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LONG-TERM MORPHOLOGICAL MODELLING FOR FEIYUN ESTUARY WITH ESTMORF

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Abstract: Within the framework of Delft Cluster Project "Ecomorphology of Estuaries and Coast", a model for the long-term morphological development of the Feiyun Estuary in Zhejiang, China, has been set up. The model has been calibrated using the field hydrographic data as well as the data on historical morphological changes. After the calibration the model has been applied to investigate the impact of the change of river discharge regime due to the construction of reservoirs in the upstream river, and of a land-reclamation and a bend cut-off project in the estuary. The morphological development in the Feiyun estuary appears to be strongly influenced by the changes of the upstream river discharges. A systematic decrease of the river discharge due to e.g. the water diversion from the Zhoushandu reservoir will cause sedimentation in the estuary. The model results indicate that the sedimentation process has not established a new equilibrium and the sedimentation rate seems to be increasing in the first 30 years. According to the model results the considered land reclamation and bend cut-off will cause sedimentation downstream of the project site due to decrease of the tidal volume. Upstream of the project site sedimentation occurs in the case of land reclamation and erosion in the case of bend cut-off. The morphological responses of the estuary to both considered cases involve multiple morphological time scales with their corresponding spatial length scales. The smallest time scale related to the local changes at the project is as small as only about one year.

Key words: Feiyun Estuary, Long-term morphological development, Human interference

1. INTRODUCTION

Feiyun Estuary flows into the East China Sea and forms the seaway to the RuiAn harbour in Zhejiang Province, China. With the development of the economics and foreign trade of RuiAn City, this harbour becomes more and more important. Therefore, it is necessary for local government to carry out the channel improvement of the Feiyun estuary. In the upstream of the Feiyun River, the large scale Sanxi reservoir has been constructed and began to store water, and the diversion from the Zhaoshadu reservoir will also be carried out. Furthermore the project of the bend cut-off of the Feiyun River is in schedule in order to improve the flood control and increase the land area of RuiAn City. All these human activities will take an important effect on the long-term morphological development of the Feiyun estuary.

This paper describes the set-up and application of a long-term morphological model for the Feiyun estuary based on ESTMORF. After that the model has been calibrated using field data it is used to study the impact of a bend cut-off in the estuary, and of the change of the flow regime in the upstream river due to the construction of reservoirs and diversion works to the long-term morphological development in the estuary.

2. THE FEIYUN ESTUARY

The Feiyun River, with a length of 203 km and a catchment area of 3252 km2, is one of eight rivers in Zheijiang Province (see Fig.1). It flows into the East China Sea at Shangwang.

The tidal influence can reach up the river as far as Tanjiao located 59 km from the river mouth in the dry season during spring tide. The downstream river reach of Tanjiao is called the estuary reach, and its upstream is called river reach.

