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NUMERICAL PREDICTIONS FOR EQUILIBRIUM PROFILE ON INTERTIDAL FLAT

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ABSTRACT: Morphology of intertidal flat is dictated by the input of sediments from rivers and the subsequent redistribution by waves, currents, and gravity-driven flows. An analytical models is develop for dynamic equilibrium profile from Falcini et al (2012) and Yamada et al (2004) equations and numerical simulations are used to predict the long-term cross-shore morphology changes on intertidal flat adjacent of river mouth. By using these models, we explore the gravity flows and sea bottom slope in determining the critical conditions for bypass of gravity-driven sediment transport. The field site of this research is located on the center of the eastern coast of Ariake Bay at river mouth of Shirakawa River, Japan. Monthly bed level measurement from February 2001 to January 2013 with the distance between 100 to 1050 m and the interval of 10 m from seawall was analyzed. Oceanographic data such as tide level, significant wave height, wave period, and wind velocity measured at an observation tower of Kumamoto Port. Water debit of Shirakawa River is obtained from Ministry of Land, Infrastructure and Transport of Japan. Based on model predictions, we found that the dynamic equilibrium profile is spatially and temporally consistent with field observations and it predicted to be deeper and boarder associated with sediment.

Keywords: Tides, waves, river discharge, morphology, intertidal flat, gravity-driven currents.

INTRODUCTION

The morphological evolutions of an intertidal flat adjacent to a river mouth are influenced by tides, wind waves, river discharge and their interactions (Le Hir *et al.* 2000; Green and Coco, 2007; Fagherazzi and Overeem (2007); and Yamada *et al.* 2009). Intertidal flats are extensive coastal regions dominated by fine cohesive sediment, and it is very sensitive to changes in sea level.

The geomorphology of intertidal mudflats is complex, imperfectly understood and very little attention has given to the importance of these areas (Friedrichs and Wright, 2004). Therefore, quantitative understanding of hydrodynamics and sediment transport associated with sea level change on intertidal mudflats is necessary for coastal protection and management of bays and estuaries.

Friedrichs and Wright (2004) had developed a model for equilibrium bathymetric profiles off river mouths associated with the shoreward, convex upward portion of deltas. They conclude that the slope of equilibrium profile dominated by wave-supported gravity flows increases with greater water depth and sediment supply, and decreases with increasing wave height and wave period. Conversely, this model considers only the effect of wave and sediment supply on mudflat area. In addition, Falcini *et al* (2012) proposed a numerical model that including the density contrast term in the fluid momentum balance allows and accurate prediction of transport under a give set of flow and wave condition for very slope shelves.

This paper is concern with analytical model of cross-shelf profiles development associated with tide and wave force, and river discharge. The model is derived analytically from Friedrichs and Wright (2004); Yamada *et al* [(2004) and Falcini *et al* (2012) in order to predict the equilibrium profile of mudflat adjacent to Shirakawa River mouth.

FIELD SITES AND MEASUREMENTS

The field site of this study is located on the center of the eastern coast of Ariake Bay in Japan, which is a closed inner bay at the mouth of Shirakawa River (Fig 1). The length, width, and depth of the bay are approximately 97 km, 20 km, and 20 m, respectively.

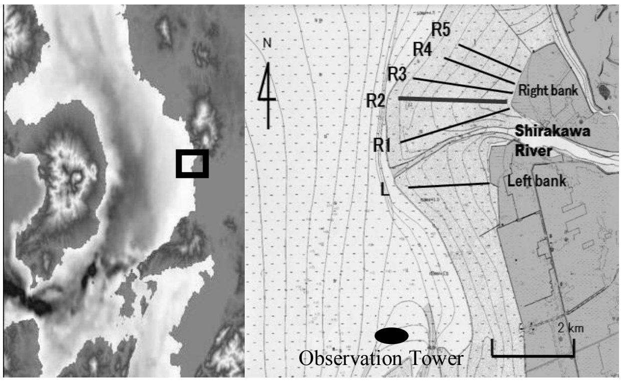

Fig. 1 Map of field site with six cross shore profile lines.

Monthly bed level measurement from May 2004 to January 2013 with the distance between 100 to 1050 m and the interval of 10 m from seawall was analyzed. Oceanographic data such as tide level, significant wave height, wave period, and wind velocity measured at an observation tower of Kumamoto Port, which located about 6 km south of the field site in this study. Water debit of Shirakawa River is obtained from Ministry of Land, Infrastructure and Transport of Japan.

