundation of the land and near coastal region, and erosion or coastline changing occurred in the sandy beach, sand spit river mouth and lagoon by tsunami. Tsunami waves can also propagate further into the river upstream. In case, the tsunami wave approaching into the coastal regions, can threaten to people, social infrastructure, etc. Then, the possibilities for the tsunami disaster always exist near the coastal and upstream areas.

February 27, 2010, magnitude 8.8, earthquake occurred in the Chilean coast. Due to this earthquake, a tsunami propagated along the Pacific Ocean. As the tsunami occurred, the tsunami warnings were issued in 53 countries. Also the 2010 Chilean Earthquake is regarded as the latest powerful earthquake. The tsunami arrived to the eastern part of Japan through the Pacific Ocean after 22 hours. At that time, tsunami wave was detected on the coast and river of Tohoku District in Japan. The recorded data showed a 1m maximum tsunami height, and the tsunami propagation distance was estimated to be of several tens kilometers, although the tsunami have been weakened by the wave propagation for a long time. Thus, a tsunami always contains a potential threat, especially in Japan, which is a country that incessantly exposed to earthquakes and tsunamis. Thus, many researchers are studying and focusing on the inundation regarding the tsunami behavior because it is closely connected with the human life and property. On the other hand, another problem such as propagation into rivers, coastal erosion is still not sufficiently clearly understood. Actually, when the tsunami propagates into rivers or overtopping, it can cause serious and dangerous damages in the river upstream area as well as in the land, because of the powerful tsunami wave energy.

In a related matter, various investigation and data analysis on tsunami behaviors have been conducted using past earthquake information to explain and understand the real phenomenon of tsunami. Tanaka et al.(2007) and Wigetunge (2009) performed the investigation of tsunami damage and studied various aspects about the influence of tsunami propagation. The survey data by Liu et al.(2005) have increased the basic knowledge of tsunami in Sri Lanka, by describing the tsunami wave run-up and inundation. Vu et al. (2002) developed a numerical model to solve a complex and difficult problems of the natural phenomenon and a variety of the dominant factors. Until now, many researchers are studying the mechanism of natural and real phenomenon.

As mentioned above, among the phenomenon of tsunami propagation, approaching tsunami wave into rivers is based on the theoretical knowledge.
From the previous research, it is understood that tsunami wave is deeply related with river mouth morphology when the wave approaches into the near coastal regions and river entrance. Further, tidal wave motion is also an important factor in this phenomenon.

Accordingly, the present paper performs field data analysis of the past data of 2010 Chilean Earthquake to clearly evaluate the influence of the river characteristic and tide on tsunami propagation. A numerical model was employed in study area. The results from the numerical study, tsunami wave indicated different aspects of the changing water surface and water level variation data involved in the effect of river mouth morphology. The discussion is about the dominant and important factors on the real phenomenon from field observation data and a numerical modeling.

2. Study Area

Miyagi Prefecture is located in Tohoku District of Japan and the eastern part is adjacent to the Pacific Ocean (Fig.1). The study area is composed the 1st and 2nd class river group and various river mouth types that are sand spit, inside the port and concrete jetties structures. Among them, the Ishinomaki Coast contain four rivers, these rivers have special river entrance structures.

![Fig.1](image)

**Fig.1**: Location of study area

3. Field Observation Data

First of all, measured data is classified by river scale, and then each river group is separated by river mouth type and coastal condition.

Thus, this region has all the ingredients for comparison research, and each river is fitted with enough data of water level and topography. These rivers have many measurement stations along the river, which provide water level variation data of 10 minutes time interval. Most rivers have the first station near the river entrance.

Generally, the astronomical tide level is used in order to estimate a wave height as the still-water level. In this study, the Ayukawa tide applied to the data analysis, and the tide station is located in the east of Ishinomaki Coast in Fig.1.

From the water level variation data of the 2010 Chilean Earthquake and Tsunami, Tanaka et al. (2011) proposed the classification of river mouth morphology in Tohoku District. The classification was completed by same general method. Finally, Table 1 summarizes the river mouth features and maximum tsunami wave height at the first station. The Old-Kitakami River, Jo River and Naruse-Yoshida Rivers belong to this classification.

<table>
<thead>
<tr>
<th>Table 1 The classification of rivers in Miyagi Prefecture</th>
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<td>River class</td>
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3.1 Application of the study area

The classification was easily adapted to the study area. From the table, river characteristics and river mouth morphology are classified in two groups which are Type 1 and Type 2 for each river. First, in Type 1, the river mouth is located inside of port or bay such as Jo River in the study area. In the case of Type 2, the river mouth is composed by sand spit or sandy coast at river entrance. And another important standard of river mouth is a constriction and non-constriction structures for the two types. The river mouth morphology can be rearranged as follows. Type 1 is a non-constriction form and Type 2 is a constriction form because river mouths of Type 1 mostly consist of the artificial concrete structure. Otherwise, the Type 2 is able to change the geometry and morphology by the ocean wave and river discharge, etc.