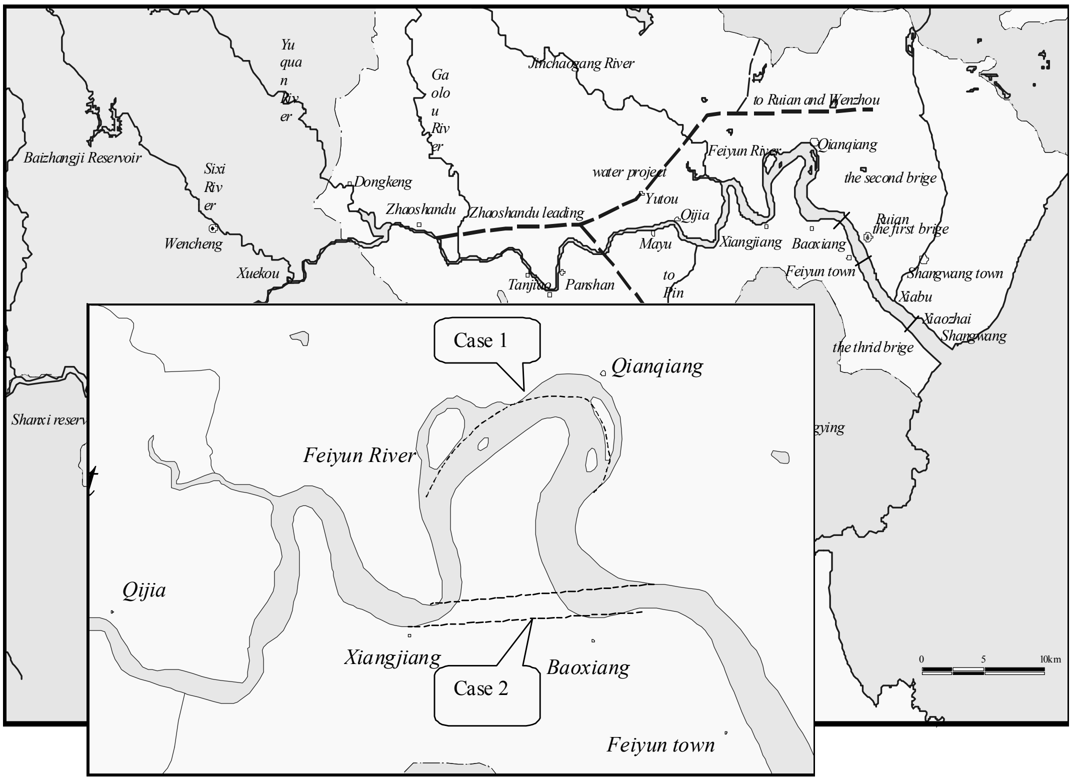

Fig. 1 The sketch of Feiyun river and its Estuary

The average discharge of the Feiyun River is 74.6m3/s measured at Xuekou station in the period 1959 to 2000. The discharge varies strongly from year to year. The maximum annual averaged discharge is 123 m^3/s and is measured in 1962. The minimum one, measured in 1967, is only 37.6 m^3/s. Furthermore strong seasonal variation of the discharge occurs within a year. In general, about 76% of the annual runoff occurs in the period April to September. The Feiyun Estuary is a macro-tidal estuary with large tidal range and strong tidal flow. The averaged tidal range at RuiAn station is 4.37m, and during spring tide it is 6.51 m.

The sediment input from the upstream river is relatively small. The averaged sediment concentration of the upstream river water measured at Xuekou station is approximately 0.17 kg/m^3, with maximum of 0.64 kg/m^3 and minimum of 0.05 kg/m^3. The annual average sediment transport is equal to 406×10^3 ton, of which 60% occurs in the monsoon period from June to September. The sediment from the upstream basin is relatively coarse, and most of it deposits in the reach upstream of Tanjiao. Much larger amount of sediment comes from the sea. The averaged sediment concentration downstream of Baoxiang is in the range of 2 to 4 kg/m^3. The turbidity maximum is located near Xiabu, where the maximum sediment concentration can achieve 5 to 6 kg/m^3. The sediment transport at the mouth is 300 to 600 thousand ton during one tidal cycle, which is about the annual sediment transport from the upstream river. The grain size of the suspended material in the estuary appears to be more homogeneous, and it consists mostly of silt.

The morphological change in the estuary clearly responds to the variation of the river discharge. Sedimentation occurs during dry period and erosion during wet period. This applies to the response to the long-term variation of discharge as well as to that to the seasonal variation of the discharge. In absolute sense the largest changes occur in the cross-sections in the downstream part of the estuary, but in relative sense the largest changes occur in the upstream part. This is another indication that the variation of the river discharge is the major cause of morphological changes in the estuary.

3. MODEL SET UP

3.1 THE ESTMORF MODEL

ESTMORF is a model for long-term morphological development of estuaries, developed by WL | Delft Hydraulics in co-operation with Rijkswaterstaat. The model is special designed for predicting the impact of natural development like sea level rise and basin runoff change, and of human interference e.g. land-reclamation, dredging works and river regulation etc. to the long-term morphological development of estuaries. It combines the description of physical processes (hydrodynamics & sediment transport) and empirical relations for morphological equilibrium, in order to obtain optimal description of the long-term morphological development. The model uses a one-dimensional network hydrodynamic model (SOBEK) for simulating the tidal flow. The simulated flow data are used to define the morphological equilibrium. The deviation of the actual morphological state with respect to the morphological equilibrium and the flow data together determine the sediment transport and the morphological changes. For more detailed information about ESTMORF one is referred to Wang et al (1998, 1999), Wang and Roelfzema (2001).

