地形 第30巻第3号
201-217頁 (2009)

JGU Transactions, Japanese Geomorphological Union
30-3, p. 201-217 (2009)

Conceptual Model for Predicting Topographic Changes of River-Mouth Bar

Kou FURUIKE[1], Takaaki UDA[2],
Masumi SERIZAWA[1] and Toshiro SAN-NAMI[1]

Abstract

Based on topographic changes of a river-mouth bar investigated at mouth of the Sagami and Shimanto Rivers, both flowing into the Pacific Ocean, a conceptual model for predicting topographic changes of a river-mouth bar was developed under assumptions of that (1) the equilibrium state of the configuration of a river-mouth bar exists and (2) the strength of the recovery of river-mouth bar topography depends upon the deviation from the equilibrium state. The offshore sand transport due to flood currents and shoreward sand transport due to waves were modeled to predict three-dimensional topographic changes of a river-mouth bar. Dynamic changes of a river-mouth bar responding flood currents and waves could be calculated using this model.

Key words: *river-mouth bar, shoreline change, predictive model, equilibrium*

Introduction

In Japan, a river-mouth bar of many large rivers has been stable for a long time under the condition of ample fluvial sediment supply from rivers because of their steep watershed and much rainfall. In recent years, however, cases have been increasing that a river-mouth bar rapidly retreats in upstream direction due to decrease in sediment supply from a river, the rapid retreat causing disappearance of a brackish water zone upstream of a river-mouth bar and wave intrusion through the river mouth (Uda et al., 1994). These are of importance in conservation and protection of a river bank and a coast surrounding a river mouth. Deformation of a river-mouth bar is caused mainly by two independent external forces: flood currents and waves. Offshore sand transport is caused by flood currents, whereas onshore sand transport occurs under the action of waves. Furuike et al. (2006) developed a model for predicting these dynamic changes of a river-mouth bar, applying the contour-line-change model of Serizawa et al. (2003), in which offshore and onshore sand transports due to flood currents and waves, respectively, are expressed by a couple of sink and source of sand. In their model, full-coupling of both external forces, i.e., a dynamic process of sand movement due to flood

Received September 1, 2008; revised April 8, 2009; accepted April 14, 2009
[1] Coastal Engineering Laboratory Co., Ltd., 1-22-301 Wakaba, Shinjuku, Tokyo 160-0011, Japan
[2] Public Works Research Center, 1-6-4 Taito, Taito, Tokyo 110-0016, Japan

currents and waves was studied, and it was predicted that sand discharged from a river-mouth bar by flood currents was transported to the shore due to the action of waves. In the present study, considering these results, a simple, conceptual model is developed to predict the long-term deformation of a river-mouth bar, on the basis of the change in a river-mouth bar of the Sagami and Shimanto Rivers, respectively flowing into Sagami and Tosa Bays, both facing the Pacific Ocean. In this study, we intend to predict the process of the disappearance and recovery of a river-mouth bar in a relatively long-term duration of several weeks or months, instead of investigating the precise process of the topographic changes due to flood currents and waves. The model is derived under the fundamental assumption that a topography recovers its original equilibrium state, when the shift from the equilibrium state occurs due to the action of waves and currents. This follows the same idea that Kraus (2003) and Kraus et al. (2004) adopted when they developed a model for predicting breaching of a barrier island. In the present study, the equilibrium state of the configuration of a river-mouth bar is assumed, and the strength of the recovery of river-mouth bar topography is determined depending on the deviation from the equilibrium state. The offshore sand transport due to flood currents and onshore sand transport due to waves were modeled to predict three-dimensional topographic changes of a river-mouth bar.

Examples of Profile Changes of River-mouth Bar

Figure 1 shows an aerial photograph of the Sagami River mouth taken in November 2005. A river-mouth bar extends from the left bank to the right with an opening of the river near the right bank. This river-mouth bar has significantly been changed with time, due not only to the action of flood currents and waves in short period of time but also

Fig. 1. Aerial photograph of the Sagami River mouth taken in November 2005.

to dredging of a navigation channel at the opening of the river and the decrease in fluvial sand supply in longer term (Uda, 2008).

Figure 2 shows the temporal change in longitudinal bar profile along a transect No. 14 crossing the centerline of the Sagami River mouth, as shown in Fig. 1. The longitudinal profile has a break in slope at a water depth of about 2 m, with a steep foreshore slope (1/7) of the bar mainly composed of coarse sand and a gentle slope (1/250) in the offshore bed composed of fine sand being found. Furuike et al. (2006) showed that coarse sand composing the river-mouth bar moves as a sand body on the seabed with a gentle slope composed of fine sand, independent of the movement of fine sand on the gentle slope, and the sand budget is kept in short term.

A base line with a slope of 1/250 through a point P, above which the river-mouth bar is formed, is drawn as shown in Fig. 2, and the cross-sectional area of the river-mouth bar ΔA is calculated. Figure 3 shows the long-term change in cross-sectional area ΔA, and shoreline recession Δy of the river-mouth bar with reference to the shoreline in 1988. The shoreline receded 168 m between 1988 and 1994, and the cross-sectional area decreased with the shoreline recession. Maximum decrease in the cross-sectional area reached 200 m^2. There exists a good correlation between two variables, so that the relationship between the shoreline recession Δy (m) and cross-sectional area ΔA (m^2) is investigated (Fig. 4). The line is described with a regression coefficient of 0.93 as

$$\Delta y = 313 - 0.82 \Delta A. \tag{1}$$

Figure 5 is an aerial photograph of the Shimanto River mouth taken in November 1995. Shimoda Port is located at the river mouth, and the Takeshima River flows into the Shimanto River near the mouth. A river-mouth bar extends from the left bank, and there is a navigation channel upstream of the river-mouth bar. Uda et al. (2004) carried out the topographic survey and grain size analysis of bed materials, and concluded that coarse materials remain at a water depth shallower than 3 m with a steep slope of 1/10,