The division can express the difference of energy loss of tsunami between the constriction form and non-constriction form. Therefore, the classification of river mouth morphology can apply to the three river mouth under the present study area, and is expected to help analysis and research about the river...
mouth morphology and tsunami wave

Measurement data and aerial photos are used to classify the river mouth type for each river in this area. Based on these criteria, the Old Kitakami River and Jo River are of Type 1 and Naruse-Yoshida Rivers are of Type 2. The Old Kitakami River and Naruse-Yoshida Rivers contain jetties structures in the river mouth, there are differences in width between inside of the river and the river mouth. The Old Kitakami River has a non-constriction type of river mouth and jetties type is straight, but the Naruse-Yoshida Rivers are the constriction structure of river mouth in accordance with classification of the river mouth of Type 2. The Jo River mouth is connected to the Ishinomaki Industrial Port and the river mouth width became narrow to upstream river as Type 1. Both types have different features.

(1) Old Kitakami River

The Old Kitakami River is located further south from Kitakami River. It belongs to the Ishinomaki Coast with Naruse-Yoshida Rivers and Jo River. The Old Kitakami River is one of the large rivers in Miyagi Prefecture with the Kitakami River. It is 249 km long and drains an area of 10,150 km². The Old Kitakami river mouth has straight jetties type, and the water depth and width are around 6.5 m and 299 m at the river entrance, respectively. The abundant river data is provided by two measuring stations along the river channel. In the Old Kitakami River it has been estimated a maximum tsunami wave height of 0.775 m for the recent tsunami event. It was comparatively high in the study area because of the river mouth type, width and depth affected the tsunami propagation. (Table 1)

Fig. 2: Water level variation of Old-Kitakami River

The tsunami waves propagate until over 21.78 km in the river upstream area, and travels along the tide. Fig. 2 shows each station water level data. Also, when the wave propagates in the river upstream area, the phase is delayed at the second station which is forwarding to the low tide level, the effect is shown clearly. (Hornevoets et al., 2004)

The tsunami fluctuation has similar pattern in other rivers. On the other hand, the phase lag is shown at the river upstream, as the tsunami wave is transmitted even in the low tidal level. The main reasons are the difference of river scale, the river discharge and the bottom condition. Although these rivers have the same river class, the Old Kitakami River has a deeper water depth than the Kitakami River, also a more broad width, and the river mouth type is a straight jetty, the river bed has substantially mild slope. For this reason, the tsunami behavior indicates the difference of maximum tsunami wave height. These rivers seem to have distinct depth around the river mouth.

(2) Jo River

The Jo River is one of the most important rivers in this tsunami event. Jo River recorded the maximum tsunami wave height, 1.12 m at 3.5 km from river mouth. From the aerial photo data, it indicate that river entrance is made up most sufficient river mouth type which is inside the Ishinomaki port and narrowing width around river entrance when the tsunami propagates into the rivers. In that case, the port or breakwater could not have reduced the energy propagation of tsunami wave.

As seen in Fig. 3, the maximum tsunami wave height was estimated nearly 1.12 m, and the height is the highest during the tsunami event in the research area. In that case, inside the port and breakwater would not help blocking the tsunami wave. Specially, the narrowing width causes the concentration of wave energy at the river mouth without the wave energy loss. Water depth is decisive to define the role of which is deeper than another coastal region because the ports have to keep a steady water depth for vessel passage. For this reason, the Jo River is qualified for research on river mouth morphology and river characteristics. In fact, the wave height
data shows the highest wave height satisfying the mechanism of wave propagation. Unfortunately, Jo River has one measurement station near the river mouth to estimate the water level variation. It is difficult to calculate the wave traveling time and propagation distance, etc. Additionally, the river scale can also be thought to be an influencing factor. River discharge, river bed condition and bottom friction are the key point for each river type. These conditions are deeply related with the change of wave height in the river upstream and downstream areas during the tsunami event.

In the Jo River it is also expected a similar behavior of water level in river region. The tsunami wave would have moved along the tidal wave at the around river mouth and river downstream, and then propagated wave will be indicated the phase lag phenomenon which is controlled by river discharge and river bed condition. Furthermore, the water level of Jo River had shown a tendency to increase consistently after the first peak wave passed. This wave behavior was only discovered in Jo River.

Fig. 4 shows the deepest and average bottom elevation of the Jo River according to the distance from the river mouth. The river bed slope has a totally steady and mild type around 7.0 km from river entrance. Since then, the slope increase rapidly. It means that the tsunami wave propagated easily into river upstream area through the flat river bed without a large mount for wave energy loss.

