WAVE SETUP DUE TO THE EXTREME EVENTS AT DIFFERENT RIVER MOUTH MORPHOLOGIES IN JAPAN

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The information of water level rise at the entrance is essential for river planning and management. In this study, an attempt is made to collect as many full data sets as possible. In total, field data from ten river mouths in Japan were compiled and analyzed. The results have been shown that the wave setup height is not only depending on wave breaking at the entrance but also affected by river discharge and river mouth morphology. Wave setup height was attained to from 2 to 14 percent of offshore wave height for the cases of water depth at entrance from 1.1m to 6.5m. The final result is obtained as a technical diagram for predicting the wave setup height at the river mouth.

Key Words **:** W*ave setup, river mouth morphology, water level rise, extreme event, river and ocean interaction*

1. INTRODUCTION

Prototype scale study on wave setup due to an extreme event at river mouths is very important in terms of river mouth morphology change, navigation transportation, saline intrusion into river and water environment especially for a river which has a lagoon or lake at the entrance.

Wave setup height is mainly caused by high wave breaking at the entrance. Each year, there have been many extremely events that caused the wave setup occurring around of Japan. Those are induced by the low pressure system from Pacific Ocean and the frequently and continuously strong wind from Japan Sea during the winter.

In this study, an attempt is made to collect as many full data sets as possible. In total, field data from ten river mouths within Japan were compiled and analyzed. However, because of each river entrance has their own morphology (**Table 1**), for instance with and without jetties construction, or with and without sand spit at river entrance so the wave setup height needs to be analyzed individually and compared between them.

The wave setup is the height of Mean Water Level (MWL) above Still Water Level (SWL). In most of cases, the estimation of wave setup at a river mouth have been based on water levels measured some distance upstream from river mouth and then compared with a tidal level that measured in deep water where wave effects can be neglected (Tanaka et al.[1])**.**

There are several researchers studied on wave setup at river entrance such as Hanslow et al.[2), 3)], Tanaka et al.[4), 5)], Dunn et al.[6)], Oshiyama et al.[7)], and Nguyen et al.[8)], nevertheless, their findings are quite different each others because of the occurrence of wave setup has distinct dependence on river mouth morphology and the magnitude of storm.

The main objectives of this study are to investigate the variation of wave setup height at ten different river morphologies, and to establish the relationship between wave setup and offshore wave height. In addition, the influences of river discharge to wave setup height are examined. The final results will be contributed a technical diagram for predicting the wave setup height at the river mouth. This study is helpful for river authority and river engineers to find out the best solution in controlling the river mouth morphology change and environment management as well as salinity intrusion into the river.

Table 1 River characteristics

River name	River length (km)	Catchment area (km^2)	Water depth (m)	No. of jetty
Natsui	67	749	1.2	0
Abukuma	239	5,390	5.7	0
Natori	55	984	4.5	2
Nanakita	45	229	1.5	1
Naruse	89	1,130	6.0	2
Old Kitakami	249	10,150	6.5	2
Kitakami			4.2	0
Nagatsura Inlet	——	——	1.1	0
Iwaki	102	2,540	4.5	2
Yoneshiro	136	4,100	3.6	0

2. DATA COMPILATION

In order to achieve the above objectives, the required data sets are the wave height in deep water, water level at some distance upstream of river, and tidal level, as well as the river discharge during the event. The average water depth at river entrance is also necessary.

(1) Study area

In this study, two group of river mouths will be concentrated on. One is facing the Pacific Ocean including Kitakami, Old Kitakami, Naruse, Naknakita, Natori, Abukuma, Natsui Rivers and Nagatsura Tidal Inlet as shown in **Fig.1**. These Rivers were impacted by the low pressure system as called typhoon 18 at the beginning of October 2006. Another two Iwaki and Yoneshiro Rivers are facing the Sea of Japan (**Fig.2**) and influenced by the continuously strong wind during January to February.

(2) Hydrodynamic data collection

The measured tidal level data was obtained from Ayukawa, Sendai, Onahama and Fukaura Ports. This measured tidal level has already included the storm surge that is pushed toward the shore by the force of the winds swirling around the storm.

Water level variations were measured at some distance upstream of each river. The differences in elevation between water level in river and tidal level are considered as the water level rise at river mouth. Depending on the location of river mouth, the closest tidal station will be chosen to compare with water level to eliminate the effect of pressure difference.

Wave information is widely available in Japan.