The bed levels at the specified cross-shore locations were measured from the crest of a seawall using an Electric Distance Meter (EDM) as explained by Yamada and Kobayashi (2004). The profile measurements were carried monthly during low water on days of spring tides. The mean sea level (MSL) is 0.14 m above the datum of the bed level. The mean high water (MHW) and mean low water (MLW) during neap (N) and spring (S) tides are indicated in Figure 2. The horizontal distance was measured from the vertical seawall located along the shore. The mean high water spring (MHWS) is 1.93 m and the mean high water neaps (MHWN) is 0.77 m.

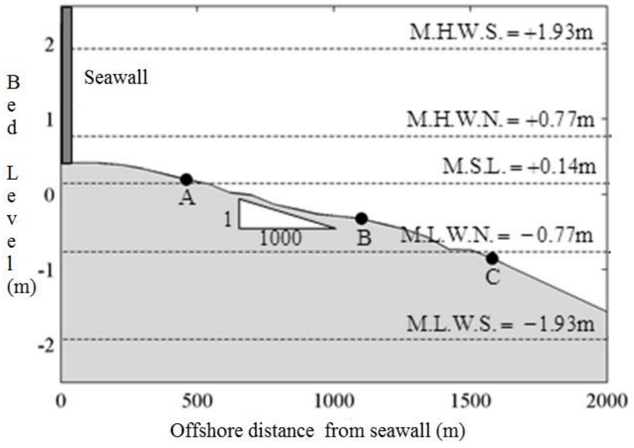

Fig.2 Cross-shore profile schematic and tide levels along survey line.

NUMERICAL DEVELOPMENT

Intertidal flats are typically associated with bays and estuaries exhibit a convex-upward profile, produced by the sediment input from the rivers. This concave profile is an expression of the rollover clinoform where the sediments of fluvial are accumulated. Models that examine the redistribution of fluvial sediments in the shelf and the formation of the rollover clinoform are usually based on conservation of sediments and the sediment flux. The continuity equation is:

$$\frac{\partial h}{\partial t} = -\frac{\partial S}{\partial x} \tag{1}$$

where h is the elevation of the shelf and S is the volume of sediment transported in the x direction.

Kenyon and Turcotte (1985) presented the simple model of sediment flux as a function of waves, currents, and gravity is proportional to the bottom slope by a diffusion equation:

$$S = -D\frac{\partial h}{\partial x}, \quad \frac{\partial h}{\partial x} = D\frac{\partial^2 x}{\partial x^2} \tag{2}$$

where D is the transport coefficient. But in reality, some deltas, currents and mass-wasting transport the sediment from the mouth of the rivers to deeper locations, therefore the diffusion equation needs to be replace with an advection-diffusion equation (Swenson *et al*. 2005) as shown below:

$$S = -kh - D\frac{\partial h}{\partial x}, \quad \frac{\partial h}{\partial t} = k\frac{\partial h}{\partial x} + D\frac{\partial^2 h}{\partial x^2} \tag{3}$$

Sediment Dispersal Model is presented in Pirmez (1998), which explain the formation of the concave-upward clinoform profile as:

$$\begin{gathered} \frac{\partial UCh}{\partial x} = W_s c_b \left(1 - \frac{\tau_b}{\tau_c}\right) p \\ u(x,z) = U\frac{\sqrt{C_D}}{\kappa}\ln\left(\frac{(h-z)+z_0}{z_0}\right) \\ \frac{\partial h}{\partial t} = \rho_B\left(\frac{\partial\ U\ C}{\partial x}\right) \end{gathered} \tag{4}$$

where, UCh is the layer-averaged suspended sediment discharge, Wsc$_b$ is net balance between the settling flux, and ρ_B is bulk density.

Friedrichs and Wright (2004) explained that sediment is moved offshore by hyperpycnal layers supported by wave and current induced resuspension. Under these conditions, a dynamic equilibrium profile is established by which all the fine sediment coming from the river is bypassed to the outer-shelf without net deposition or erosion. The time averaged, depth-integrated momentum balance for a wave-supported sediment gravity flow is given approximately by a balance between the downslope pressure gradient and mean bottom stress (Fig. 3) :

$$\alpha g s C \rho_s^{-1} = c_d |u| u_g \tag{5}$$

where, α is the sine of bed slope, g is the acceleration of gravity, ρ is the density of siliceous sediment and s is submerged weight, C is the depth-integrated mass concentration of sediment and c_d is bottom drag coefficient.

