Study on Numerical Model of Topography Change due to Tsunami

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Authors carried out numerical study on the topography change due to tsunami in Kesennuma bay when Chilean tsunami had occurred. In the site, huge erosion was observed at the narrow strait and large amount of sediment transport in the form of suspended load according to large tractive force was expected. We proposed some parameters on the topographic change model in order to reproduce such condition by means of numerical simulation. In comparison with the observed bathymetry, it was found that the effect of moving bed condition had to be considered in the equivalent roughness coefficient and that vertically uniform eddy diffusivity estimated by use of the turbulence scale well reproduced horizontally predominant sediment transport under the tsunami.

Key Words : *tsunami erosion, Chilean tsunami, Kesennuma bay, Numerical analysis*

1. INTRODUCTION

It is pointed out that tsunami associated with devastating scour and accumulation could result in collapse of coastal structures and blockage of intakes. Actually, in the Dec 2004 Indian ocean tsunami, the disasters caused by sediment transport were reported in some suffered countries. Most cases accompanied by sediment transport due to tsunami are well known to cause erosion predominantly, so it is significant to grasp the hydraulic condition under which it might occur and to predict it quantitatively.

There are some studies on topographic change model by a tsunami based on suspended sediment flux model, such as Takahashi et al.[1)], Fujii et al.[2)], which investigated the response of the Kesennuma bay when the Chilean tsunami had attacked. They successfully reproduced the distribution of the erosion and accumulation of the sediment in the harbor qualitatively, but could not do quantitatively. On the other hand, Nishihata et al.[3)] estimated the topographic change inside the Kirinda fishing port in Sri-Lanka caused by the Dec 2004 Indian ocean tsunami quantitatively with sediment transport model based on the physical mechanism introduced by Tajima[4)]. However, it was applied to the local region along the breakwater and has not been examined for the prediction of wide and huge topographic change by a tsunami. In addition, it still remains the problem how to determine the eddy diffusivity coefficient for vertical direction.

In this study, latter model shall be applied to the case of Kesennuma bay in Japan as the 1960 Chilean tsunami had attacked so that the scope of application

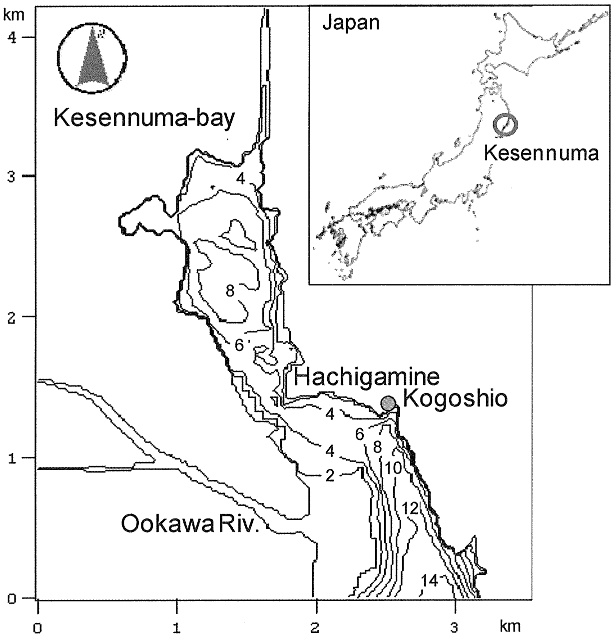

Fig.1 Location map and bathymetry

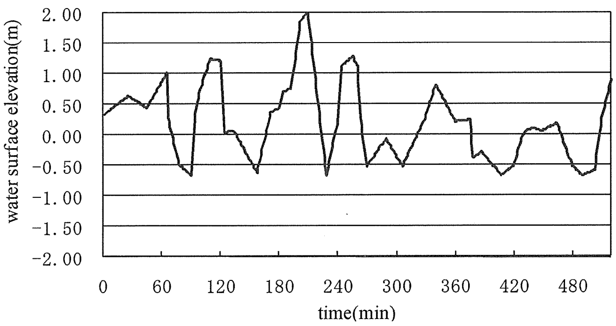

Fig.2 Incident tsunami wave elevation

of the model should be verified. Furthermore, we discuss and propose appropriate model parameter to express the sediment transport when huge debris moving due to the tsunami occures.