3.2 SET UP AND CALIBRATION OF THE MODEL

The ESTMORF-Feiyun model consists of one single branch representing the estuary from Zhaoshandu reservoir to the river mouth in Shangwang with the length of 69 km (see Fig.1). At the upstream boundary the discharge is prescribed as boundary condition, and at the downstream boundary water level is prescribed. The branch is divided into 110 sections, with a length of about 0.5 to 1.0 km. The cross-section profiles of each section have been derived from the October 1993 data set.

First the flow model is calibrated before the morphological model is set up. Fig. 2 shows that the agreement between the computed and measured water level and flow velocity is good.

The most important empirical relation used in ESTMORF is the relation between the cross-sectional area under Mean Water Level and the tidal volume through the cross-section:

$$A_e = \frac{1}{2} c_a V \tag{1}$$

Herein

A_e = equilibrium cross-sectional area under MWL,

V = tidal volume (integration of absolute value of discharge over tidal period),

c_a = coefficient,

By assuming the existing situation (in 2001) is in equilibrium, the coefficient c_a can be calculated from the model. For various upstream river discharges the results for every cross-section are altogether depicted in the Fig.3. We can see that the coefficient for the downstream reach is close to a constant without being affected by the discharge variation. Apparently this part is mainly controlled by the tidal flow. For the upstream reach and middle reach, the coefficient changes with the discharge variation, the larger the basin discharge is, the smaller the equilibrium coefficient. This part of the estuary, especially the upstream reach, is strongly influenced by the river discharge.

