Numerical analysis of tsunami wave intrusion into a river

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ABSTRACT

Tsunami intrusion into a river is crucial in natural disaster research. An estimated tsunami intrusion distance is useful to improve the evacuation plan for the second disaster in river upstream. However, it is difficult and complicated to understand the real phenomena of tsunami propagation into a river, especially the 2011 Tohoku tsunami. The analysis of field survey was not sufficient to assess the tsunami characteristics in rivers. Thus, a numerical analysis was carried out according to the river topographical feature. This study pointed out the problem of the empirical function based on the field survey. It was discussed that the characteristics of tsunami propagation into a river in this paper using a numerical analysis.

1. INTRODUCTION

On March 11, 2011, the off the Pacific Coast of Tohoku Earthquake of magnitude 9.0 generated a massive tsunami. It caused severe damages due to the tsunami waves in Tohoku District. Buildings and infrastructures were destroyed as well as almost hydraulic measurement stations near the coastal area. Moreover, river upstream area was influenced by the tsunami propagation into rivers. The tsunami wave caused the second disasters in the upstream area of river such as the tsunami overtopping over the river embankment and tsunami intrusion (Nandasena *et al*., 2012). Recently, this phenomenon is considered as the potential disaster due to the tsunami propagation into rivers. It is needed more study in understanding the tsunami phenomena.

According to the tsunami intrusion into rivers, many researchers have found that a relationship between river topographical characteristics and various flow patterns (Abe, 1986; Saleh *et al*., 2013). It was found that the river bed slope is the one of important parameters when the tsunami wave propagates into the rivers by analyzing field survey data and numerical simulation (Yasuda, 2010; Adityawan *et al*., 2012). Kayane *et al*.(2013) suggested the empirical functions of the tsunami intrusion distance and tsunami height dissipation according due to river bed slopes using the field survey of three prefectures in Tohoku District after the 2011 Tohoku Tsunami. However, the previous study has many difficulties that available field data was not sufficient because the measurement stations in rivers and coasts were washed away by the powerful tsunami. The empirical functions have been proposed without the effect of the initial tsunami height. It is difficult to generalize about each tsunami event. Thus, a numerical simulation is required to assess the tsunami propagation characteristics. It is crucial to show the relationship between the important parameters and real phenomena.

In this study, the effect of river bed slope has been studied by a numerical simulation. To achieve the tsunami propagation characteristics in rivers, several river slopes and different initial wave conditions have been applied to hypothetical numerical domain. Furthermore, the problem of the empirical function will be pointed out in this paper. It would be suggested the improvement of the empirical function. This study can be used to identify the tsunami propagation characteristics into the river.

2. NUMERICAL METHOD

2.1 Governing equations

The 1-D shallow water equations model is employed to assess the tsunami intrusion characteristics in rivers. The Manning roughness is used to solve the energy dissipation term in the momentum equation. Eq.(1) and Eq.(2) is the continuity equation and the momentum equation, respectively.

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial}{\partial x}\left(\frac{1}{2} g h^2\right) = gh(S_o - S_f) \tag{2}$$

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where, t is time, x is space, h is total water depth, u is depth average velocity, S_o and S_f is bed slope and friction slope, respectively, and g is gravity acceleration.

2.2 Numerical schemes

The numerical schemes are that FORCE-MUSCL scheme and 3-Order Total Variation Dimensionless (TVD) schemes are used to calculate the governing equations. Monotone Upstream-centered schemes for Conservation Laws (MUSCL) is widely used in many numerical analyses, especially it provides a high accuracy, and good performance for various flows such as a complex flow condition, further MUSCL scheme was combined with the First Order Centered scheme (FORCE) which was used to improve the numerical result (Liska and Wendroff, 1999). A shock capturing method using the Total Variation Diminishing Runge-Kutta scheme has been employed in this numerical model for reducing the numerical oscillations and wave shocks during the simulation. There schemes is commonly used in the numerical simulation. It was developed to improve the wave shock and numerical divergence.

The governing equations which is continuity equation and momentum equation can be rewritten in vector form as Eq.(3) in order to apply the Finite Volume Method (FVM) solution,

$$\frac{\partial E}{\partial t}+\frac{\partial F}{\partial x}=S \tag{3}$$

where, it is shown that flux vector form can be expressed as

$$E=\begin{pmatrix} h \\ hu \end{pmatrix} \tag{4}$$

$$F=\begin{pmatrix} hu \\ hu^2+\frac{1}{2}gh^2 \end{pmatrix} \tag{5}$$

$$S=\begin{pmatrix} 0 \\ gh(S_o-S_f) \end{pmatrix} \tag{6}$$

Eq.(3) is integrated over the element, and using Green's Theorem is applied to the equation of vector form. Thus, Eq.(7) is written as

$$\frac{\partial V}{\partial t}=-F'(x)+S \tag{7}$$

$$F'(x_i)=\frac{F_{i+1/2}-F_{i-1/2}}{\Delta x} \tag{8}$$

The space derivation function of F can be simulate by using finite volume center scheme as Eq.(8). This formulation depends on how the flux variables are evaluated. The FORCE-MUSCL schemes have been used to solve the flux variables.