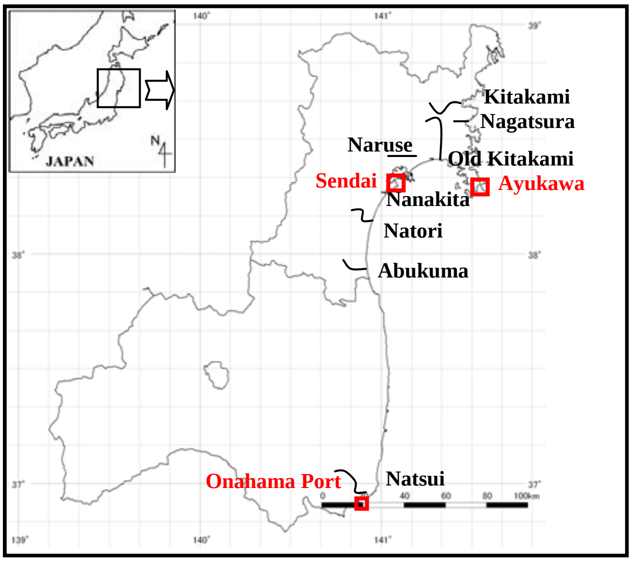

Fig.1 Location of rivers facing Pacific Ocean

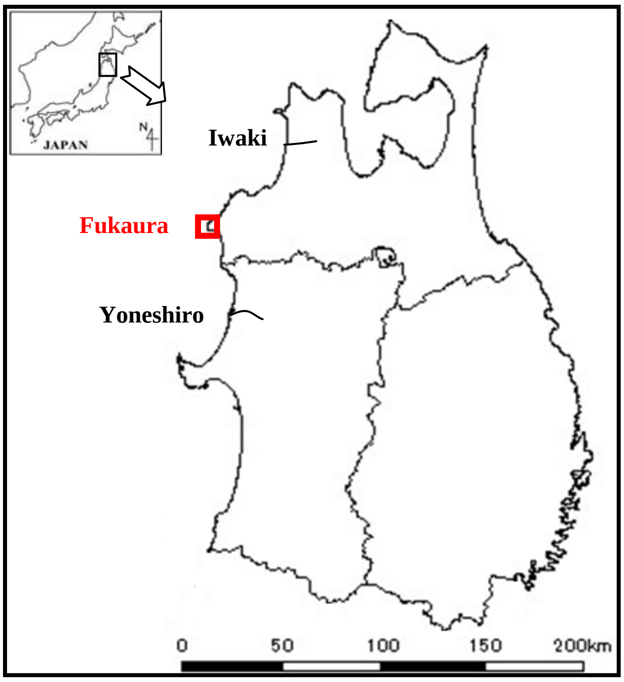

Fig.2 Location of rivers facing Japan Sea

However, for this study area there are four suitable wave stations to get the offshore wave height namely Enoshima, Sendai, Onahama and Fukaura stations. The obtained wave data in Enoshima station was used to estimate the wave setup height for the Kitakami River and Nagatsura Inlet. Sendai wave data was employed for the Old Kitakami, Naruse, Nanakita, Natori, and Abukuma Rivers. Onahama wave data was used for the Natsui River. And Fukaura wave data was taken for the Iwaki and Yoneshiro wave setup analysis.

This study has also been attempting to collect the monthly fresh water discharge and for each river.

Due to the complex hydrodynamic conditions in front of river mouths, the water depth is temporal and spatial changed. The latest cross-sections were collected. **Fig.3** is an example of latest water depth cross-section in the Yoneshiro River mouth and the average water depth is approximately equal to 3.6m.

