The Effects of Flooding on Shirakawa Delta Morphology

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ABSTRACT

Floods can significantly alter the morphology of a delta, from inputting increased volumes of sediments to modifying the reach of incoming waves, currents, and other gravity-driven forces occurring within the near shore. Kumamoto experienced flooding in July 2012. This flood event altered the equilibrium profile of the intertidal flat area of the Shirakawa River. This research looks at these modifications and attempts to explain their long-term implications on the overall delta morphology.

Data collected over a 30-year period was analyzed and profiles were generated to better analyze and assess the trend in delta morphological changes. Numerical predictions on delta morphology in the presence of gravity-driven sediment transport were applied to investigate the morphological changes related to the flood event. The slope of equilibrium profile is lower and steeper offshore, helping to explain the models created before and after the flood occurred.

1. INTRODUCTION

Recently, some types of extreme weather and climate events have increased in frequency and/or magnitude, such as the increase of storm surges in along coastal areas; wind speeds of tropical cyclones; precipitation; and heavy rain. Moreover, populations and assets at risk have also increased with consequences of disaster risk (Intergovernmental Panel on Climate Change [IPCC], 2012).

The estuarine tidal flat or delta area has played an important role in the protection of marine resources and disaster prevention in coastal areas. Delta morphology is dictated by the input of sediment from rivers and its redistribution by currents, gravity-driven flow, and waves. The delta prograding system often displays a compound-clinoform geometry which, divided, consists of a subaerial delta couplet, as shown in Figure 1 (Swenson, Paolo, Pratson, Voller, & Murray, 2005).

The area near the river mouth exhibits a convex-upward profile as an expression of the rollover clinoform where the sediments of fluvial origin are accumulated (Fagherazzi & Overeem, 2007) as a result of the distribution of shear stress in a natural system (Pirmez, Pratson, & Steckler, 1998; Kirby, 2000) and it contributes to the delta formation. The gentle slopes of inner continental shelves rarely support autosuspension of turbid flows by gravity. Through this condition, the mixture of water and sediments becomes highly stratified, and a dense sediment layer at the shelf floor dictates both deposition rates and the formation of the clinoform geometry. The stacking of clinoform-shaped deposits

makes up the bulk of stratigraphic sequences (Mitchum, Vail, Thompson, 1977).

The previous modelling studies of tidal-dominated flat were carried out by Friedrichs and Aubrey (1996), and the analytical model for clinoforms was formulated by Friedrichs and Wright (2004). However, their model can be applied only in the clinoform topset, in which sediment is bypassed to the clinoform foreset without net deposition or erosion. In addition, Falcini, Fagherazzi, & Jerolmack (2012) established the inclusion of the density contrast term in the fluid momentum balance and allows an accurate prediction of transport under a given set of flow and wave conditions for very sloped shelves.

The geomorphology of these tidal flats is complex and imperfectly understood; sparse attention has been given to the importance of these areas. Therefore, understanding the hydrodynamics and sediment transport associated with external forces, such as heavy rains and typhoons, is crucial to study.

Figure 1. Definition of model delta propagation; after Swenson et al. (2005)

This research is expected to provide some contributions on environmental protection and support to planners and decision makers on managing coastal resources. The primary aim of this study is to examine a numerically generated model used to analyze cross-shore profile changes of the Shirakawa River Delta as associated with tidal and wave forces as well as with river discharge due to floods.

2. HISTORICAL FLOODING OF STUDY AREA

The Shirakawa River originates at Mount Aso and goes through the city of Kumamoto for about 78 km. Rain falling within the Mount Aso area takes approximately two hours to travel and affect communities downstream of the Shirakawa River, even if there is no rainfall experienced downstream. The annual data of water levels from 1956–2012 is shown in Figure 2. Kumamoto experienced three significant flood events between 1978 and 2012. On August 30, 1980, the first significant flood event was experienced, and inundation was estimated at 2,300 m³/s. The second significant flood event occurred July 2, 1990, with estimated water levels of 2,300 m³/s; and the third event was July 12, 2012, in which the water level exceeded 2,300 m³/s (Figure 3).

On July 12, 2012, the torrential rainfall received caused significant landslides in the mountainous area, and significant flooding was experienced in the lower areas along the Shirakawa River. Rainfall lasted over a 24-hour period with an accumulated 507.5 mm of precipitation, 62 mm less than the 30-year average. According to the Japan Society of Civil Engineering Western Branch in Kyushu, 30 people died, 2 people were missing, 11 people were injured, 313 house were completely destroyed, and 1,500 houses were half-destroyed.

3. FIELD MONITORING DATA

3.1. Field Site and Data Analysis

The field site of this research is located along the eastern coast of the Ariake Bay situated at the mouth of the Shirakawa River (Figure 4). Long-term monitoring data using echo sounding (eight times during 1976 to 2003), including the subtidal area, were conducted by Port and Airport Research Institute, Japan (Kuriyama & Hashimoto, 2004) and were used under permission of collaboration research. Also, an observation on June 2013 after a flash flood occurred was done by using HydroSurveyor, M9. Oceanographic data, such as tide level, significant wave height, wave period, and wind velocity, were measured at the observation tower at the Kumamoto Port. Measured water levels and river discharge rate of the Shirakawa River were obtained from the Ministry of Land, Infrastructure and Transport of Japan.