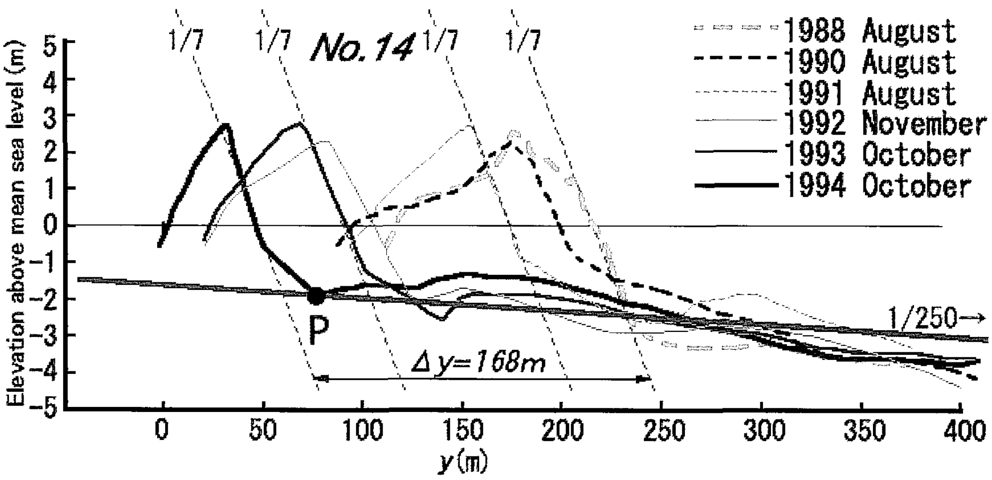

Fig. 2. Changes in longitudinal profile along a transect crossing centerline of river-mouth bar of the Sagami River.

while fine materials deposit at a depth deeper than 3 m.

Figure 6 shows the temporal changes in longitudinal profile of the river-mouth bar. A river-mouth bar with a berm height of 3.5 m and a foreshore slope of 1/8 has been stable for a long time, but recently the landward movement of the river-mouth bar occurred due to sand transport to the back of the river-mouth bar associated with wave overtopping and resulting dredging in the navigation channel at the back of the river-mouth bar to maintain the depth. Also artificial embankment on the river-mouth bar was carried out in 2004 (Fig. 6) to prevent sand from transporting to the navigation channel.

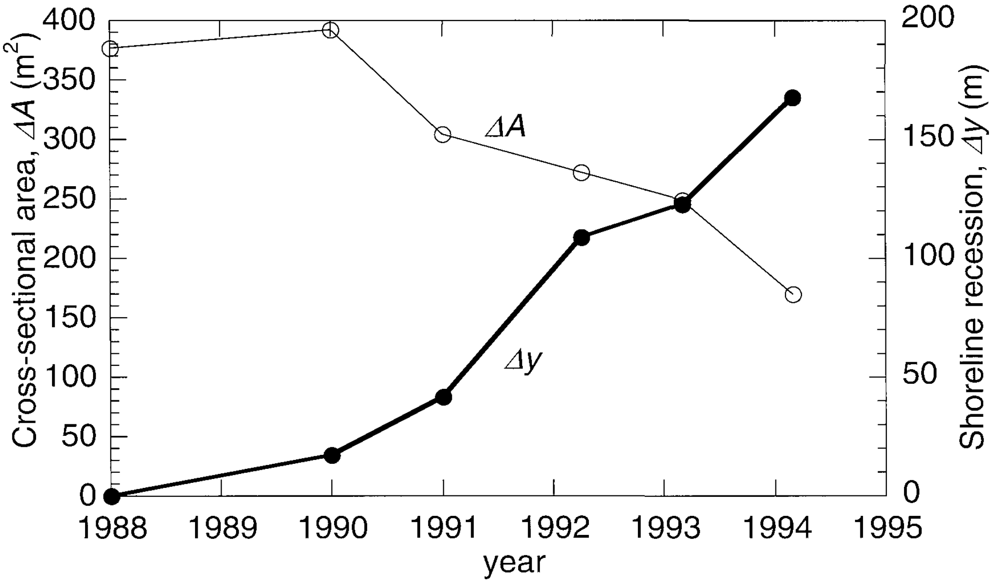

Fig. 3. Change in shoreline recession Δy and cross-sectional area of river-mouth bar ΔA of the Sagami River.

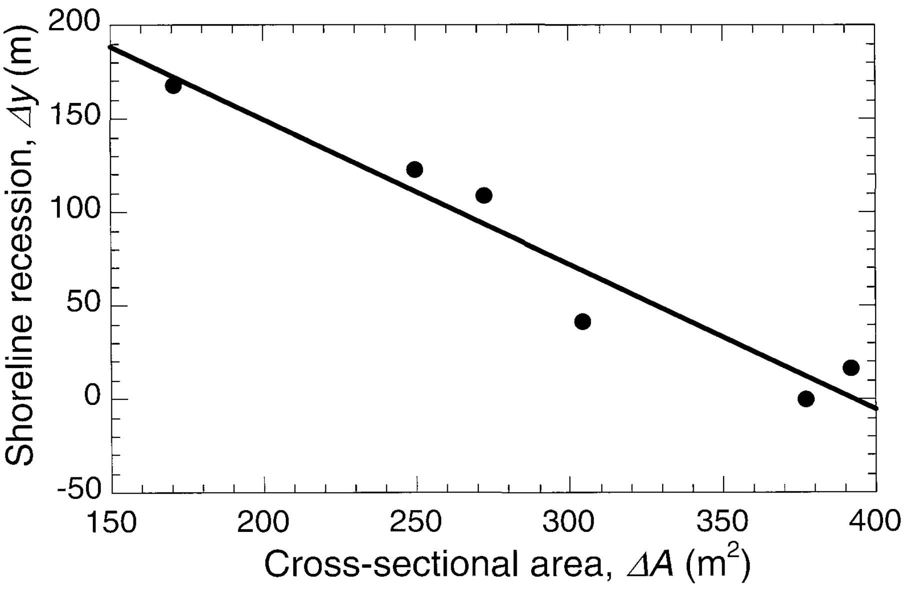

Fig. 4. Relationship between shoreline recession Δy and cross-sectional area of river-mouth bar ΔA of the Sagami River.