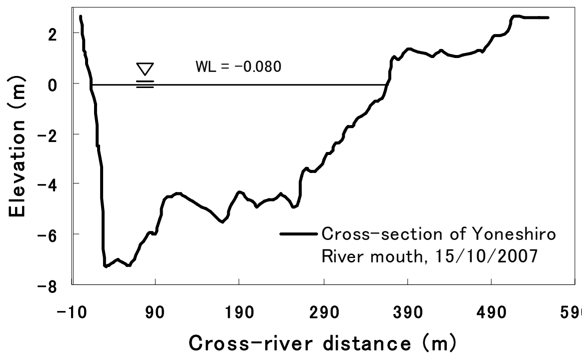

Fig.3 Water depth cross-section of the Yoneshiro River mouth

3. RESULTS AND DISCUSSION

(1) Water level rise at the river mouth

Monthly water level rise (WLR) which is equal to water level in the river mouth minus to tidal level, wave height in deep water, H_0, and river discharge in the Kitakami River, Q, are plotted in the **Fig.4**. At the time of WLR occurrence, the wave height and river discharge equal to 5.56m and 96m^3/s, respectively. Hence, the WLR starts increasing together with wave height while river discharge is still very small. This suggests that the WLR during this part is mainly influenced by wave motion such as wave breaking at the entrance. However, the maximum of WLR attains as the discharge reaches to 1598m^3/s and wave height decreases to 4.1m, it means the river discharge affected to the WLR but smaller in order of magnitude compare to the effect of wave height. There was a suddenly increase of discharge in the Kitakami River is due to the gate operation in the upstream of river.

The energy dissipation in the side walls of a narrow jettied entrance is often as significant as that due to breaking (Dunn et al.[6]). When the wave propagates up the entrance, the side wall dissipation induces diffraction which in turn tends to reduce the wave setup. This is a consequence of the irrotationality of the wave motion away from the rock walls. In jettied Natori entrance, there is still obtained a little wave setup but it occurs at the same time with wave height and fresh river discharge (**Fig.5**). Therefore, it is not possible to separate the wave set up due to wave breaking.