In Fig. 5, the maximum tsunami wave height is estimated 0.67 m at the Nobiru Station which is located in 0.5 km from the river mouth. The Naruse-Yoshida Rivers also indicated a phase lag, and tsunami wave propagate along the high tidal wave at the each station of river upstream area. (Nielsen, 2009)

Consequently, from the field data and previous research, we recognized that the importance of river mouth morphology when the tsunami propagates into rivers and wave behavior is affected by the river characteristics. The proposed classification of river mouth type would help to understand between the differences of river mouth type, and with the Naruse River.
the tsunami wave motion expected in rivers.

4. Numerical Analysis

In general, Type 1 is a non-constriction river mouth with narrowing width which have a higher maximum tsunami height compared with Type 2 from field data. Therefore, with the results from field data analysis, in order to evaluate the mechanism of the tsunami wave energy loss due to river mouth morphology, we conduct a numerical experiment.

Accordingly, numerical results provide useful information about hypothesis of river mouth morphology, and it will be able to expect the change of tsunami behavior.

As a first step, a numerical experiment was conducted with an ideal topography and representative river mouth structure, and then the numerical model was adapted to the real topography.

4.1 Numerical model

(1) Governing Equations

In this study, the wave motion is simulated by the horizontal two-dimensional shallow water equation model because the target water depth is a shallow water depth. This model is well known for the use with depth averaged velocity, including bottom friction. The main equations of the numerical model are written as

\[
\frac{\partial \eta}{\partial t} + \frac{\partial q_y}{\partial x} + \frac{\partial q_x}{\partial y} = 0 \quad (1)
\]

\[
\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q_x^2}{d} \right) + \frac{\partial}{\partial y} \left( \frac{q_y q_x}{d} \right) + g \frac{\partial \eta}{\partial x} - \frac{\partial}{\partial x} \left[ \frac{dQ}{d} \right] = 0 \quad (2)
\]

\[
\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q_x q_y}{d} \right) + \frac{\partial}{\partial y} \left( \frac{q_x^2}{d} \right) + g \frac{\partial \eta}{\partial y} - \frac{\partial}{\partial y} \left[ \frac{dQ}{d} \right] = 0 \quad (3)
\]

where, \( q_y \) and \( q_x \) are the depth integrated flow discharges, respectively; \( \eta \) is the water surface elevation; \( d \) is the water depth; \( f_c \) is the bed friction coefficient; \( Q \) is the discharge, defined as \( Q = \sqrt{q_y^2 + q_x^2} \). To solve the governing equations, the numerical scheme was employed the Crank-Nicolson method in calculation domain. In the ocean area, a wave absorbing zone is approached at the lateral boundaries to minimize wave reflection.

The bottom friction is assumed constant within the first five meshes, and a free slip boundary condition is applied at the surfaces of the coastal structures. These factors should be considered in numerical calculation, especially, the river bed condition and bottom friction are important factors to calculate wave height in shallow water depth or river area. In the numerical model was employed the Manning coefficient approaching method. The wave simulation model was based on Vu et al. (2002) in this study.

4.2 Numerical test cases

(1) Hypothesis geometry

Six different river mouth morphologies were tested. The test cases were designed based on the representative river mouth types in real field. The main purpose of the numerical test is to investigate hypothesis about the tsunami wave propagation before the numerical simulation of real field.

Fig. 7 shows the top view of total computational domain, which is composed of sea, river, and land boundaries. To calculate the bottom friction, the Manning coefficient is 0.035 and the squared grid size is of 50 m vertically and horizontally. To reduce the influence of reflection wave, the embankment was placed on the river channel at both sides. The total length of the coastal area is 10 km, river area is 20 km, and the width of river channel is 400 m. Bathymetry data was considered the Ishinomaki Coast.

As seen in Fig. 8, the bathymetry data of the sea and river area are composed by two different slopes along the center line, and the line is the initial condition to solve the calculation domain.
In Fig. 9, the cases have one feature about river mouth morphology. In this section, Case 1 is without structure type as a reference case. Case 2 and Case 3 have the jetties structure of different angle.

![Fig.9: The river mouth structures of test cases](image)

These types remind the Old Kitakami River, Case 4 and Case 6 type is from the Jo River. Finally, Case 5 is recreated in the Naruse-Yoshida Rivers mouth.

Moreover, additional four cases about the Case 5 are performed to explain the relation between the changes of river mouth width and tsunami wave height. Fig. 10 shows the concept of the constriction and expresses the wave height in the river and ocean area according to the changing relative width. Initial wave height \( H_o \), wave height in the river \( H_r \), total river width \( b_1 \) and opened river mouth width \( b_2 \) were used to calculate the ratio about wave height and a relative river width. The dot lines indicate the opening rate of river mouth. The bathymetry data and boundary condition were applied the same as previous numerical test cases.