Figure 2. Maximum annual water levels

Figure 3. Discharge rates of Shirakawa River

Figure 4. Map of field site illustrating six cross shore profile lines used to collect data

The spatial distributions of mud thickness on the intertidal zone due to a flash flood were measured in September 2012, as shown in Figure 5.

3.2. Numerical Analysis

A fundamental underpinning of most models of coastal morphodynamic behavior is the notion that dynamic equilibrium states exist and that changes, either erosion or accretion, occur in ways that minimize

Figure 5. Spatial distribution of mud thickness on intertidal zone due to flush flood caused by torrential rainfall on July 12, 2012

departures from those states. Cross-shore equilibrium profiles are estimated using the advection-diffusion equation (Swenson et al., 2005). In order to judge the achievements of equilibrium states under each extreme event, a model from Falcini et al. (2012) for critical bypass depth or rollover point of the delta area, which include effects of fluid-induced pressure gradients, was used.

4. NUMERICAL DEVELOPMENT

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. Kenyon and Turcotte (1995) 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 (Equation 1).

$$S = -D \frac{\partial h}{\partial x} \quad \frac{\partial h}{\partial t} = D \frac{\partial^2 h}{\partial x^2} \quad (1)$$

Where h is the elevation of the shelf, S is the volume of sediment transported in the x direction, and D is a 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 replaced with an advection-diffusion equation (from Swenson et al., 2005) as shown in Equation 2.

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

Friedrichs and Wright (2004) described 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 as:

$$\alpha g s C \rho_s^{-1} = c_d |u| u_g \quad (3)$$

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

In this study, our model solves the conditions associated with sediment bypass on the inner shelf or bypass zone. This implies the existence of critical bypass depth, H_c , at the condition where the net deposition must occur.

As we consider the critical bypass depth, H_c , and the conservation of sediment mass in the down slope direction is a steady-state hypothesis, then the inner slope, α , can be determined by combining the bulk Richardson number as:

$$\alpha = \frac{c_d u_g}{R_i |u|} + Q_{sf} \frac{\partial}{\partial x} \left(\frac{1}{u_g W(x)} \right) + \frac{1}{g C W(x)} \frac{\partial}{\partial x} (u_g^2 W(x)) \quad (4)$$

Due to long-term prediction of the cross-shore profile of delta morphology based on advection-diffusion of the Swenson model and the influence of flood, wave, and tide as:

$$\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} = \alpha_1 \frac{\partial^2 h}{\partial x^2} + \frac{\partial}{\partial x} \left(\alpha_2 \frac{\partial h}{\partial x} \right) + B_{(x)} \quad (5)$$

Where α_1 is diffusion coefficient of tide, α_2 is diffusion coefficient of wave, and $B_{(x)}$ is tidal current.

5. RESULT AND DISCUSSION

Monthly measurements of the cross-shore profile along six lines for about 12 years clarified the characteristic of the mudflat. The profiles along each line of bed-level measurement 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.

Figure 6 explains the change of bed level of Shirakawa River mouth at four sites, where the right bank has cross sections 1 and 3, the river mouth has cross section 2, and the left bank has cross section 4. In this study, we use monitoring bed-level data of the years 1978 and 2003 and consider the effect on intertidal flats due to river floods or other extreme weather events.

By determining the critical bypass depth (H_c), it is possible to express the cross-shore profile changes

with consideration to intertidal area and external forces, such as floods or others extreme weather events. Figure 7 shows the cross-shore profile of the Shirakawa River mouth. The black line is the bed-level profile in 1978, and the black dotted line is the bed-level profile in 2003. The other solid 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, $Q_r = 300$ m³/s).

The solid lines are those obtained by fitting the cross-shore profile of 2003, which considers the river flow rate is more than 1500 m³/s and the average of external force (wave height, $WH = 0.38$ m; wave period, $T = 3.0$ s; and water debit, $Q_r = 1600$ m³/s) and suspended sediment concentration ($C = 0.01$ kg/m³). By inputting the external forces into Equation 4, the critical depth become -2.42 and -1.96 m. So it is possible to calculate the initial depth of a long-term prediction model by defining the critical depth and to express a certain extension forward of the bed-level trend and the slope gradient of Shirakawa River mouth. But this prediction model is only good to apply on the topset beds, not for the bottom beds, so we improved it by using Equation 5 as displayed in Figure 9.

Figure 8 shows the measurement of the the cross-shore profile change of the Shirakawa River mouth from 1978, 1997, and 2013 after a flash flood caused by the torrential rainfall occurring on July 12, 2012. Considering spatial distribution of mud thickness on the intertidal area in Figure 5, the tendency distribution of mud deposition thickness was closer to the river mouth and thicker in the coastal direction. Due to this flooding, the monthly measurement of bed level for about six years on the river mouth is indicated that the maximum average accretion along the measured profiles was 30 cm, or three times larger than those in the past.