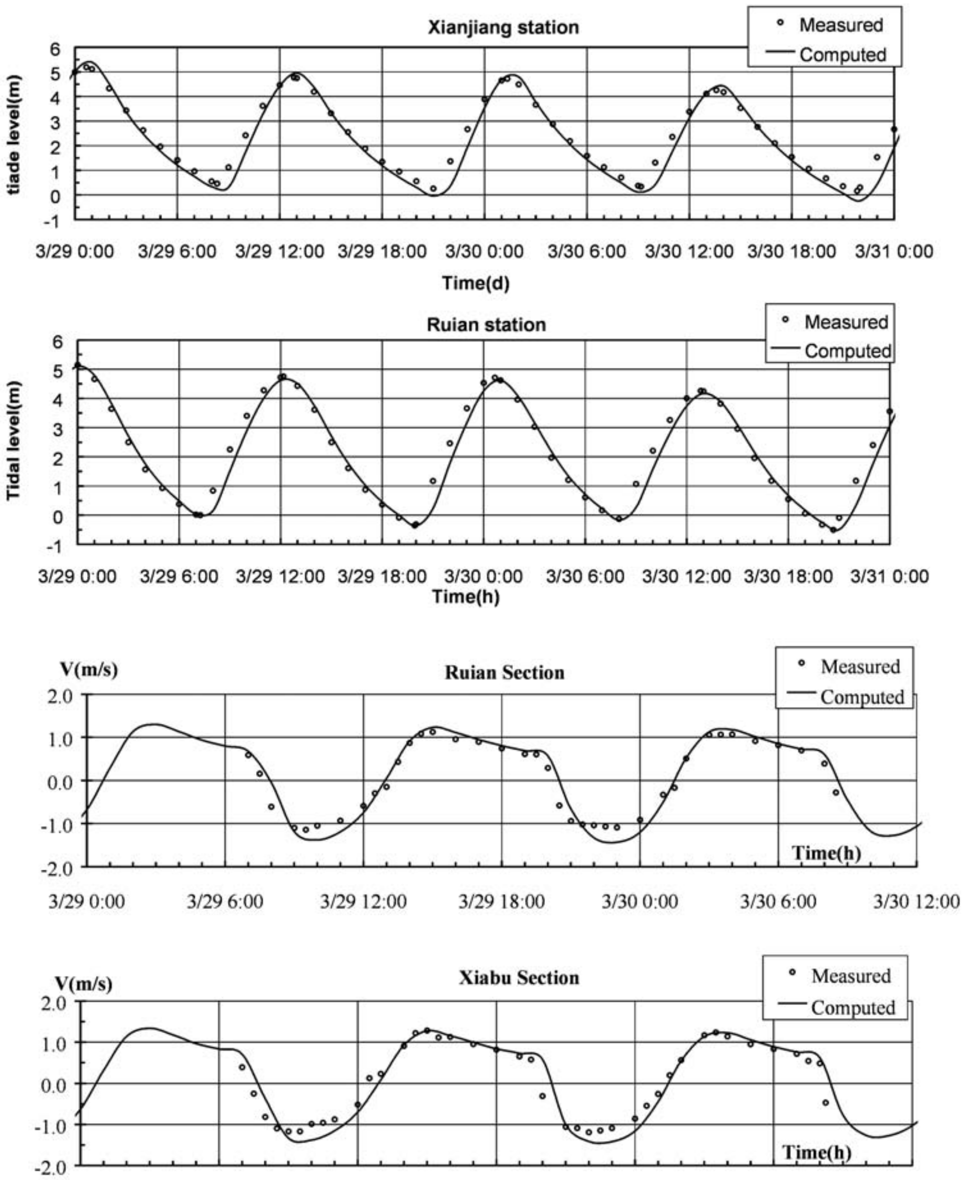

Fig. 2 Comparison between calculated and measured water level and flow velocity

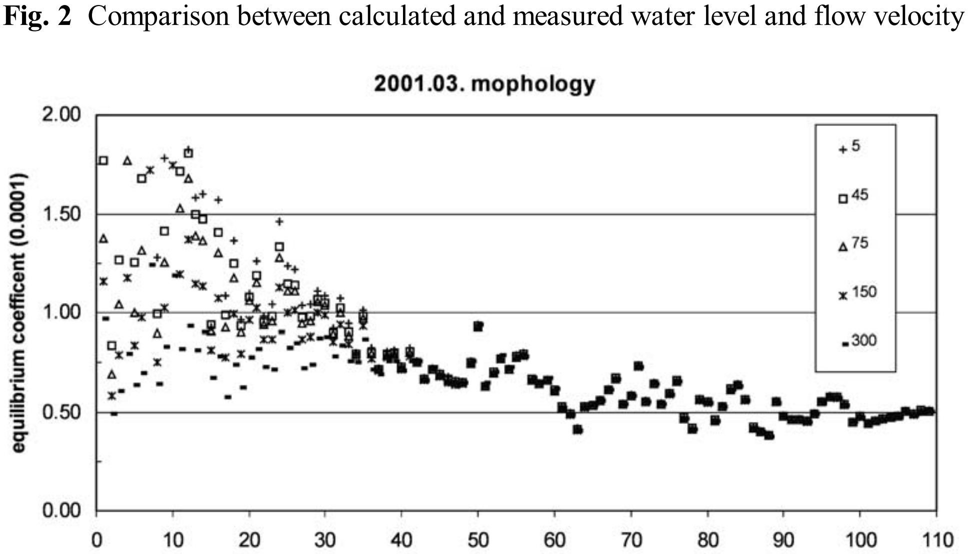

Fig. 3 Ratio between cross-sectional area and half tidal volume

The values of ca for each section calculated with Q=75 m^3/s, i.e. about the long-term averaged discharge, is used in the model. The model has been calibrated for the period 1993 to 2000, with the global equilibrium concentration C_E as the main calibration parameter. Because the morphological development of the estuary strongly responds to the discharge variation according to the field observation, the measured monthly discharge in this period is used in the calibration simulation. The model results are evaluated for the cumulative (wet) volume changes of the model branch in three river reaches. The comparison between the measured and the computed amount of the sedimentation/erosion is shown in Table 1. The agreement between the calculated and the measured quantity of deposition/erosion is quite good. The table shows also that in absolute sense the change in the upstream part is the smallest but in relative sense it is the largest.