Similar to the case in Fig. 2, a base line with a slope of 1/70 through a point P, above which the river-mouth bar is formed, is drawn as shown in Fig. 6, and the cross-sectional area of the river-mouth bar ΔA is calculated. Figure 7 shows the change in cross-sectional area ΔA and shoreline recession Δy of the river-mouth bar since 1970,

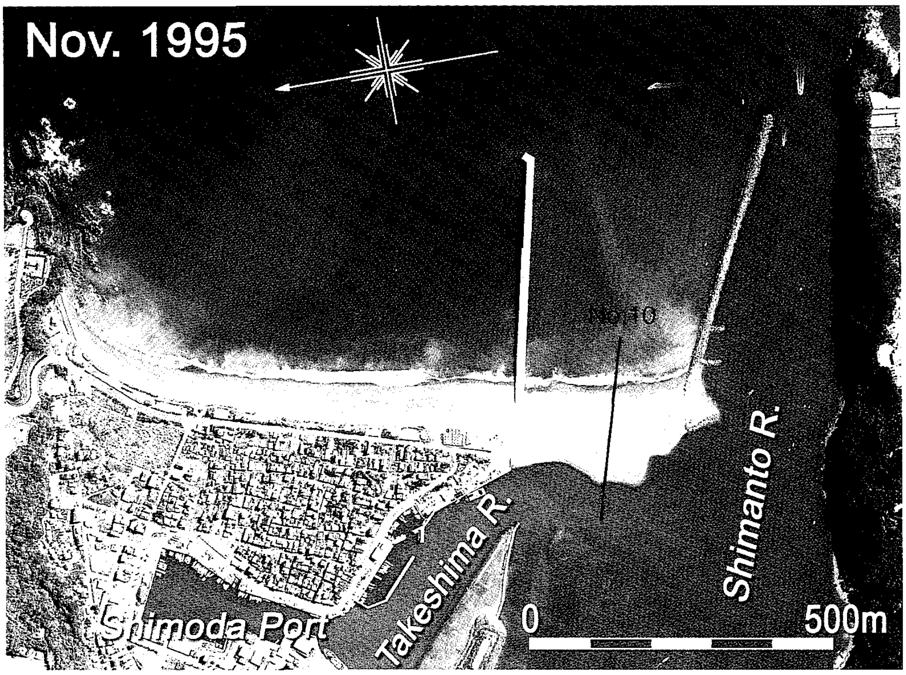

Fig. 5. Aerial photograph of the Shimanto River mouth in November 1995.

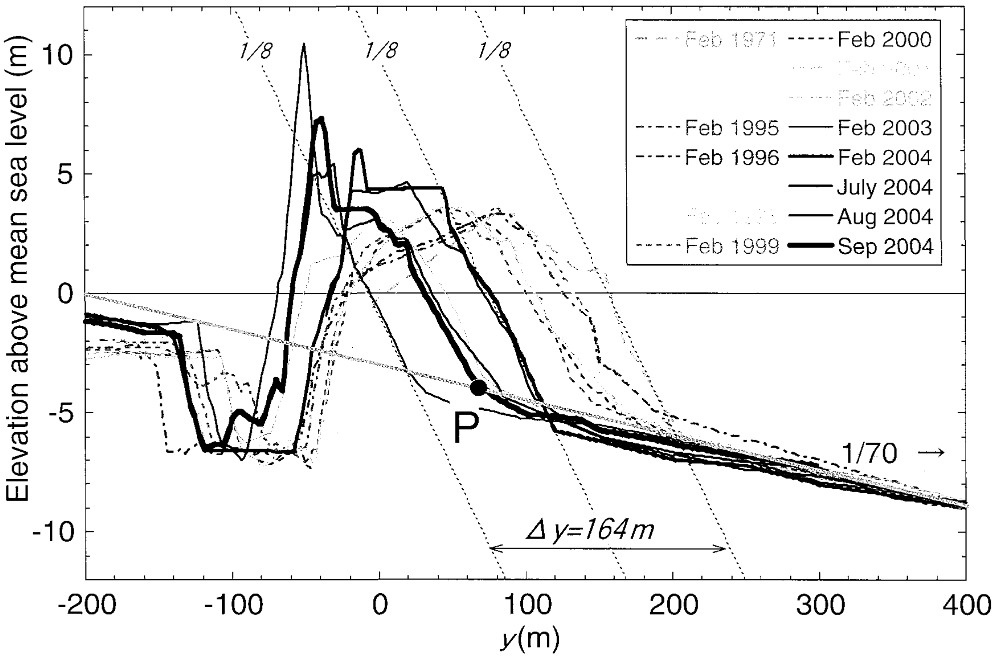

Fig. 6. Changes in longitudinal profile along a transect crossing centerline of river-mouth bar of the Shimanto River, as shown in Fig. 5.

similar to Fig. 3 in the Sagami River. There is a good correlation between the two variables, so that the correlation between them was examined (Fig. 8). The relationship between the shoreline recession Δy (m) and sectional area ΔA (m^2) is given as follows with a correlation factor of 0.90:

$$\Delta y = 243 - 0.21\,\Delta A \tag{2}$$

The coefficients in the two equations are different, but the same functional relationship is obtained, implying that the shoreline recession of a river-mouth bar is closely related with the volume of sand available for forming a river-mouth bar.

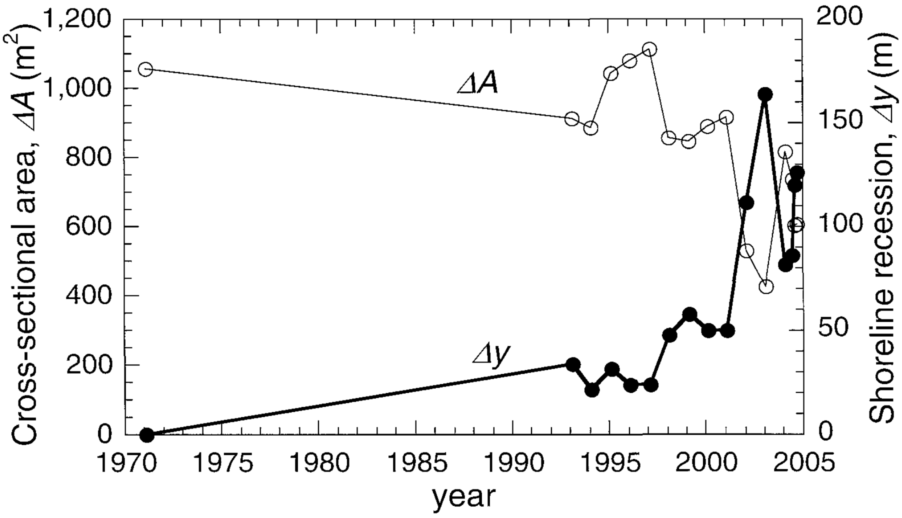

Fig. 7. Change in shoreline recession Δy and cross-sectional area of river-mouth bar ΔA of the Shimanto River.