2. OUTLINE OF STUDY

(1) CONSIDERING SITE

We studied the numerical model on topographic change due to tsunami through the case of the 1960 Chilean tsunami. The considering site is Kesennuma bay. The measured data of the sea bottom level before and after the tsunami was submitted by Kawamura and Mogi[5] and it showed the erosion to the amount of about 2.6 million m^3 within the site. The location map with depth contour before the tsunami is indicated in the **Fig.1**. Here, the time series of the surface elevation was recorded at the tide gage in Kogoshio, so we converted it to the off-shore wave height with multiplying corrected coefficient 0.924 according to the previous study by

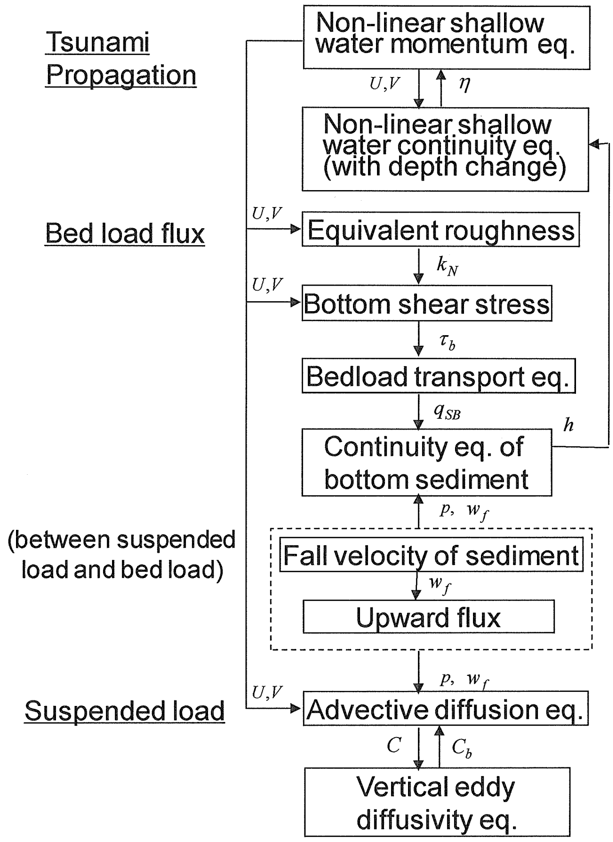

Fig.3 Flow of computation

Takahashi et al. [6] and gave it as the incident tsunami wave elevation at the bay mouth boundary (southward) for 520 minutes(**Fig.2**). The phase difference of water elevation was given at the boundary considering the tsunami propagation from the source origin.

(2) NUMERICAL MODEL

On computing the tsunami propagation accompanied by topographic change, we adopted the numerical model introduced by Nishihata et al.[3] which had been applied to the disaster of the Dec 2004 Indian ocean tsunami in the Kirinda fishing port in Sri-lanka. This model is able to consider not only the tsunami propagation ruled by the non-linear shallow water equation but also sediment transport for bed load and suspended load by solving the advective diffusion equation. It also takes account of vertical translation between the bed load and suspended load derived from upward and settling flux.

Computation flow is shown in the **Fig.3**.

a) TSUNAMI PROPAGATION MODEL

Momentum and continuity equations based on the non-linear shallow water theory are used for tsunami propagation computing. The computational domain is constructed with 25m staggered grid and the computing method is leap-frog scheme, where advection term of the momentum equation is solved by the predictor-corrector method with up-ward wind difference scheme. For the friction term, we do not use Manning's roughness coefficient usually adopted in tsunami computation but give the friction coefficient which we evaluate from the friction velocity determined by the logarithmic distribution of current in each time step. We consider the change of depth h in the contiuity equation as following,

$$\frac{\partial \eta}{\partial t} = -\frac{\partial U(h+\eta)}{\partial x} - \frac{\partial V(h+\eta)}{\partial y} - \frac{\partial h}{\partial t} \tag{1}$$

Here, x and y are horizontal axes, η is water surface elevation, U and V are depth-averaged current velocities.

b) COMPUTATION OF BEDLOAD

In this study, bed load sediment transport is estimated as the function of bottom shear stress. In preparation, it is necessary to estimate the friction velocity and equivalent roughness coefficient under the intensive sheet flow condition due to the tsunami. The bottom shear stress is expressed as following law of resistance from the logarithmic distribution law for averaged current velocity,

$$\sqrt{|\vec{\tau}_b|/\rho} = u_{*b} = \kappa|\vec{U}|/(\ln(h/z_0)-1) \tag{2}$$

Where ρ :density of flow, u_{*b} :bottom shear velocity, κ :Karman's constant(=0.4), z_0 :height of roughness(= $k_N/30$), k_N :Nikuradse's equivalent roughness. Sediment diameter d is representative of k_N if bottom condition is rigid, while k_N is supposed to become larger than d because sheet flow is assumed to be predominant when tsunami attacks. Kobayashi et al. [7] conducted the movable bed experiment under such condition and defined the equivalent roughness as following,

$$k_N = 5\psi d \tag{3}$$

On the other hand, Herrmann and Madsen[8] proposed the empirical formula as below valid up to the degree of 6-7 shields number.

$$k_N = 2d + 4.5(\psi - \psi_{cr})d \quad (\psi \geq \psi_{cr}) \tag{4}$$

The formula for bedload sediment transport is Tajima's model[4] which is related to bottom shear stress and includes the influence of bottom slope. This model is identical to Meyer-Peter-Muller's law of bedload sediment transport, except for the effect of bottom slope.