The key velocities associated with eq. (5) are downslope velocity of gravity current (ug), wave orbital velocity (uw) and the absolute amplitude of instantaneous velocities. Then by consider the Richardson number for the wave boundary layer:

$$\alpha gsC\rho_s^{-1} = c_d \left|u\right| u_g \tag{6}$$

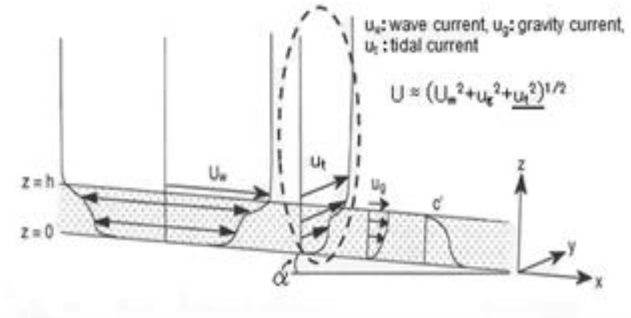

Fig.3 Schematic of cross-sectional of velocity flows (Wright *et al*., 2004)

The combining of the Eqs (5) and (6) for the critically stratified case of Ri = Ric, then the relation for equilibrium bathymetric slope is:

$$\alpha\left\{1-\left(\alpha R_{ic}c_d^{-1}\right)^2\right\}^{-3/2} = 8\left(\omega H\right)^{-3}\left(\sinh kh\right)^3 Q_r gsc_d R_{ic}^{-2}\rho_s^{-1} \tag{7}$$

In order to predict the equilibrium profile at intertidal area at estuary, then, the wave height, wave breaking and shoaling effect are included to eq. (7):

$$\alpha\left\{1-\left(\alpha R_{ic}c_d^{-1}\right)^2\right\}^{-3/2} = \left\{8\left(\omega H\right)^{-3}\left(\sinh kh\right)^3 + u_c^{-3}\right\} Q_r gsc_d R_{ic}^{-2}\rho_s^{-1} \tag{8}$$

Following is a definition of bypass zone between the shoreline and the location where net sediment deposition takes place (Fig. 4) given by Falcini *et al* (2012). They only focus on wave-induced sediment suspension, not include the specific inner shelf zone, deposition or erosion but only look to bypass zone.

In accordance with the Eqs 4 and 5, the amplitude of wave orbital velocity, u_w, is given by linear theory as:

$$u_w = \omega A\left(\sinh kH\right)^{-1} \tag{10}$$

Here, A is wave amplitude, ω is the wave angular velocity, and k is the wave number. Then, the downslope velocity, u_g, of wave supported gravity current can be calculated by eq. 11 as follows:

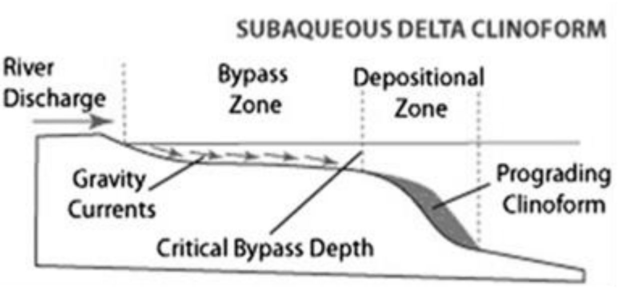

Fig.4. Wave-driven gravity currents to a subaqueous cliniform (Falcini *et al*, 2012).

$$u_g = u_w\left(\alpha Ri_c c_d^{-1}\right)\left\{1-\left(\alpha Ri_c c_d^{-1}\right)^2\right\}^{-1/2} \tag{11}$$

*

In this study, our model solves the conditions associated with sediment bypass on inner-shelf or bypass zone. This implies the existence of critical bypass depth, Hc, at which the condition where the net deposition must occur. Therefore, we can write gravity current discharge (UgChW) and sediment flux (Jgf) as

$$u_g ChW = J_{gf} \Rightarrow Ch = \frac{J_{gf}}{u_g W} \tag{12}$$

The Bulk Ricardson number provides a useful scale represent stratification within the boundary layer (in this study Ri= 0.14). Then, the cross-shore profile could predicted by Eq. 14.