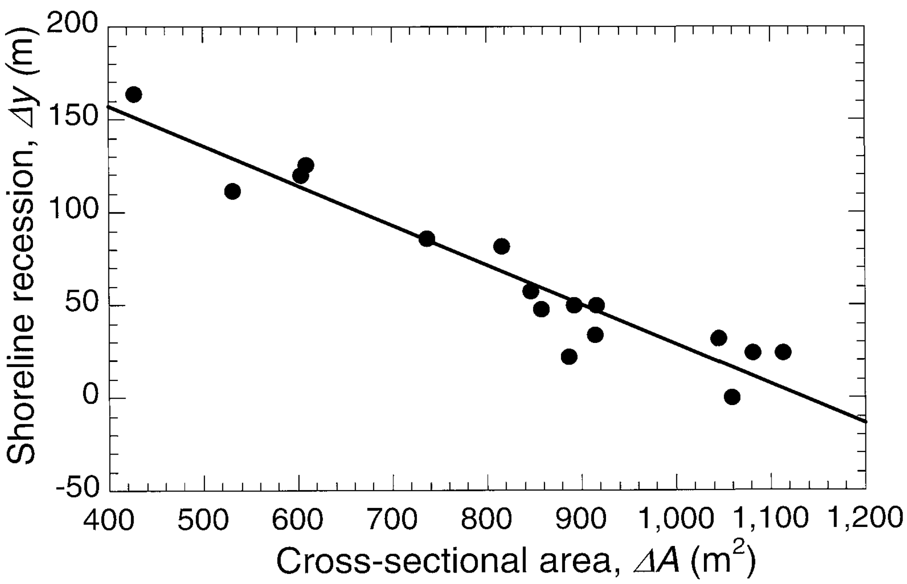

Fig. 8. Relationship between shoreline recession Δy and cross-sectional area of river-mouth bar ΔA of the Shimanto River.

Concept of Deformation of River-mouth Bar

The topography of a river-mouth bar deforms in three-dimensional way in response to the intermittent action of flood currents and waves. In particular, sand transport is concentrated during periods of floods and rough waves (Uda et al., 2004). The change in longitudinal profile of the river-mouth bar (Figs. 2 and 6) illustrates that the bar profile retreats in parallel with keeping the berm height and the foreshore slope constant on the seabed with a uniform slope as the shoreline recedes. This strongly infers that an equilibrium state exists and the profile changes are induced depending on the deviation from the equilibrium state of the bar topography.

Taking these profile changes into account, the movement of a sand body on the original seabed and its deformation are studied in the modeling. The intensity of the external force is assumed to be constant, and sand transport is assumed to be proportional to the deviation from the equilibrium state, considering that the topographic change be minimal in the equilibrium state.

Although an actually measured shape of the river-mouth bar shows a distorted triangle (Figs. 2 and 6), this study assumes a trapezoidal shape (Fig. 9) and a constant berm height. In addition, the riverbed and sea bottom are assumed to be expressed by a uniformly sloping bed, considering the measured profiles (Figs. 2 and 6).

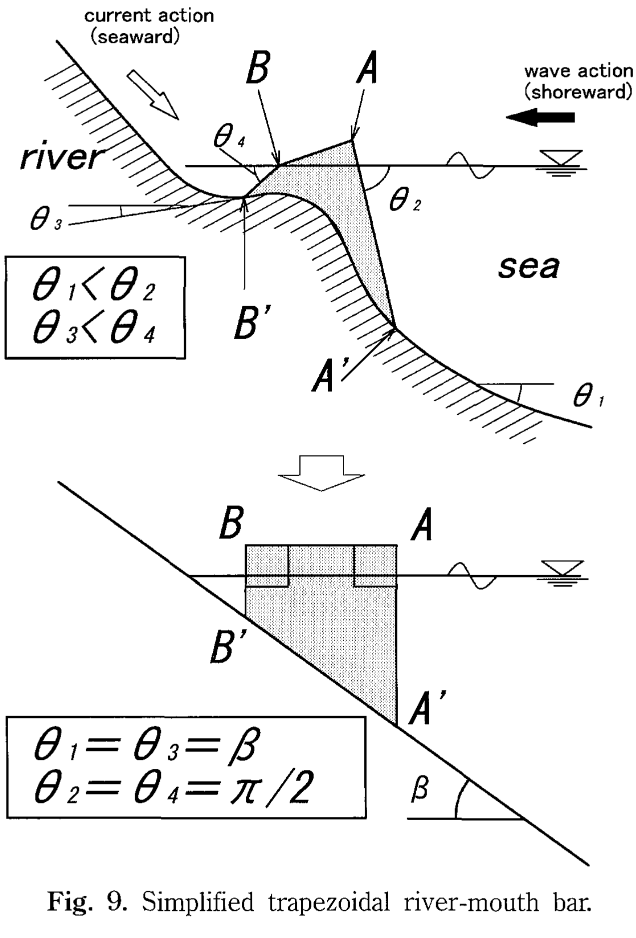

Fig. 9. Simplified trapezoidal river-mouth bar.

Deformation of a river-mouth bar is caused by action of flood currents and waves. The two kinds of action are separately considered here. Figure 10(a) shows the case in which the action due to flood currents balances with that of waves. In this case, the equilibrium shape of a river-mouth bar is expressed by a constant height Z_0, width B_0 and length L_0.

Figure 10(b) shows the deformation of a river-mouth bar due to flood currents, when the action of flood currents exceeds that of waves. The top of the bar is eroded due to overflow, and eroded sand deposits off the river-mouth bar in a cross section. This case assumes that seaward transport q is described as Eq. (3) considering the deviation from the equilibrium state of river-mouth bar:

$$q = k(1 - Z/Z_0) \text{ or } q = k(1 - L/L_0) \quad (3)$$

where Z is the height of the bar, L is the length (Fig. 10(b)), and k is a coefficient. Regarding the planar change, the tip of the river-mouth bar is eroded, and the eroded sand is transported off the river-mouth bar.

When the action of waves exceeds that of flood currents, run-up waves overflow the top of a river-mouth bar, as shown in Fig. 10(c). Erosion occurs at the top of a river-mouth bar, and sand is transported shoreward and deposited at the back of the river-mouth bar. In this case, sand transport with the same type of Eq. (3) is written. Regarding the planar change, sand is transported in the upstream direction.