Continuity equation is balanced with depth changing ratio, bedload sediment transport flux, sediment pick-up ratio and settling velocity as following,

$$(1-n)\frac{\partial h}{\partial t} = -\nabla \vec{q}_{SB} - p + w_f C_b \tag{5}$$

where n is the porosity of bottom material and is assumed 0.4, w_f is fall velocity of sediment grains from Jimenez Madsen[9], C_b is concentration of suspended load at $z_b = 7d$, which we shall mention after. P is pick up function at the height and Herrmann and Madsen's formula[8] is referred.

c) COMPUTATION OF SUSPENDED LOAD

Concentration of suspended load is solved by following advective diffusion equation,

$$\frac{\partial Ch}{\partial t} + U\frac{\partial Ch}{\partial x} + V\frac{\partial Ch}{\partial y} = p - w_f C_b + \frac{\partial}{\partial x}\left(\varepsilon h\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon h\frac{\partial C}{\partial y}\right) \tag{6}$$

We suppose isotropic turbulence, therefore, we define horizontal eddy diffusivity coefficient as $\varepsilon = \kappa u_* h/2$. C is depth-averaged concentration of suspended load, however, actual concentration tends to take distribution for vertical direction. Takahashi et al. [1] considered unsteady suspended load concentration in vertical direction under the condition that unsteady bottom shear stress due to tsunami was exerted, and proposed the empirical formula of sediment exchange ratio between bedload and suspended load instead of $p - w_f C_b$ in the right hand side of equations(5) and (6) through the experiment. However, this sediment exchange formulae are defined within the limits that the shields number is around 1. In our study, vertical distribution of suspended load concentration is set by the analytical solution of diffusive equation which should be discussed later, so the unsteady state is unable to be taken into account. Nevertheless, computing bed load sediment flux and suspended sediment flux separately makes it possible to consider horizontal unsteady suspended sediment concentration as outer force suddenly changes. When setting the eddy diffusivity coefficient, we shall execute parametric study and determin the appropriate one which can successfully evaluate the amount of erosion and accumulation by the numerical analysis using the analytic solution of the following advection diffusive equation for one dimensional vertical direction,