![Fig.10: Illustration of the river width change at river entrance](image)

(2) Initial wave condition

This wave model is restricted to apply the initial wave condition and boundary condition. Basically, the wave inlet boundary is assumed that the regular sinusoidal wave of wave height 0.8 m, a wave period of 1 hour, and the assumption stands on the basis of the estimated tsunami wave height at the Miyato station, near the Naruse-Yoshida Rivers entrance in the Ishinomaki Coast.

To apply the numerical model, 10 minutes data is converted to 5 seconds data. The Miyato station data was used to linearize the measurement data. The wave initial condition was employed at the left side of the total calculation domain.

![Fig.10: Initial wave condition in the wave absorbing zone](image)

(3) Test case results

In the results of numerical test cases indicated the river mouth type, constriction type, and maximum wave height by the Table 2, and the maximum wave height was used to compare the influence of tsunami propagation according to the river mouth type. The measurement point is located 1.25 km from the river mouth. Case 2, Case 3, Case 4 and Case 6 can be classified Type 1, Case 5 is Type 2. Among the test cases, Case 3 and Case 5 include the constriction structures.

![Table 2 Summary of the numerical test results](image)

As a result, Type 1 case was calculated with a higher wave height than Type 2, especially, the constriction structure obviously shown the large difference of wave height. In this regard, this type will be more effective to defend the tsunami propagation into rivers. Notably, in Case 6, it was estimated the highest wave height that the coastal structure, a port and breakwater cannot prevent the propagation of long wave like a tsunami wave. Thus, in Type 1 river mouth, the wave energy loss is smaller than Type 2 and the energy can be keep for long distance, so that Type 1 has higher wave height, and it is possible to spread farther until the river upstream area.

Furthermore, the results of second test cases are presented in Fig. 12. The figure shows the relationship between wave height and rate of opened river mouth. The maximum wave height is based on the Case 5 results of the first numerical test.
To compare the changing quantity of wave height, it is expressed a non-dimensional wave height using the initial wave height. Each calculation points are in the same position with the first test cases.

In Fig.12, the more relative width is broader, the more it can seems to reduce the influence of wave propagation, and when the relative width have more than half over, the wave height in river channel reach increased to 1.5 times over compared with the initial wave height. The results of the second part in the numerical test would be expected to apply the analysis and numerical simulation when the changing river mouth entrance due to a long-shore currents, sediment transport, and erosion in the sand spit or sand coast like Type 2.

The test cases results showed that the tendency of wave propagation coincide with the coastal wave theory. Therefore, the tsunami wave behavior can be explained clearly by the comparison study of maximum wave height according to the river mouth morphology. It is that the river mouth type and structures are a significant and important factor when the tsunamis approach to the river mouth and entrance, as well as propagation to rivers upstream area.

Consequently, we would expect the incoming tsunami motion through the river entrance. Also, we can simulate and calculate the potential tsunami scenario of assumption to coastal area and river mouth where accidents may happen.

4.3 Application of real topography

In the results of the numerical test, each case has a specific maximum wave height according to the river mouth type, and the test results presented a good agreement and a reasonable solution about the tendency of tsunami wave motion. Therefore, the model can be adapted to the real study area. It would support the theoretical background about the river mouth morphology.

(1) Numerical domain

The calculation area was decided on the Jo River, based on the field observation data and numerical test. Initial conditions and boundary conditions were applied under the same conditions before the numerical test. Grid size is 30 m × 30 m, respectively. Fig.13 shows the top view of the calculation domain. Also, it was expressed the breakwater and coastal structure.

(2) Numerical calculation results

In Fig.14, the tsunami showed the concentration of wave energy near the river entrance. Totally, the maximum wave height was estimated higher inside the port.

The concentrated wave energy move to the river upstream area, Fig.15 shows the change of maximum wave height along the river. The tsunami wave propagate higher and higher to the river upstream area, wave height is decreasing to around 1 m at around 4 km from the river mouth. In process of tsunami propagation into rivers, it was understandable that wave energy have decreased and lost by river characteristics. The numerical results described the effect of tsunami wave height in comparison with the measurement data at 3.5 km despite of the water level data near the Jo River mouth could not be compared with the numerical result. It is that the wave
height of numerical calculation was close to the measurement wave height 1.12 m at 3.5 km from the river mouth. The numerical model simulated closely the tendency of natural phenomenon in Fig.16, although the tsunami wave height still presents a gap between the results of the measurement data and the numerical model.

Furthermore, when the inundation in river upstream area, occurs the present results can be applied to establish the natural disaster prevention and treatment.

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