$$R_i = \frac{g^{'}Ch}{\left|u\right|^2} \Rightarrow Ch = \frac{R_i\left|u\right|^2}{g^{'}} \tag{13}$$

$$\frac{J_{gf}}{u_g W} = \frac{R_i\left|u\right|^2}{g^{'}} \tag{14}$$

The depth-integrated momentum balance for a wave-supported sediment gravity flow under steady and non-homogeneous condition is given by Skene *et al*., (1997) and Friedrichs and Wright (2004) :

$$\frac{1}{W}\frac{\partial u_g^2 hW}{\partial x} = -\frac{1}{2}\beta g^{'}\frac{\partial Ch^2}{\partial x} + g^{'}\alpha Ch - \left(E + c_D\right)\left|u\right|u_g \tag{15}$$

where α and β are the sine and the cosine of the bottom slope angle respectively; g=Rg is a gravity factor . Eq. (12) contains three sources and sinks of momentum; the fluid pressure gradient, buoyancy, and friction, which are the first, second and third terms on the r.h.s., respectively.

The closure of Eq.(13) is given by conservation of water (Eq.14) and sediment mass (Eq.14) bellow:

$$\frac{\partial u_g hW}{\partial x} = WEu_g \qquad (16)$$

$$\frac{\partial u_g ChW}{\partial x} = 0 \qquad (17)$$

Conservation of sediment mass in the down slope direction (Eq. 14) is a steady-state hypothesis, and in this model used by associated with sediment bypass on the inner-shelf. As we consider the critical bypass depth, Hc, then the Eq. (12) – (14) can be rewrite as:

$$g^{'}\frac{J_{gf}}{u_g W}\left(\gamma - \beta Q_{gf}\frac{\partial}{\partial x}\left(\frac{1}{u_g W}\right)\right) = \left(W + c_D\right)|u|u_g \qquad (18)$$

where, γ = (β/2)E and the gravity current discharge is Qgf = ughW and the sediment discharge is Jgf = ugChW. And by combining the bulk Ricardson number, then the inner slope, α, can determined as:

$$\alpha = \frac{c_D u_g}{R_i |u|} + Q_{gf}\frac{\partial}{\partial x}\left(\frac{1}{u_g W(x)}\right) + \frac{1}{g^{'}CW(x)}\frac{\partial}{\partial x}\left(u_g^2 W(x)\right) \qquad (19)$$

RESULTS AND DISCUSSIONS

Monthly measurement of cross-shore profile along six lines for about 12 years were clarified the characteristic of mudflat. Fig. 5 shows the profiles along the each line of bed level measurement is increased gradually with offshore distance. The shape of the measured profiles was convex upward and the average slope of mudflats at Shirakawa River was in the range of 1/600 – 1/1200. The slope of equilibrium profile becomes lower and steeper with increasing the cross-shore distance.

By determining the critical bypass depth (Hc), it is possible to express the intertidal profile changes with consider to intertidal area and external forces such as floods or others extreme weather events (Fig.6).

Long term monitoring of bed levels (8 times during 1957 to 2003) including the subtidal area using echo sounding were conducted by Port and Airport Research Institute (Kuriyama and Hashimoto, 2004). In this study, we using data of 1978 and 2003 with consider to effect of intertidal flats due to river flood.

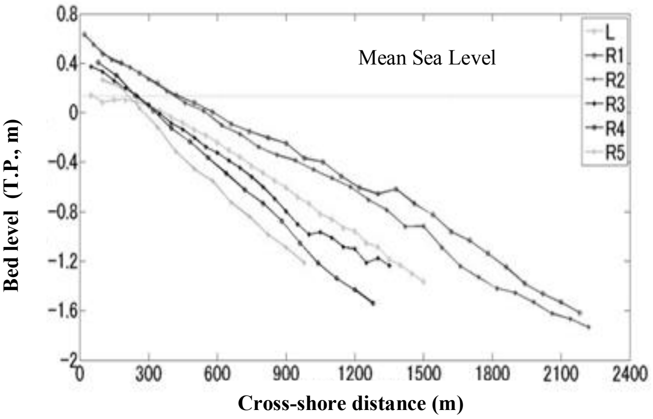

Fig.5. Average cross-shore profile along six lines (January 2001 – January 2013)