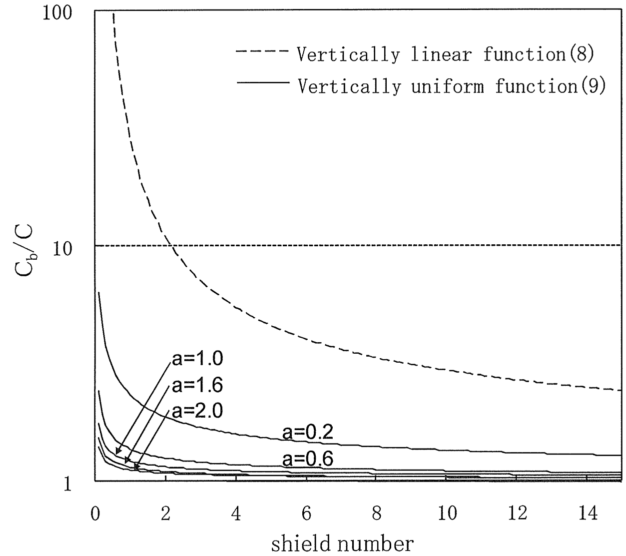

Fig.4 distribution of suspended sediment concentration for the parameter a

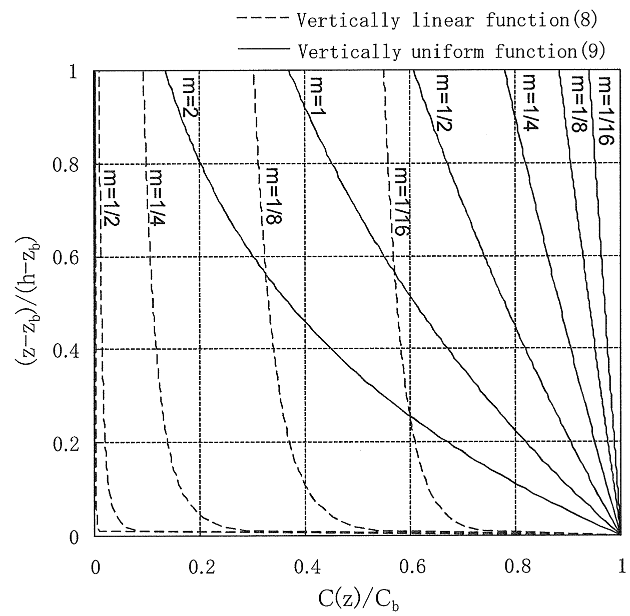

Fig.5 distribution of suspended sediment concentration for the parameter m

$$\nu_s \frac{\partial C}{\partial z} + w_f C = 0 \tag{7}$$

where, ν_s is eddy diffusion coefficient and if vertically linear function $\nu_s = \kappa u_{*b} z$ is given,

$$C_b = \frac{C(1-m)(h-z_b)}{h(z_b/h)^m - z_b} \tag{8}$$

Here, $m = w_f / \kappa u_{*b}$.

On the other hand, since tsunamis are supposed to induce intensive sheet flow, if vertically uniform function $\nu_s = \kappa u_{*b} ha$ is given as well as Fujii et al.[2)] assuming that the turbulence scale is constant multiplication of water depth ($= ah$),

$$C_b = \frac{Cm/a}{1-\exp(-m(h-z_b)/(ha))} \tag{9}$$

where, parameter to study is a, which we shall verify the adequate value in next chapter.

To comprehend the influence on sediment transport caused by the difference of eddy diffusivity coefficient, we execute sensitivity analysis for a and m. Here, we assume that the sediment diameter is 0.1mm. **Fig.4** is the analytical distribution of suspended sediment concentration near the bottom according to non-dimensional shear stress. Suspended sediment concentration near the bottom is asymptotic to the depth-averaged sediment concentration with the increase of the shear stress, and uniformity of concentration is more conspicuous in case using equation(9) than using equation(8) furthermore under the condition that a takes larger value. This effect is also seen in the **Fig.5** that the smaller the parameter m is(shear stress is larger), the more homogenized the concentration of suspended load for vertical direcition is. Under the condition that homogenization of concentration progresses vertically, C_b takes relatively small value, then,settling flux in the eq.(5) and (6) are weakened, while horizontal advection and diffusion of suspended load are strengthened.

3. VERTIFICATION FOR THE COMPUTED MODEL

(1) OUTER FORCE BY TSUNAMI

First of all, to grasp the outer force by the tsunami we confirme current velocity field which dominantly influence on the topographic change. The computation model which reproduces the large sediments transport(case7, see **Table 1**) is selected. Takahashi et al.[10)] certified the current velocity field by using the aircraft surveying data and obtained large current velocity at the narrow straight in the bay. Our computation represents such fast current at that area as well, but failes to express the eddies which had been observed at the head of the bay and estuary of Ookawa river. **Fig-6** shows the velocity field and the maximum shields number predicted by the computation. Largest shields number more than 15 is computed at the narrow straight around Hachigamine, where distinct erosion had been observed.

Table 1 Computed cases and results

Case	Equivalent roughness k_n	eddy diffusion coefficient	Erosion		Accumulation		Net	
			million m^3	cal./obs.	million m^3	cal./obs.	million m^3	cal./obs.
Obs.	-	-	2.59	-	0.82	-	-1.77	-
1	*d50*	uniform (a=1.2)	1.72	0.66	0.69	0.84	-1.03	0.58
2		(a=1.0)	1.71	0.66	0.56	0.68	-1.15	0.65
3	*5φ d50*	uniform (a=1.2)	2.43	0.94	1.02	1.24	-1.41	0.80
4		(a=1.0)	2.43	0.94	1.02	1.24	-1.41	0.80
5	*Herrmann' equation(4)*	vertically linear	1.44	0.56	0.89	1.09	-0.55	0.31
6		uniform (a=1.2)	2.45	0.95	0.99	1.21	-1.46	0.82
7		(a=1.0)	2.44	0.94	1.00	1.22	-1.44	0.81
8		(a=0.8)	2.43	0.94	1.01	1.23	-1.42	0.80
9		(a=0.5)	2.38	0.92	1.03	1.26	-1.35	0.76