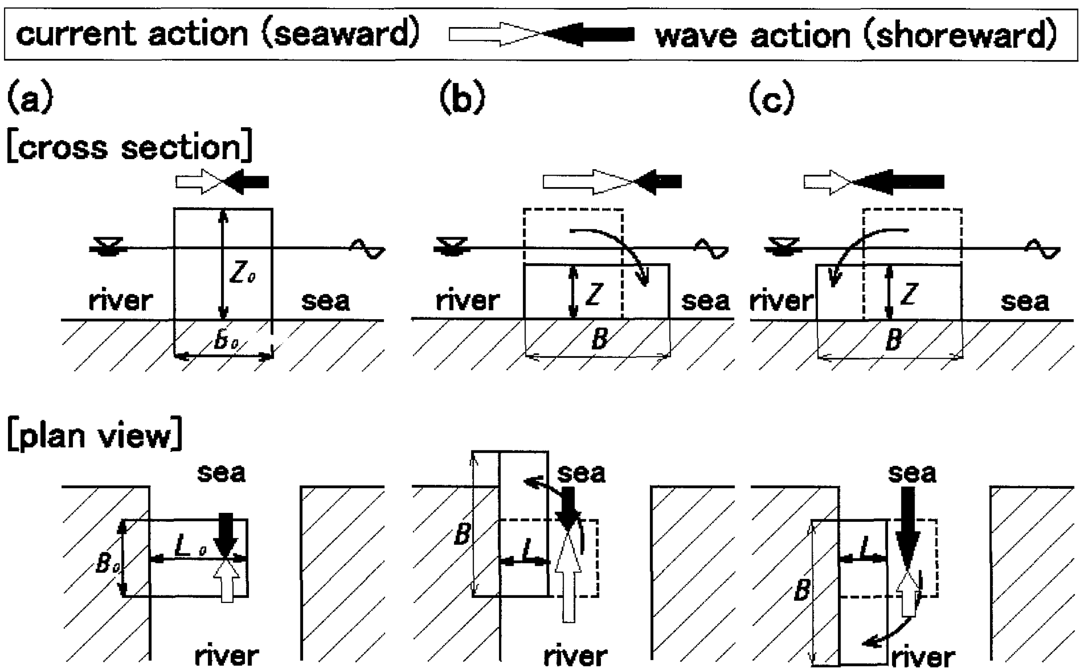

Fig. 10. Pattern of short-term change of river-mouth bar.

Conceptual Model

Model for predicting change in longitudinal profile

The change in longitudinal profile in the restoration period of a river-mouth bar from the terrace produced by flood currents is modeled, as schematically shown in Fig. 11(a). It is assumed that the cross-section of a river-mouth bar is of trapezoidal, and the height above mean sea level and the width are denoted by Z_0 and B_0, respectively. Consider such a river-mouth bar, and assume that mass conservation is always satisfied. When assuming that the height and width of a river-mouth bar have a small deviation

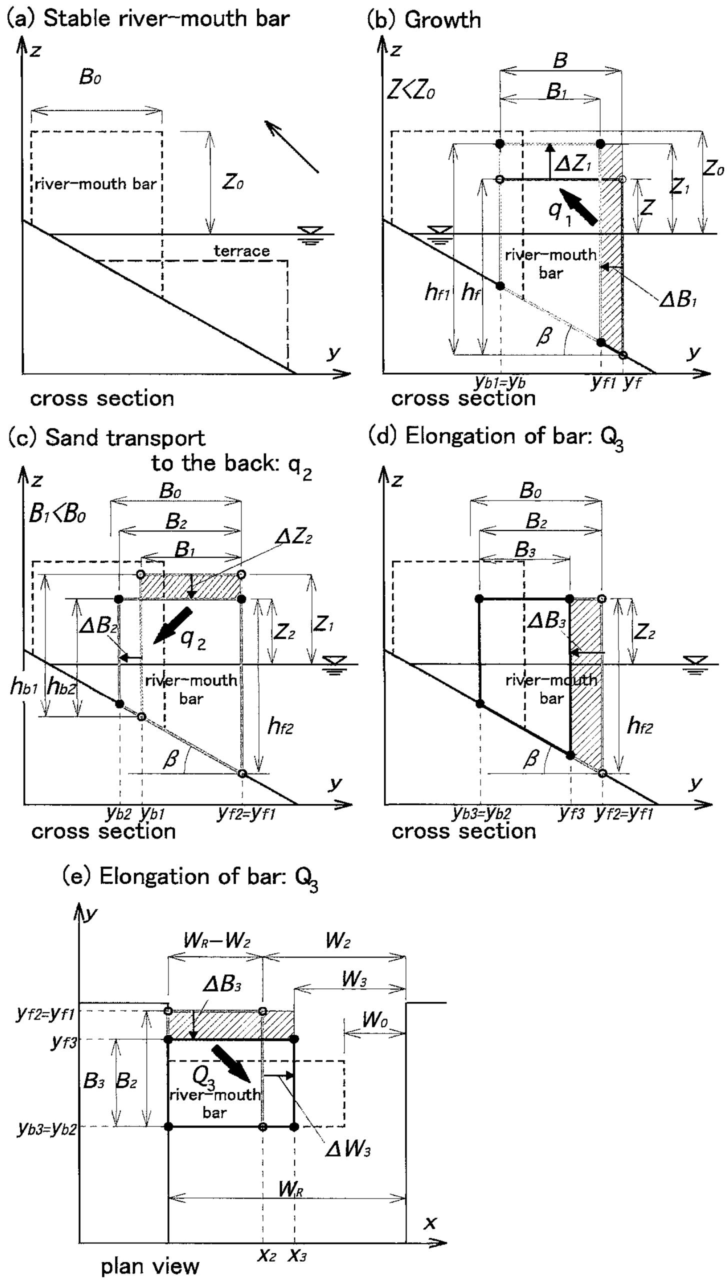

Fig. 11. Schematic diagram showing restoration of river-mouth bar after flood.

from the equilibrium state shown in Fig. 11(a), restoration force in proportional to the deviation will be generated, and the equilibrium form of a river-mouth bar is recovered by subsequent wave action. When the bar height Z is sufficiently low so that wave run-up is permitted, as shown in Fig. 11(b), the offshore slope of a river-mouth bar is eroded, and the eroded sand is transported toward the top of the river-mouth bar to accumulate. The rate of shoreward sand transport q_1 is proportional to the deviation from the height of the equilibrium bar Z_0, when $1-Z/Z_0 \geq 0$ and is expressed by

$$q_1 = K_1(1-Z/Z_0) \tag{4}$$

where K_1 is a coefficient. When $1-Z/Z_0 < 0$, q_1 is 0. The increment in the height of the bar ΔZ_1 and the height after an infinitesimal time Δt_1 become

$$\Delta Z_1 = q_1 \Delta t_1/B \tag{5}$$

$$h_{f1}=h_f + \Delta Z_1. \tag{6}$$

Furthermore, ΔB_1 can be determined as the solution of a quadratic equation of ΔB_1 regarding the shaded trapezoidal area in Fig. 11(b) given $q_1 \Delta t_1$, seabed slope $\tan\beta$ and h_1.