Table 1 Calibration of amount of sedimentation(-) /erosion(+) of three river reaches ($10^6 m^3$)

Reach		upstream Pingyangkang to Qiejiachun	middle Qiejiachun to Baoxiang	downstream Baoxiang to Shangwang	whole reach Pingyangkeng to Shangwang
Initial volume		13.47	94.09	130.49	238.08
Ended volume	measured	11.66	103.80	137.45	252.90
	computed	12.86	100.02	140.69	253.60
Sedimentation / erosion	measured	-1.81	9.71	6.96	14.82
	computed	-0.61	5.93	10.20	15.54

4. APPLICATION OF THE MODEL

Two study cases are considered with the ESTMORF model of the Feiyun Estaury. The first case is about the effect of the variation of the river discharge, and the second one is about the impact of the bend cut-off in the estuary on the long-term morphological development.

4.1 IMPACT OF DISCHARGE VARIATION

In the upstream of Feiyun River basin, the large scale Sanxi reservoir has been constructed and began to store water. The discharge of the Feiyun River is changed with decreasing in the wet season and increasing in the dry season. Furthermore the diversion from the Zhaoshandu reservoir located in the downstream of the Sanxi reservoir will be carried out. All this kind of human interference will change the river discharge and will thereby have an important effect on the long-term morphological development of the estuary.

Here we investigate the effect of a systematic change of the long-term averaged discharge, due to e.g. a diversion work. For this purpose a series of simulations of 30 years with constant river discharges have been carried out. Discharges lower as well as higher than the measured averaged discharge in the past have been used. Fig.4 shows the total sedimentation / erosion amount in the whole estuary at the end of the simulations, i.e. after 30 years. The relation between the calculated total amount of sedimentation / erosion G and the discharge Q appears to be well represented by

$$G = A \lg \frac{Q}{Q_c} \tag{2}$$

Herein Q_c represents the critical discharge at which no sedimentation / erosion occurs. As Fig.4 shows it is close to the long-term averaged discharge (75 m^3/s). That Q_c is not exactly equal to 75 m^3/s is due to the fact that the coefficients in the empirical relations for the morphological equilibrium are derived from the 2001 bathymetry, whereas the 1993 bathymetry is used as initial condition in the model. Therefore it is better to use Q_c=75 m3/s when Eq.(2) is applied. Moreover, in absolute sense the largest sedimentation / erosion occurs in the downstream part, but in relative sense the largest change occurs in the upstream part.

Based on this relation it is predicted that a diversion of 20 m^3/s from the upstream river will cause about 10 million m3 sedimentation in the estuary in 30 years.

More seriously is the fact that no morphological equilibrium seems to establish according to the simulations. Fig.5 shows how the simulated erosion for a high discharge and the sedimentation for a low discharge develop in time. The sedimentation / erosion rate does not decrease but increases in time. The explanation for this is that e.g. the sedimentation caused by a decrease of the river discharge will cause a decrease of tidal intrusion in the estuary. This means that the tidal range and the tidal volume in the estuary will decrease, which in turn causes more sedimentation in the estuary. The model suggests thus that a diversion of river discharge can trigger much more serious sedimentation problem in the estuary than one might expect by comparing the diverted discharge to the tidal discharge in the estuary.

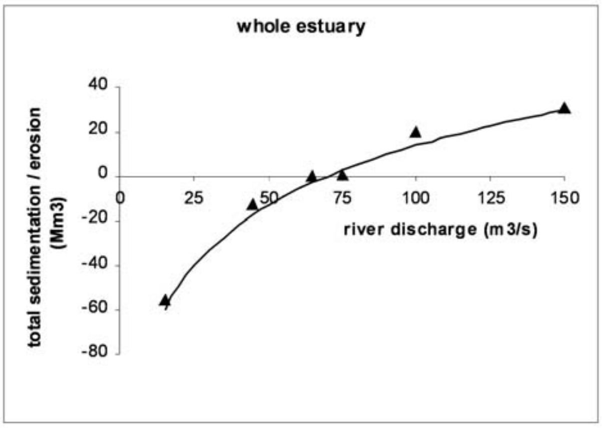

Fig. 4 The relation between river discharge and the amount of sedimentation/erosion