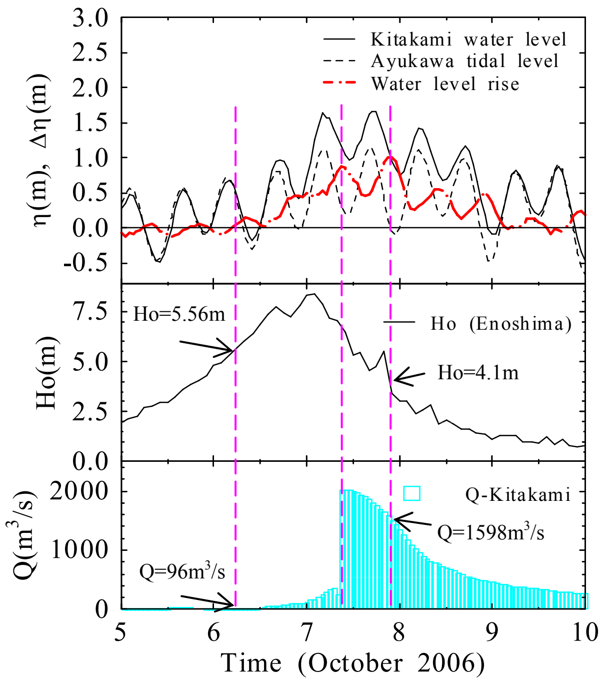

Fig.4 Hydrodynamic condition and water level rise at the Kitakami River

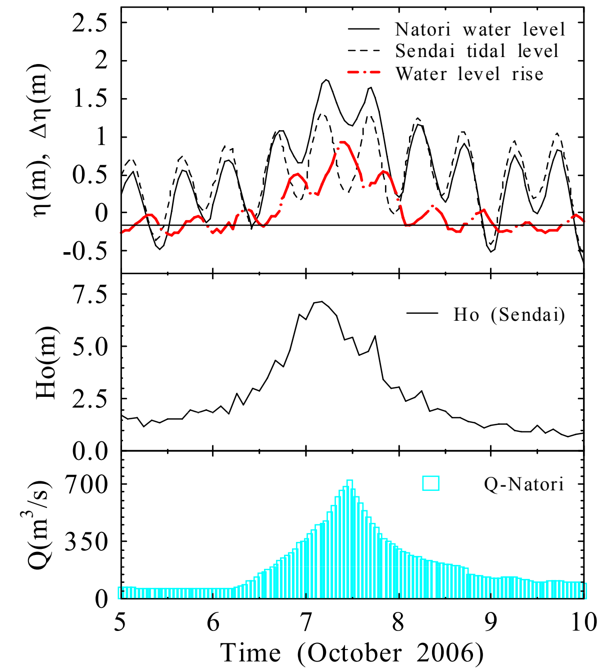

Fig.5 Hydrodynamic condition and water level rise at the Natori River

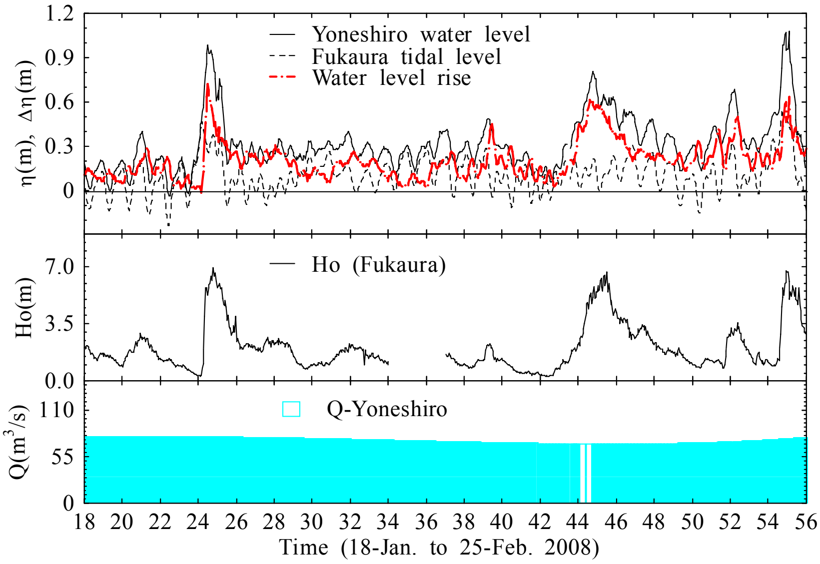

Fig.6 Hydrodynamic condition and water level rise at the Yoneshiro River

This kind of phenomenon is again confirmed in the Naruse River.

As mentioned above, the frequently and continuously high wave caused by strong wind from Japan Sea was attacked to the coastline in every winter. **Fig.6** illustrates the hydrodynamic conditions of the Yoneshiro River from 18th January to 25th February in 2008. There were several events that caused the wave height higher than 6.5m and a very significant water level rise was attained in this river.

The almost constant of fresh river discharge in the Yoneshiro River suggested that the water level rise during the events was mainly caused by wave breaking at the entrance.

(2) Backwater effects

The water level rise at a river entrance can be attributed not only to wave set up, but also to backwater effect due to constriction of the flow caused by shallow and narrow of rivers or tidal inlets during ebb tide thus saline water that gets into river during high tide might not flow back to the sea. The water level in river is always higher than tidal level even during ebb tide and small wave condition.

These effects are clearly seen in the Nagatsura Inlet, Nanakita and Natsui Rivers which have the average water depth at entrance around 1.1m to 1.5m. Therefore, for wave setup analysis we have to neglect this backwater effect by only considering the water level rise values during the high tide period.

(3) Relationship of wave setup height and offshore wave height

To investigate the wave setup height due to wave only the effects of backwater and river discharge are neglected by only considering the water level rise values during the high tide level. All suitable data sets were plotted in the **Fig.7**. The relationship of wave setup height and offshore wave height can be estimated by using the following equation.

$$\Delta\eta = aH_0 \tag{1}$$

where $\Delta\eta$ is the wave setup height at the entrance, H_0 the offshore wave height, a regression slope.

The regression slope, which also means the percentage of wave setup height compare to offshore wave height, is obtained by using the linear regression analysis that used the "least squares" method to fit a line through a set of data. These results illustrate that the wave setup height decreases as water depth increasing. The regression slopes at the Nanakita and Natsui Rivers in this study are well in agreement with the results obtained by Oshiyama et al.[7].

(4) Analytical solution

Bowen et al.[9] has developed an analytical solution for wave setup on a sloping beach. The radiation stress, S_{xx} is defined as the excess flow of momentum due to the presence of the waves. In steady state, the shoreward flux of momentum must be independent of x, the perpendicular to the shore. Momentum balance equation becomes.

$$\frac{d\eta}{dx} = -\frac{1}{\rho g(h+\eta)}\frac{dS_{xx}}{dx} \tag{2}$$

where η is the difference between the still level and mean sea level in the presence waves, h the local water depth, g the gravitational acceleration, ρ