$$\Delta B_1 = (-h_{f1} + (h_{f1}^2 - 2\tan\beta\, q_1 \Delta t_1)^{1/2})/\tan\beta \tag{7}$$

New locations of the foot of the bar are described:

$$y_{f1} = y_f - \Delta B_1,\ y_{b1} = y_b \tag{8}$$

Similarly, when the width of a river-mouth bar B is narrower than the width of the equilibrium bar B_0 (Fig. 11(c)), the top of the bar will be eroded, and the eroded sand sinks back of the bar. In this case, the rate of sand transport q_2 is expressed by Eq. (9) in proportional to the deviation of the width B when $1-B_1/B_0 \geq 0$.

$$q_2 = K_2(1-B_1/B_0) \tag{9}$$

where K_2 is a coefficient. When $1-B_1/B_0 < 0$, q_2 is 0. The decrease in the height of the bar ΔZ_2 and the height after an infinitesimal time Δt_2 become

$$\Delta Z_2 = q_2 \Delta t_2/B_1 \tag{10}$$

$$h_{b2} = h_{b1} - \Delta Z_2 \tag{11}$$

$$h_{f2} = h_{b2} + B_1 \tan\beta \tag{12}$$

ΔB_2 can be calculated in the same way as Eq. (7).

$$\Delta B_2 = (-h_{b2} + (h_{b2}^2 - 2\tan\beta\, q_2 \Delta t_2)^{1/2})/\tan\beta \tag{13}$$

New locations of the foot of the bar are described:

$$y_{f2} = y_{f1},\ y_{b2} = y_{b1} - \Delta B_2 \tag{14}$$

The height Z_2 and width B_2 of a river-mouth bar after the time $\Delta t = \Delta t_1 + \Delta t_2$, as in Figs. 11(b) and 11(c), are given by the following equations:

$$Z_2 = Z + \Delta Z_1 + \Delta Z_2 \tag{15}$$

$$B_2 = B + \Delta B_1 + \Delta B_2 \tag{16}$$

In the calculation, Eq.(4) - Eq.(16) are recurrently used. The deviations after time steps diminish, and the profile approaches an equilibrium condition not until the equilibrium state without shoreward transport from the sea bottom and sinking of sand to the back of the river-mouth bar is attained.

Model for predicting changes in planar shape

The planar form of a river-mouth bar can be modeled as schematically shown in Figs. 11(d) and 11(e). The equilibrium opening width of the river is denoted by W_0. Assume that the opening width W_2 has a small deviation from the equilibrium opening width W_0 in the similar way as in Fig. 11(a). Under this condition, force to restore the opening width to the equilibrium state will be generated depending on this deviation. When the opening width W_2 is larger than the equilibrium opening width W_0, as shown in Fig. 11(e), sand is transported to the tip of the river-mouth bar, resulting in deposition of sand and elongation of the river-mouth bar. In contrast, when the opening width W_2 is smaller than W_0, the tip of the river-mouth bar will be eroded, resulting in offshore discharge of sand as is the case during floods. In this case, the rate of offshore discharge of sand, Q_3, from the tip of the river-mouth bar is proportional to the deviation, and is expressed

$$Q_3 = K_3(1-(W_R - W_2)/(W_R - W_0)). \tag{17}$$

where K_3 is a coefficient. When introducing sand transport rate per unit length $q_3 = Q_3/((W_R - W_2) + \Delta W_3)$, the increase in the width and height of the bar, ΔW_3 and ΔZ_3, respectively, after an infinitesimal time Δt_3 become

$$\Delta W_3 = Q_3 \Delta t_3 / B_2 (2h_{b2} - \Delta B_2 \tan\beta + B_1 \tan\beta)/2 \tag{18}$$

ΔB_3 can be calculated in the same way as Eq. (7).

$$\Delta B_3 = (-h_{f2} + (h_{f2}^2 - 2\tan\beta\, q_3 \Delta t_3)^{1/2})/\tan\beta \tag{19}$$

New locations of the foot of the bar are described:

$$y_{f3} = y_{f2} - \Delta B_3,\ y_{b3} = y_{b2} \tag{20}$$

Finally, the opening width W_3 and width B_3 of a river-mouth bar after the time Δt (Fig. 11(d)) are given by the following equations:

$$W_3 = W_2 - \Delta W_3 \tag{21}$$

$$B_3 = B_2 - \Delta B_3 \tag{22}$$

where ΔB_3 is indicated in Fig. 11(d) and W_R is a river width. From the conservation of sand volume, the location of tip of the bar X_3 after the time Δt is written as

$$X_3 = X_2 + \Delta W_3 \tag{23}$$

The planar shape of the river-mouth bar approaches an equilibrium form, so that the opening width of the river finally coincides with W_0.

Model for predicting three-dimensional changes of river-mouth bar

Combining the predictive model for cross-sectional changes with that for planar changes of the river-mouth bar, a three-dimensional model can be derived. In the derivation, the sediment transport equations, Eq. (4), (5) and (9), are used. The height Z_3 of the river-mouth bar after the time Δt is given as follows:

$$Z_3 = Z_2 = Z + \Delta Z_1 + \Delta Z_2 \tag{24}$$

Sand transport q during the time Δt is assumed to be the summation of q_1, q_2 and q_3 with time steps Δt_1, Δt_2 and Δt_3, respectively, where $\Delta t = \Delta t_1 + \Delta t_2 + \Delta t_3$.

The above-mentioned concept that restoring force is generated in response to the deviation from the equilibrium state has been used in the contour-line-change model (Serizawa et al., 2003; Uda et al., 2004) and Kraus et al.'s model (2004) for predicting the breaching of a barrier island. In the present study, a model for predicting three-dimensional changes in river-mouth bar topography considering the action of flood currents and waves was developed, focusing on three components of the height and width of the river-mouth bar and the opening width of the river.

Results of Model Calculations

Four cases of model calculations were carried out under the condition listed in Table 1. In Case 1, the deformation process of a river-mouth terrace topography, formed by flood currents, with the flat top bottom and the foreset slope expressed by a vertical line, is predicted in the two-dimensional calculation domain. In Case 2, the deformation process of a river-mouth terrace topography is predicted in the same way as Case 1, but the calculation condition differs in that sand volume of the river-mouth terrace is

Table 1. Calculation conditions.