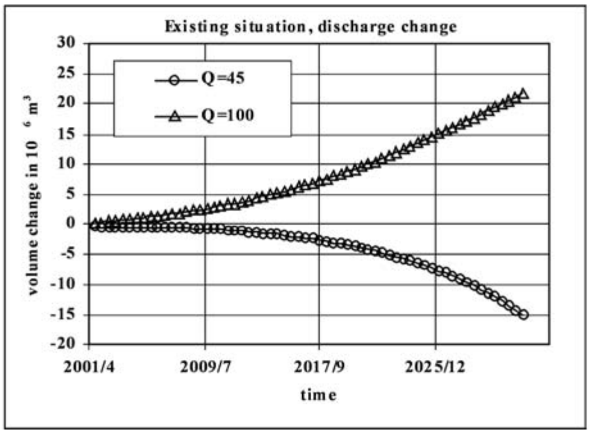

Fig. 5 Development of sedimentation erosion in time

4.2 IMPACT OF BEND CUT-OFF AND LAND RECLAMATION

Two cases, for training the Feiyun Estuary in order to increase the land area of RuiAn City and to improve the flood control, have been studied. The first considered case concerns land reclamation of about 287 ha along the bend from Xianjiang to Baoxiang (Case 1 in Fig.1). The second considered case is the bend cut-off combined with land reclamation of about 467 ha in the old bend area (Fig.1).

For each of the two cases a simulation of 10 years has been carried out with the model. The simulated morphological changes along the estuary after 1 year and after 10 years are depicted in Fig.6. The corresponding amounts of sedimentation / erosion in the three reaches are given in Table 2.

For the case of land reclamation, erosion occurs at the project site and sedimentation in the reaches downstream and upstream of the project site. The land reclamation has the effect that the cross-sections at the project site become smaller, which explains the erosion there. Sedimentation downstream of the project site is caused by the decrease of the tidal volume due to the reduced tidal storage area. Sedimentation upstream of the project site is caused by the fact that the water level in this reach becomes higher due to the land reclamation. The difference between the mechanisms behind the sedimentation in the two reaches explains why the sedimentation downstream is much higher than upstream.

In the case of bend cut-off sedimentation occur in the reach downstream of the project site for the same reason as in the other case. Upstream of the project site erosion occurs due to the drop of water level in this reach. It is noted that according to the model results the morphological response to the considered bend cut-off is quite different than in a case of a non-tidal river. The primary response to a bend cut-off in a non-tidal river is the regressive erosion upstream. Downstream of the cut-off sedimentation occurs but it is temporary since the morphological equilibrium in this reach does not change. In the considered estuary case the erosion upstream appears to be much less and the sedimentation downstream is much stronger and it is permanent instead of temporary.

Fig.7 shows the development of the cross-sectional areas at a number of locations. The figure reveals that there are more than one morphological time scales in the development. Take as example case 1, land reclamation, the smallest time scale has the order of magnitude of 1 year. This time scale is related to the local changes at the project site and the corresponding length scale is thus the size of the land reclamation. The larger time scales are related to e.g. the sedimentation downstream of the reclamation and to the redistribution of the sediment eroded at the project site within the estuary. Furthermore it is noticed that the morphological time scales of the considered estuary are relatively very small. The reason of this is the small size of the estuary and the high sediment transport in the estuary.