Figure 6 shows cross-shore profile of Shirakawa estuary. Black line is bed level profile on 1978, and black dotted line is bed level profile on 2003, respectively. Solid blue lines are those obtained by fitting the cross-shore profile of 1978, which include the external force (wave height WH = 0.18 m, the wave period T = 3.0 s and water debit Qr = 300 m^3 / s). The solid red line are those obtained by fitting the cross-shore profile of 2003, which consider to river flow rate is more than 1500m^3/s and the average of external force (wave height, WH = 0.38 m, wave period T = 3.0 s, and water debit, Qr = 1600 m^3/s). By substituting the external forces to Eq.12, then the critical depth has become -2.42 m and -1.96 m. Thus, it is possible to calculate the initial depth of long-term prediction model by defined the critical depth, to express a certain extent forward of bed level trend and the slope gradient of Shirakawa River mouth.

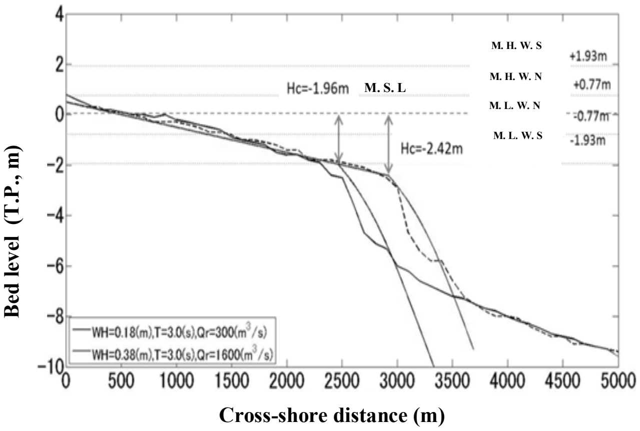

Fig. 6. Long term prediction model

Long-term prediction model was conducted for adaptation of Shirakawa River mouth by using the Eq.16. To predict the cross-shore profile, then the topography measured on 2003 is fitting as shown on Figure 7. The wave height is WH = 0.38(m), wave period T = 3.0 (s), water debit Qr = 1600 (m^3 / s), and suspended sediment concentration C = 0.01 (kg / m^3).

Relation between water debit (Qr) and mudflat profile have clarified by changed the amount of sediment supply to 1000, 1600 and 2200 m^3/s. Equilibrium slope profile will be steeper with increase of water debit (Fig 8).

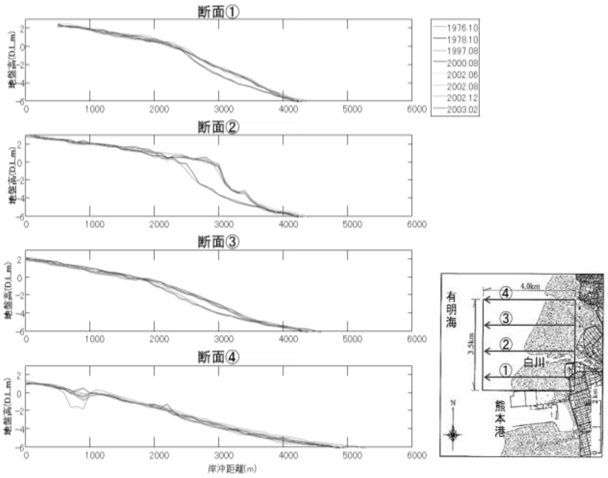

Fig.7 Cross-shore distance of Shirakawa river mouth (modified from Port and Airport Research Institute)

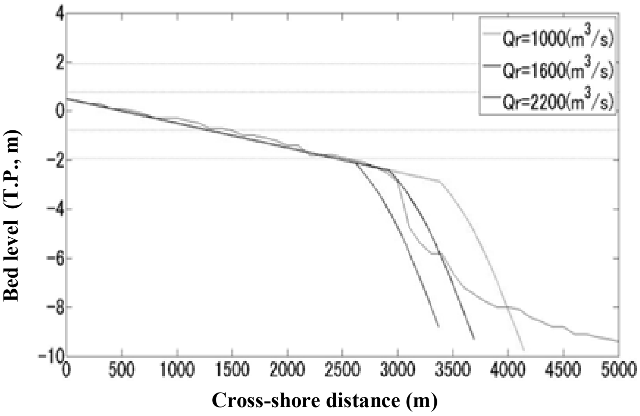

Fig. 8 Prediction of equilibrium profile changes by sediment supply.