In the MUSCL scheme, the flux variables (h, hu) at the left and right side of the cell i is redefined that the variable value (hu) at the right (+) and left (-) of the cell i+1/2 are approximated as below

$$(hu)^{+}_{i+1/2}=(hu)_{i+1/2}-\frac{1}{2}\delta_{i+1}(hu) \tag{9}$$

$$(hu)^{-}_{i+1/2}=(hu)_i+\frac{1}{2}\delta_i(hu) \tag{10}$$

where,

$$\delta_i(hu)=\phi_i(r_i)\left(\frac{(hu)_{i+1}-(hu)_{i-1}}{2}\right) \tag{11}$$

$$r_i=\frac{(hu)_i-(hu)_{i-1}}{(hu)_{i+1}-(hu)_i} \tag{12}$$

here, ϕ_i : function of flux limiter, and r_i : ratio of gradients on the cell interface.

The flux limiter is commonly used in high resolution numerical schemes. It is very useful function in controlling the numerical simulation. The Superbee flux limiter is employed in this numerical model. The flux limiter value is determined by the ratio of gradients (Roe, 1986).

2.3 Hypothetical cases and boundary conditions

The numerical simulation is carried out to obtain the tsunami intrusion distance from the river mouth by using several hypothetical domains. The range of river slope is 0.00021 ~ 0.00193, 14 cases totally as seen in Table 1. As an example, **Fig.1** shows the hypothetical calculation domain of river slope 0.00053.

The computation conditions are that the grid size is 100 m and time interval is 1 sec. Total calculation time is 7200 sec. At the river mouth boundary condition, 3 m and 5 m solitary wave is used in the numerical simulation as shown in **Fig.2**. The boundary condition of river upstream area is the open boundary condition. The river flow discharge was not considered as the significant parameter on the left-hand side in this numerical simulation. Manning coefficient was used to calculate the bottom friction term as 0.025.

Table 1. Hypothetical cases for river bed slope

Case No.	Slope	Case No.	Slope
Case 1	0.00021	Case 8	0.00046
Case 2	0.00025	Case 9	0.00049
Case 3	0.00028	Case 10	0.00053
Case 4	0.00032	Case 11	0.00088
Case 5	0.00035	Case 12	0.00123
Case 6	0.00039	Case 13	0.00158
Case 7	0.00042	Case 14	0.00193

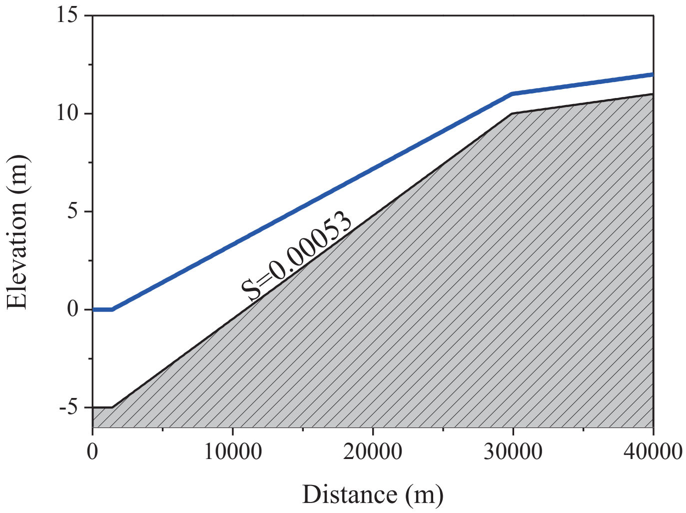

Fig.1 Numerical calculation domain (S = 0.00053)

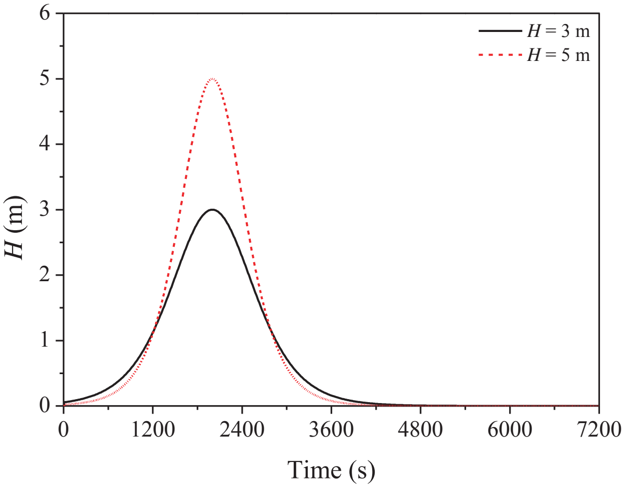

Fig.2 Wave inlet boundary condition at the river mouth (0.0 km)

3. ANALYSIS RESULTS

3.1 Empirical function of tsunami intrusion distance

Iwate Prefecture is eight rivers, Miyagi Prefecture is 9 rivers, and Fukushima Prefecture is 21 rivers, total 38 rivers data were used to estimate the tsunami intrusion distances. The empirical function was suggested by the relationship between tsunami intrusion distance and river slope using the field survey data (Kayane *et al.*, 2013). The empirical function of the tsunami intrusion distance end was suggested as below

$$x_p = 48.4S^{-0.71} \tag{13}$$

where, x_p is end of tsunami intrusion distance from river mouth, S is river bed slope.