Stable berm height	$Z_0 = 4$ m
Stable bar width	$B_0 = 200$ m
Stable opening width	$W_0 = 200$ m
Coefficient of sand transport	$K_1 \cdot \Delta t_1 = 250$, $K_2 \cdot \Delta t_2 = 250$, $K_3 \cdot \Delta t_3 = 100,000$
Time steps	80

larger than that of Case 1, with a large volume of sand necessary for reforming the river-mouth bar being supplied. In Case 3, the sand volume of the river-mouth terrace is smaller than that of Case 1, supposing that the river-mouth terrace topography is formed due to a flood after part of sand in the river-mouth bar is artificially removed, and therefore, sand volume for the river-mouth bar with the same size as Case 1 to develop is insufficient. In Case 4, the deformation process of a river-mouth terrace is predicted in the three-dimensional calculation domain.

Figure 12(a) shows the result of Case 1. Sand deposited below 1-m water depth due to floods is transported shoreward, and a river-mouth bar is gradually formed with time, and finally a stable bar appears. The result of Case 2 is plotted in Fig. 12(b). When sand volume is sufficiently large, the width of the recovered river-mouth bar becomes larger, and shoreline advance is found. In contrast to this case, Case 3 in which part of sand is artificially removed from the river-mouth area shows that the location of the river-mouth bar formed retreats (Fig. 12(c)), because the sand volume available for the formation of the river-mouth bar decreases. This result qualitatively explains the retreating process of a river-mouth bar observed at the Sagami River mouth (Fig. 2). These three results of the calculations suggest that when a river-mouth bar is discharged due to flood currents, a river-mouth bar with the same size before the flood will be reformed at the same location, unless sand of the river-mouth bar is artificially removed.

Figure 13, the result of Case 4, shows the three-dimensional change of a flat-topped terrace at the river mouth into a river mouth bar. The re-accumulation process of sand discharged by flood currents is well reproduced by the numerical simulation, in which a three-dimensional river mouth is reformed again, with narrowing the width of the river.

Conclusions

The decrease in flood discharge of a river weakens the action of flood currents, which results in shoreward movement of a stable river-mouth bar, whereas the increase in flood discharge induces offshore movement of the river-mouth bar. The decrease in sand volume composing a river-mouth bar induces shoreward movement, as is the case when river-mouth dredging was carried out. Inversely, the increase in sand volume induces offshore movement of a river-mouth bar with the shoreline advance, as is the case that fluvial sand was supplied from upstream. The increase in water depth around a river mouth accelerates wave action to cause shoreward movement of a river-mouth bar, whereas the decrease in water depth around the river mouth induces offshore movement of a river-mouth bar. It was found from the numerical simulation that sand volume of a river-mouth bar at its base is very important in determining the location of a river-mouth bar. This model can qualitatively predict the change in the location of a river-mouth bar in the case of (1) the decrease in sand volume of a river-mouth bar due to the river sand supply or beach nourishment, and (2) the decrease in sand volume due to beach erosion.

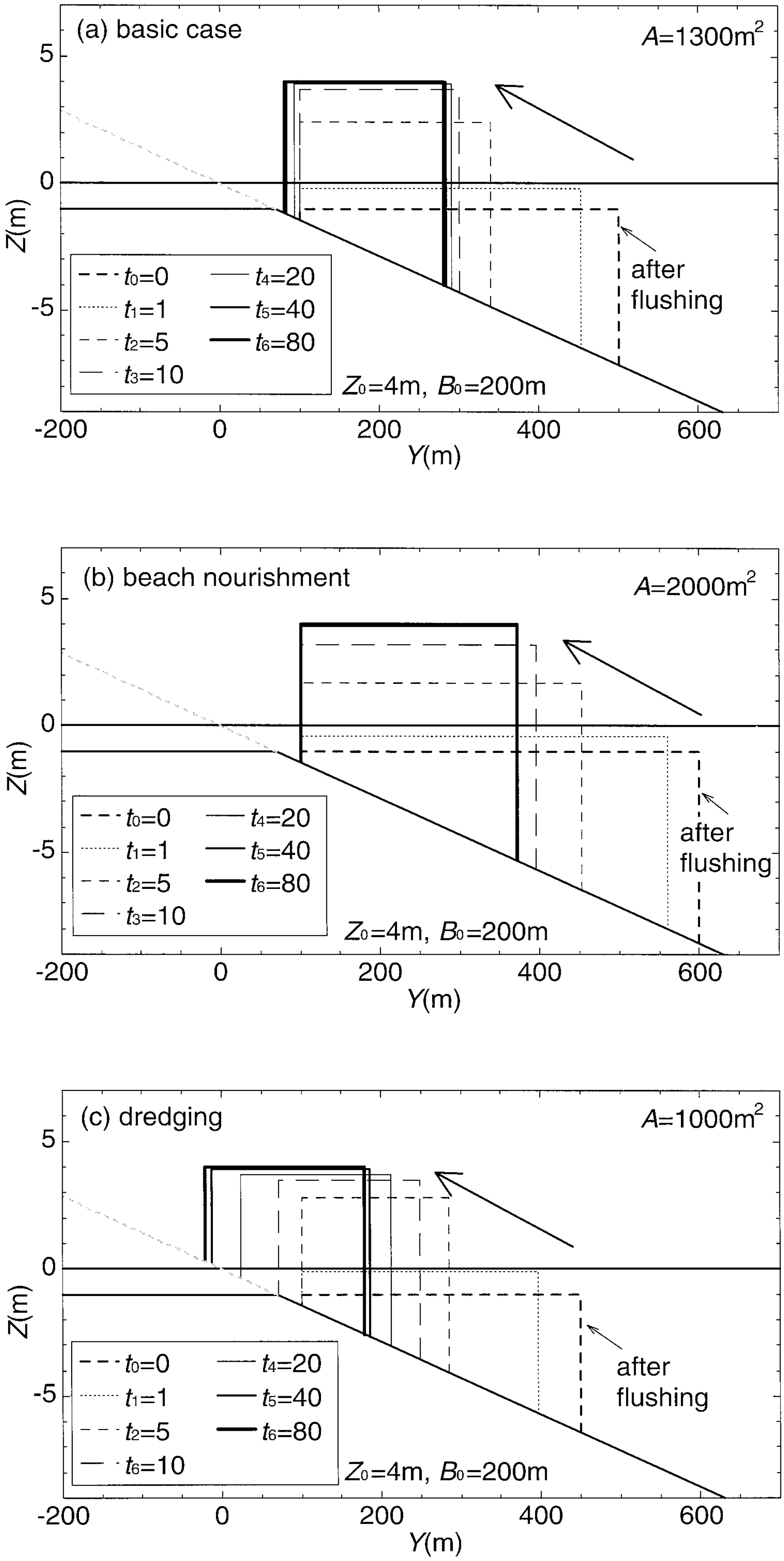

Fig. 12. Results of numerical simulation of two-dimensional change of river-mouth bar.