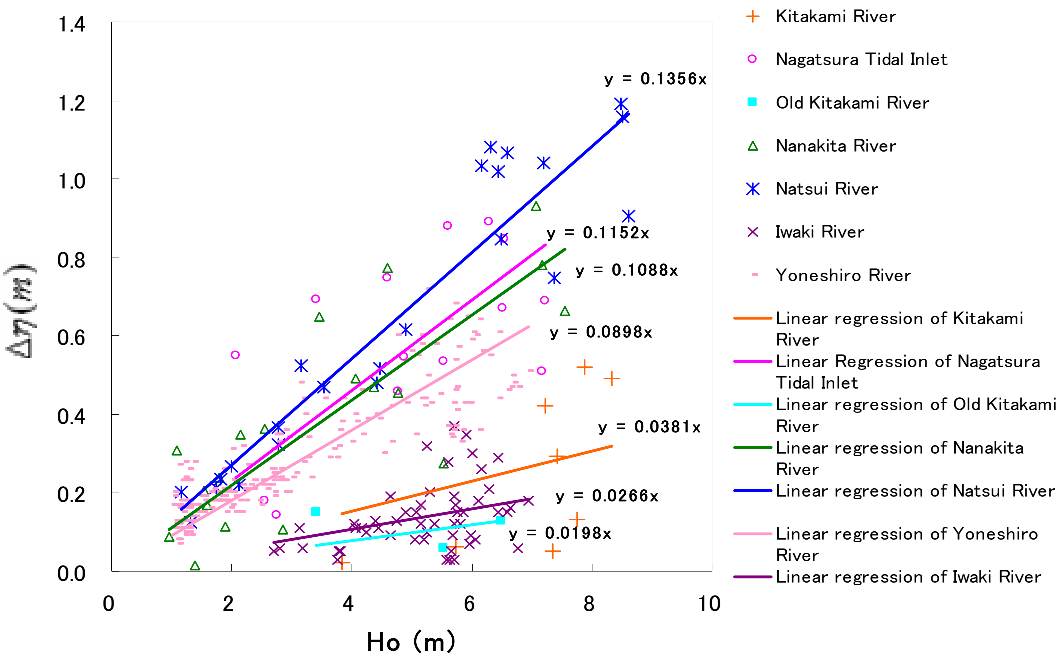

Fig.7 Relationship of the wave setup height and offshore wave height

the water density.

Integrating Eq.(2), we have the solution for η as,

$$\Delta\eta = K(h_b - h) - \frac{1}{16}\gamma^2 h_b, \tag{3}$$

where $K = \dfrac{1}{1+8/3\gamma^2}$ is a coefficient related to breaker index γ. If γ =0.8 then K=0.19, h_b=H_b/0.8 water depth at breaking point, H_b is the wave breaking height. In this study, the local water depth, h, was assumed equal to average water depth at river mouth, h_R. Replacing all into Eq.(3) becomes

$$\Delta\eta = 0.19\left(H_b - h_R\right) \tag{4}$$

Sunamura and Horikawa[10] has found that the ratio of H_b/H_0 is a function of beach slope, i, and wave steepness, H_0/L_0. The formula is expressed as

$$\frac{H_b}{H_0} = i^{0.2}\left(\frac{H_0}{L_0}\right)^{-0.25} \tag{5}$$

Dividing Eq.(4) for H_0 and substitute Eq.(5) into Eq.(4) we obtained

$$\frac{\Delta\eta}{H_0} = 0.19\left\{\left(\frac{H_0}{L_0}\right)^{-0.25} i^{0.2} - \frac{h_R}{H_0}\right\} \tag{6}$$

Equation (6) is an analytical solution of wave setup at river mouth. This equation was applied to current data sets at different wave steepness values. The beach slope in whole study area was approximately equal to 0.05. The result has shown that analytical result is always higher than observed results of wave setup (**Fig.8**). This might be because of we used theoretical breaker index assumption and consequence affects to K value. Therefore, the current data sets are in turn to calibrate again K coefficient. The best fit line was found at K=0.095 (**Fig.8**).

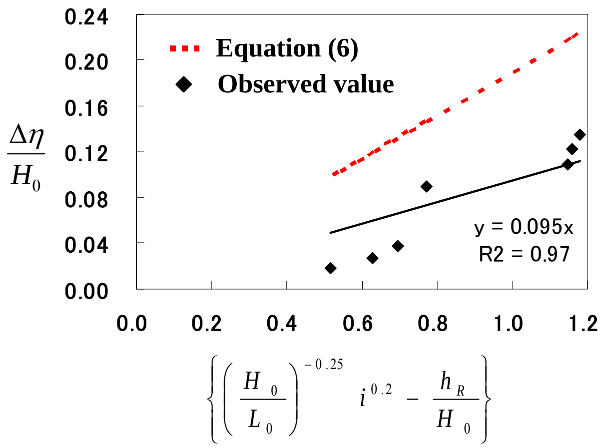

Fig.8 New empirical K coefficient

(5) Empirical solution

For technical point of view, the empirical diagram of relationship between wave setup height and water depth at the river mouth as well as offshore wave height is very important for engineers to predict the wave setup. The result can be seen in the **Fig.9**. The empirical logarithm relationships are expressed as follows.