The empirical function was obtained from the single tsunami event. Therefore, it is needed that the effects of the tsunami height due to the different locations and tsunami events have to consider in determining the tsunami intrusion distance.

3.2 Numerical simulation result

Fig.3 shows the calculated wave heights at the river mouth, 2.0 km and 4.0 km from the river mouth during the numerical simulation. It is found that the wave height is related with increased propagation distance from the river mouth. The water level fluctuation was occurred due to the sloping river bed during the initial time step. In the numerical analysis, the end of the tsunami intrusion distance is defined that the water level variation is less than 10 cm at the longitudinal distance from the river mouth.

3.3 Comparison on numerical simulation result and empirical function

The computed tsunami intrusion distance can be indicated on the empirical function of tsunami intrusion distance. The comparison with the empirical function and the simulation result is depicted in **Fig.4**. Overall, the numerical simulation has produced similar reducing pattern of tsunami intrusion distance although the empirical function is based on the 2011 Tohoku Tsunami event. The overestimate of tsunami intrusion distance is shown in the range of mild river slope compared to the empirical function. As the result, it is found that the tsunami intrusion distance is deeply related to the river bed slope from the comparison result. It also depends on the initial tsunami height near the river mouth in the numerical simulation result.

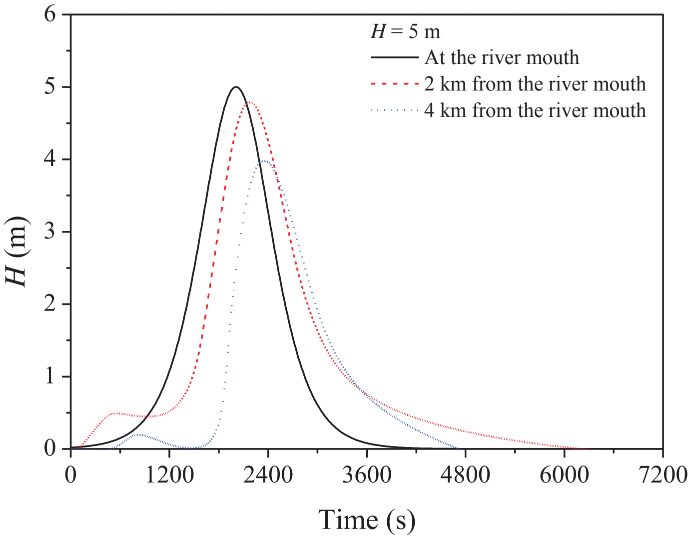

Fig.3 Calculated temporal wave height along the river ($S = 0.00053$, $H = 5$ m)

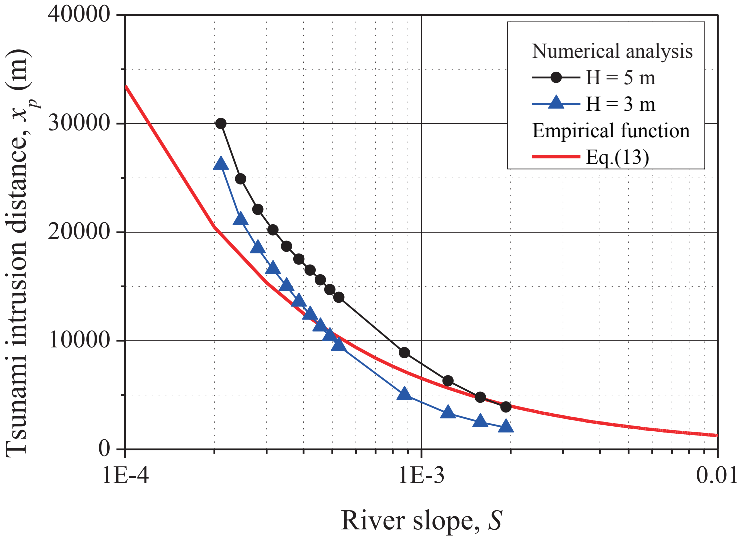

Fig.4 Comparison between empirical function of intrusion distance and numerical analysis results due to wave height(H) and river slope(S)

4. CONCLUSIONS

- The 1-D numerical analysis has been carried out successfully to show the effects of river bed slope and initial tsunami height. It was found that the end of the tsunami intrusion distance was deeply related to the river bed slope as one of the significant parameters.
- The tsunami intrusion distance into a river was influenced by the tsunami height at the river mouth although the decreasing patterns were similar in the different initial wave heights.
- The previous empirical function of the tsunami intrusion distance was suggested without the effect of the tsunami height at the river mouth. It is required to improve the influence of the tsunami physical characteristics. The numerical analysis is also needed to reflect various natural parameters such as river width, curvature, etc. Furthermore, it would be able to discuss the relation of tsunami height dissipation along the river. Lastly, it is hoped that this study would be useful to understand the real tsunami phenomena into a river.

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