Figure 6. Bathymetric measurement of Shirakawa River mouth (1976–2003)

By relating the critical bypass, H_c , to the advection and diffusion models of river delta morphology (Figure 9), it was found to be in good agreement to explain the cross-shore profile change related to the flooding.

6. CONCLUSION

The slope of an equilibrium profile landward will increase with depth and sediment supply and will decrease with increasing tidal current, wave height, and wave period. By determining the critical bypass depth (H_c), it is possible to predict the equilibrium profile changes for the intertidal and tidal zone.

Figure 7. Long term prediction model

Figure 8. Cross-shore profile of Shirakawa River mouth

Figure 9. Comparison between bathymetry measurement and model of Shirakawa River cross-shore profile

The geomorphological response of the Shirakawa River Delta indicated that foreset slope and critical bypass depth were advanced offshore due to a flash flood with over 1,500 m³/hr, and it was controlled by tide and located below mean low water spring (MLWS). The numerical model was found to be in good agreement to explain the phenomena before and after the flood occurred with the parameter fitting to the change of the cross-shore profile.

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REFERENCES

- Fagherazzi, S., & Overeem, I. (2007). Models of deltaic and inner continental shelf landform evolution. *Annual Review of Earth and Planetary Sciences*, 35, 685–715. <http://dx.doi.org/10.1146/annurev.earth.35.031306.140128>
- Falcini, F., Fagherazzi, S. & Jerolmack, D. J. (2012). Wave-supported sediment gravity flows currents: effects of fluid-induced pressure gradients and flow with spreading. *Continental Shelf Research*, 33(1), 37–50. <http://dx.doi.org/10.1016/j.csr.2011.11.004>
- Friedrichs, C. T., & Aubrey, D.G. (1996). Uniform bottom shear stress and equilibrium hypsometry of intertidal flats. In C. Pattiaratchi (Ed.), *Mixing in estuaries and coastal seas* (pp. 405–429). Washington, D.C.: American Geophysical Union. <http://dx.doi.org/10.1029/CE050p0405>
- Friedrichs, C. T., & Wright, L. D. (2004). Gravity-driven sediment transport on the continental shelf: Implications for equilibrium profiles near river mouths. *Coastal Engineering*, 51(8–9), 795–811. <http://dx.doi.org/10.1016/j.coastaleng.2004.07.010>
- Intergovernmental Panel on Climate Change. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation*. Stanford, CA: Intergovernmental Panel on Climate Change.
- Japan Society of Civil Engineering. (2013). *Western branch in Kyushu: Inspection report for heavy raining and flood in Northern Kyushu, July 2012*. Japan Society of Civil Engineering.
- Kenyon, P. M., & Turcotte, D. (1995). Morphology of a delta prograding by bulk sediment transport. *Geological Society of America Bulletin*, 96(11), 1457–1465. [http://dx.doi.org/10.1130/0016-7606\(1985\)96%3C1457:MOADPB%3E2.0.CO;2](http://dx.doi.org/10.1130/0016-7606(1985)96%3C1457:MOADPB%3E2.0.CO;2)
- Kirby, R. (2000). Practical implications of tidal flat shape. *Continental Shelf Research*, 20(10–11), 1061–1077. [http://dx.doi.org/10.1016/S0278-4343\(00\)00012-1](http://dx.doi.org/10.1016/S0278-4343(00)00012-1)
- Kuriyama, Y., & Hashimoto, K. (2004). *Sediment budget on an intertidal flat at the mouth of the Shirakawa River, Japan* (Technical Report No. 1074). Yokosuka City, Kanagawa: Port and Airport Research Institute. Retrieved from <http://www.pari.go.jp/cgi-bin/search-en/detail.cgi?id=200403107401>
- Mitchum, R. M., Jr., Vail, P. R., & Thompson, S., II. (1977) Seismic stratigraphy and global changes of sea level: Part 2. The depositional sequence as a basic unit for stratigraphic analysis: Section 2. Application of seismic reflection configuration to stratigraphic interpretation. In C. E. Payton (Ed.), *Seismic stratigraphy-applications to hydrocarbon exploration to hydrocarbon exploration* (pp. 165–184). Tulsa, OK: American Association of Petroleum Geologist.
- Pirmez, C., Pratson, L. F., & Steckler, M. S. (1998). Clinoform development by advection-diffusion of suspended sediment: Modeling and comparison to natural systems. *Journal Geophysical Research: Solid Earth* 103(B10), 24141–24157. <http://dx.doi.org/10.1029/98JB01516>
- Swenson, J. B., Paolo, C., Pratson, L., Voller, V. R., & Murray, A. B. (2005). Fluvial and marine controls on combined subaerial and subaqueous delta progradation: Morphodynamic modeling of compound-clinoform development. *Journal of Geophysical Research*, 110(F2), 1–16. <http://dx.doi.org/10.1029/2004JF000265>