$$\frac{\Delta\eta}{H_0} = -0.0611 * \ln\left(\frac{h_R}{H_0}\right) + 0.0129 \tag{7}$$

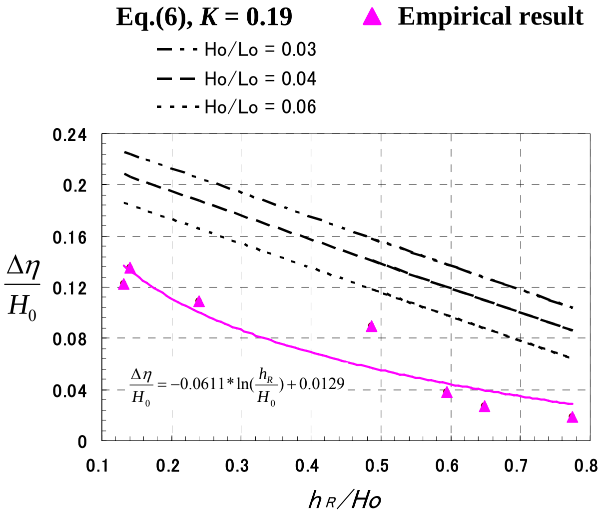

Fig.9 Empirical and analytical results of wave setup at a river entrance.

Both empirical and analytical solutions were shown that the wave setup height is inversely proportional to water depth at the entrance.

The wave setup is getting lower as wave steepness is higher.

4. CONCLUSIONS

A comprehensive study on wave setup due to the extreme events at different river entrance morphologies was carried out. Wave setup at river entrance is not only depending on the offshore wave height but also depend on the river discharge and morphology of river mouth. Wave setup height was attained from 2 to 14 percent of offshore wave height for the cases of average water depth at the entrance from 1.1m to 6.5m. Wave setup height is inversely proportional to the average water depth at river mouth.

The new K coefficient is suggested to use for analytical solution. The analytical solution with new calibrated K=0.095 is in agreement with empirical result.

Study on prototype scale of wave setup is not easy to be achieved since the difficulty of full field measurements. This empirical study is helpful for river authority, river management and engineers to find out the best solution in controlling the river mouth morphology change and environment.

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REFERENCES

1) Tanaka, H., Nagabayashi, H. and Yamauchi, K.: Observation of wave set-up height in a river mouth, *Proceedings of 27th International Conference on Coastal Engineering*, pp. 3458-3471, 2000.
2) Hanslow, D.J. and Nielsen, P.: Wave setup on beaches and in river entrances, *Proceedings of 23rd International Conference on Coastal Engineering*, pp. 240-252, 1992.
3) Hanslow, D.J., Nielsen, P. and Hibbert, K.: Wave setup at river entrance, *Proceedings of 25th International Conference on Coastal Engineering*, pp. 2244-2257, 1996.
4) Tanaka, H. and Lee, H.S.: Influence of jetty construction on morphology and wave set-up at a river mouth, *Coastal Engineering Journal*, Vol.45, No.4, pp.659-683, 2003.
5) Tanaka, H. and Lee, H.S.: Study on water level fluctuation due to wave set-up in a river mouth, *Journal of Hydraulic, Coastal and Environmental Engineering, JSCE*, Vol.62, No.2, pp.210-223, 2006.(in Japanese)
6) Dunn, S.L. and Nielsen, P.: Wave setup in river entrances, *Proceedings of 27th International Conference on Coastal Engineering*, pp 3432-3445, 2003.
7) Oshiyama, S., Lee, H.S. and Tanaka, H.: Water level variation at a mouth of small to medium scale river, *Annual Journal of Coastal Engineering JSCE*, Vol.48, pp.411-415, 2001.(in Japanese)
8) Nguyen, X.T. Tanaka, H. and Nagabayashi, H.: Wave setup at river and inlet entrances due to an extreme event, *Annual Journal of Coastal Engineering JSCE*, Vol.54, pp.321-325, 2007. (in Japanese)
9) Bowen, A.J., Inman, D.L. and Simmons, V.P.: Wave 'set-down' and set-up, *Journal of Geophysical Research*, Vol.73, No.8, pp.2569-2577, 1968.
10) Sunamura, T. and Horikawa, K.: Two-dimensional beach transformation due to waves, *Proceedings of 14th International Conference on Coastal Engineering*, pp.920-938, 1974.

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