Figure 9 shows the prediction of equilibrium profile changes by suspended sediment concentration. The increasing of sediment concentration will be changed the mudflat profile to be sharper and more onshore.

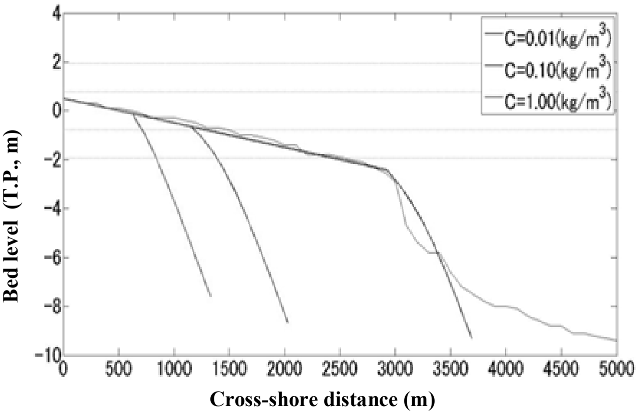

Fig. 9 Prediction of equilibrium profile changes by suspended sediment concentration.

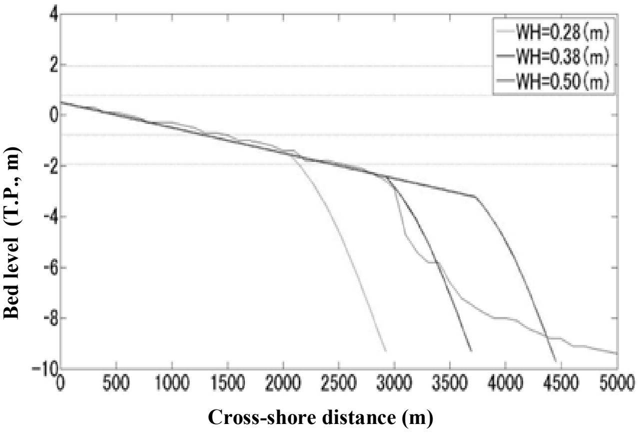

Fig.10 Prediction of equilibrium profile changes by wave height

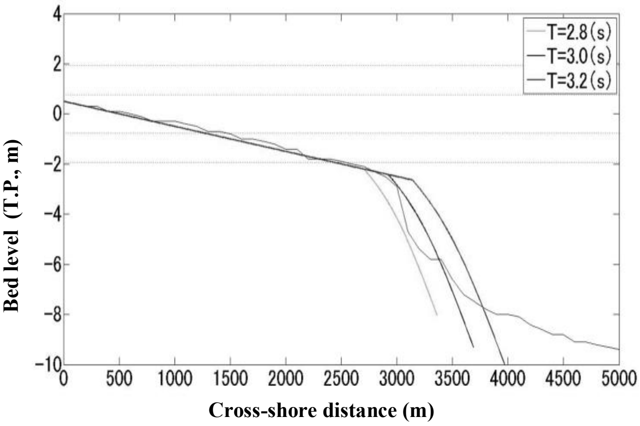

Fig.11 Prediction of equilibrium profile changes by wave period.

The increasing and decreasing of wave height and wave period will be contributed to the equilibrium profile of mudflat. The model shown that, the equilibrium profile will be broader with the increase of wave height (Fig.10) or wave period (Fig.11). The increasing and decreasing of wave height and wave period will be contributed to the equilibrium

CONCLUSION AND FUTURE STUDY

The slope of equilibrium profile on intertidal area at Shirakawa River is convex upward and it becomes lower and steeper to offshore. In addition, the slope of an equilibrium profile associated with the landwards, will increase with depth and sediment supply, and decreases with increasing of tidal current, wave height, and wave period.

By determining the critical bypass depth (Hc), it is possible to predict the equilibrium intertidal profile changes with consider to intertidal and tidal zone.

Furthermore, the prediction of cross-shore profiles changes related to extreme events is needed due to adaptation of disaster risk on coastal area. Then, the investigation of long term prediction model should include spreading, deposition or erosion and more offshore distance.

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