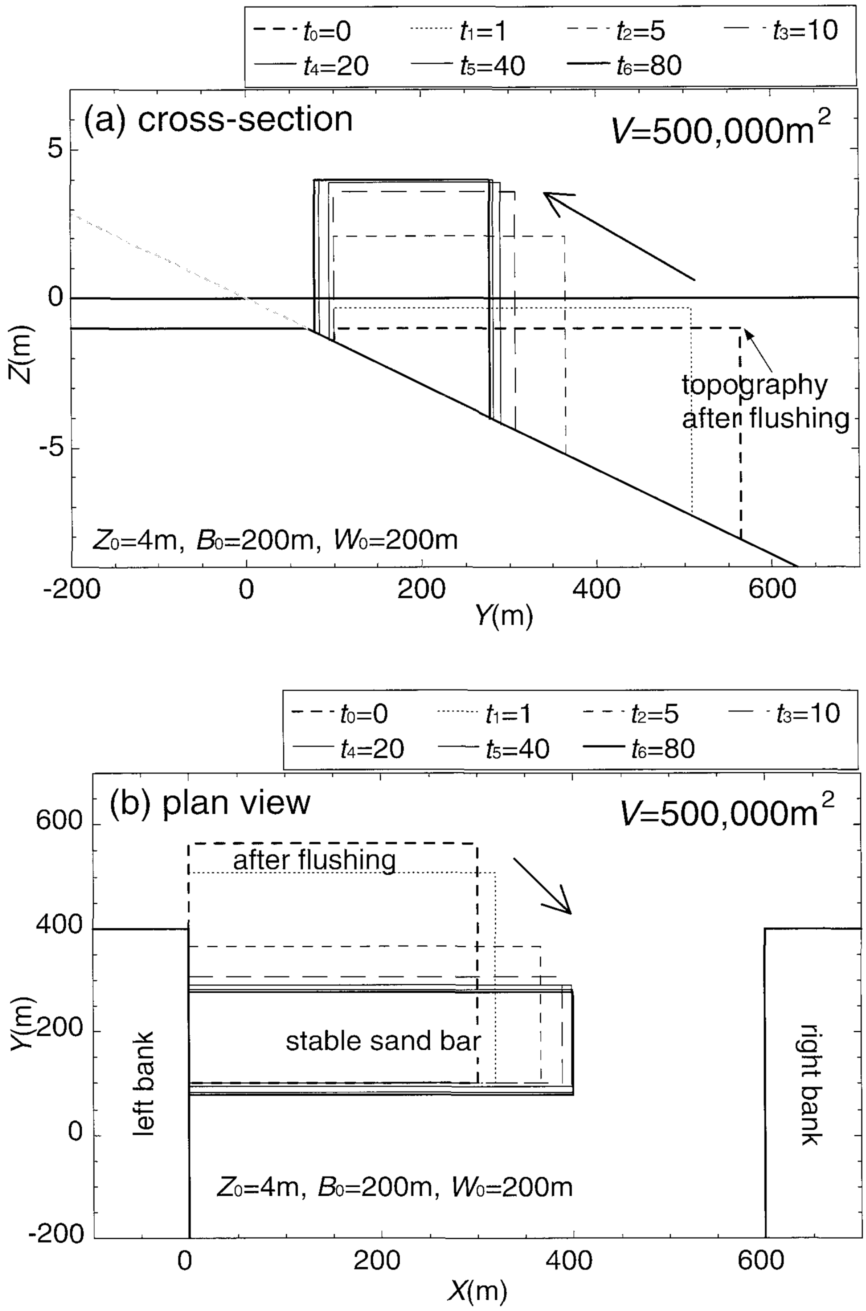

Fig. 13. Results of numerical simulation of three-dimensional change of river-mouth bar.

References

Furuike, K., Uda, T., Serizawa M. and San-nami T. (2006) Model for predicting dynamic changes of a river mouth bar: Proc. 30th ICCE, ASCE, 3295–3307.

Kraus, N. C. (2003) Analytical model of incipient breaching of coastal barriers: Coastal Eng. Jour., 45(4), 511–531.

Kraus, N. C. and Hayashi K. (2004) Numerical morphologic model of barrier island breaching: Proc. 29th ICCE, ASCE, 2120–2132.

Serizawa, M., Uda T., San-nami, T., Furuike K. and Kumada T. (2003) Improvement of contour line change model in terms of stabilization mechanism of longitudinal profile: Coastal Sediments '03, ASCE, 1-15.

Uda, T., Takahashi A. and Matsuda H. (1994) Nationwide characteristics of topography of river mouth and river mouth improvement: Technical Report of Public Works Res. Institute, No. 3281, 123p. (in Japanese)

Uda, T., Serizawa M. and Takahashi I. (2004) Prediction of restoration of river mouth bar after flood by contour-line-change model: Annual Jour. Coastal Eng., JSCE, **51**, 541-545. (in Japanese)

Uda, T. (2008) Effect of rivers to coastal topography and seabed material: *In* Unoki, S., Yamamoto M. and Seino S., ed. *River and Sea*, Chap. 3, 36-44, Tsukiji-shokan, Tokyo. (in Japanese)

河口砂州変動予測のための概念モデル

古池　鋼[1]・宇多高明[2]・芹沢真澄[1]・三波俊郎[1]

要　　旨

わが国では，河川からの豊富な土砂流出があったため安定的に推移してきた河口砂州が，流出土砂量の急減とともに上流方向へと急速に遡る例が数多く生じている．これらは河口部の保全上大きな問題となる．本研究では，まず相模川および四万十川河口における河口砂州変動の実態を明らかにし，これらにもとづいて河口砂州の変形パターンを模式化し，これをもとに河口砂州変動の概念的予測モデルを構築した．モデルの基本概念は，等深線変化モデルでなされている仮定と同様，河口砂州の幅や高さが，波浪や洪水流の作用に応じたある平衡状態を有し，それからのずれがあると復元力が働き，平衡状態へ戻るとの考え方に基づく．これにより河川流・波浪の作用によりある変位が生じた場合，新たな均衡状態へと向かう現象を３次元的変形も含めて予測するモデルを開発した．また上流から土砂が供給された場合や，海岸侵食あるいは土砂採取により河口部の土砂量が減少した場合における河口砂州の前進・後退を説明する概念モデルが構築できた．

[1] 海岸研究室（有）
[2] 財団法人土木研究センター