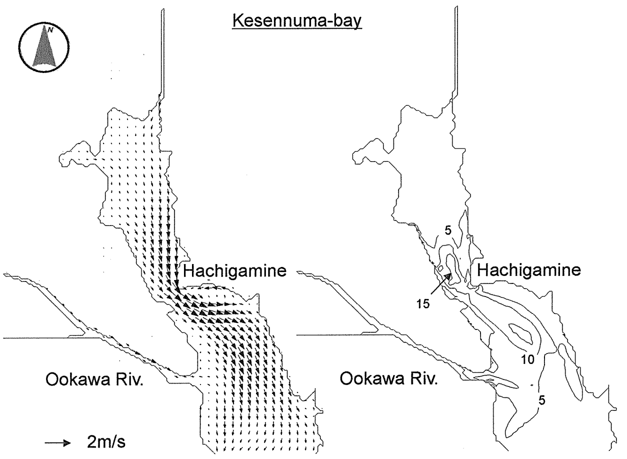

Fig.6 Computed velocity(left) and maximum shields number(right)

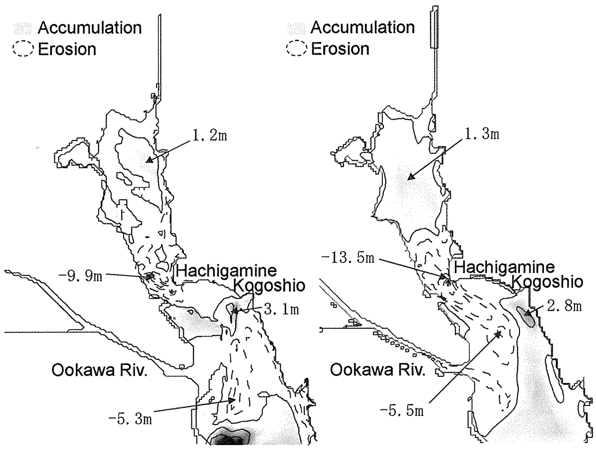

Fig.7 Planar distribution of accumulation and erosion (left:observation, right:computation(case7))

(2) PARAMETERIC STUDY FOR THE MODEL

We select 9 cases to verify the topographic change model with tsunami for the parametric study(see **Table 1**). Here, we assume that the grain diameter uniformly takes 0.1mm, porosity 0.4. Following 2 items are concerned with the study.

a) EQUIVALENT ROUGHNESS COEFFICIENT

We examine the model in the case that Nikuradse's equivalent roughness is given with the diameter d, by the equation (3) of Kobayashi et al. [7], and by the equation (4) of Herrmann and Madsen[8]. **Table 1** also shows the computed results and the former cases demonstrate less erosion than that in observation. It seems difficult to reproduce the bottom erosion and accumulation under the tsunami by setting the general roughness coefficient because the increase effect of roughness due to the movement of bottom sediment itself could not be expected. On the other hand, latter cases are able to consider such effect and computed results for erosion and accumulation are well agree with the observed one, except for case5.

b) VERTICAL DISTRIBUTION OF DIFFUSIVITY COEFFICIENT

Two kinds of vertical distribution function are considered. One is the linear function, i.e., equation(8) and the other is the uniform one, i.e., equation(9), where the parameter a is changed from 0.5 to 1.2.

Table 1 demonstrates that vertically uniform function reproduces the amount of erosion more accurately than vertically linear one. In vertically uniform distribution of the eddy diffusion coeffcient, turbulent scale parameter a gives little influence on the computed results, but computed results well accord with the observed one when a takes the value around 1.0. **Fig-7** is the comparison of computed and observed erosion and accumulation distribution in the case of $a = 1.0$ (Case7). Large erosion at the narrow straight and accumulation at the inner part or mouth of the bay are successfully simulated.

4. CONCLUSION

Through numerical analysis when the Chilean tsunami occurred at Kesennuma bay in Japan, computational model of topographic change by tsunami was improved. Following concluded remarks were attained in this study.

(1) Since sheet flow is predominant under huge tsunami, it is essential to set the equivalent roughness to consider the effect of moving bottom sediment itself.

(2) Vertically uniform model on eddy diffusivity coefficient to compute suspended load flux tends to afford fine reproducibility and agrees well with the observed results if the turbulent scale is taken as same degree as water depth.

(3) There are some issues such that sediment size distribution is unclear, destruction of training jetties and observed eddies in the bay could not be reproduced in computation, and that the assumption of vertically steady state of suspended sediment concentration may influence on the accuracy of analysis. However, it is verified that setting above parameter adequately enables to estimate total eroded and accumulated sediment volume accurately even if huge outer force due to tsunami is exerted as shields number exceeds over 10.

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