Table 2 Comparison of the amount of sedimentation / erosion for three river reaches (10^6 m^3)

case	time scale	upper part Pingyangkang to Qiejiachun	middle part Qiejiachun to Baoxiang	lower part Baoxiang to Shangwang	The whole reach Pingyangkeng to Shangwang
1	after 1 year	-0.023	-1.226	-7.151	-8.400
	after 10 year	-0.026	-1.600	-9.648	-11.275
2	after 1 year	-0.091	-6.488	-19.870	-26.449
	after 10 year	0.648	-10.157	-31.119	-40.627

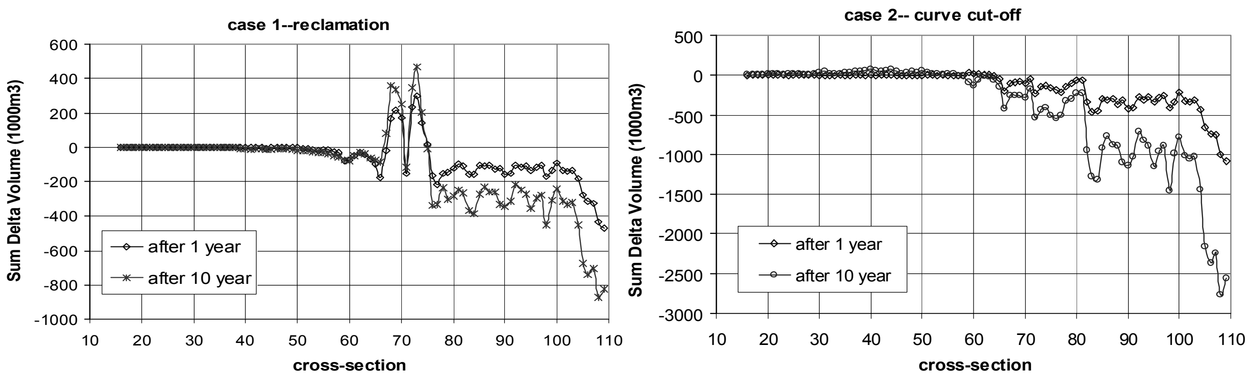

Fig. 6 Simulated morphological change along the estuary

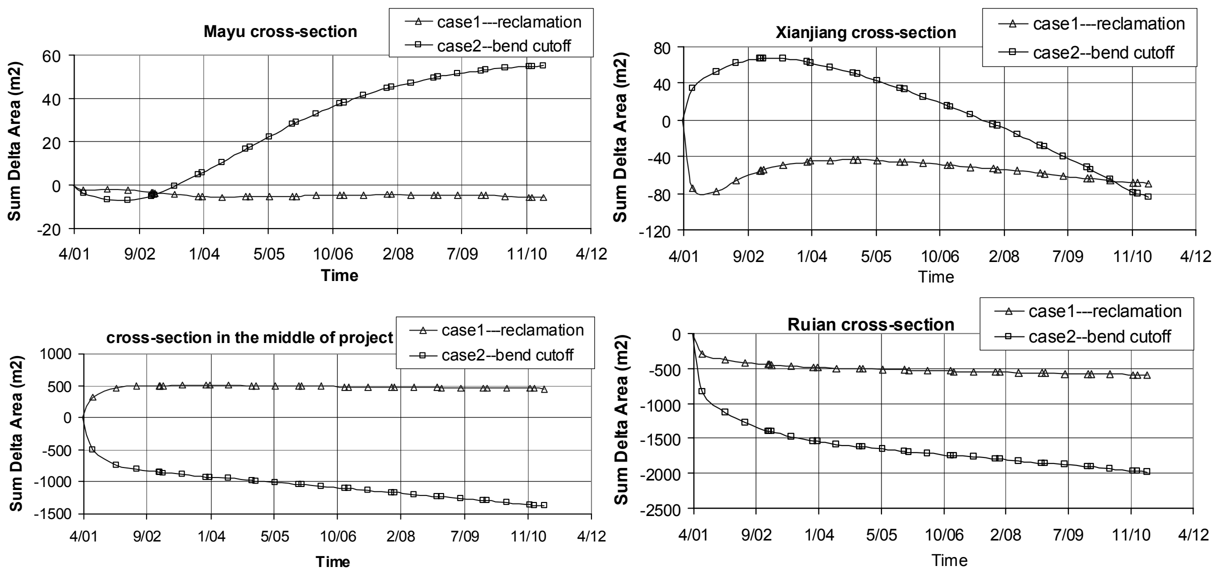

Fig. 7 Change of cross-sectional areas

5. CONCLUSIONS

Based on ESTMORF, a model for the long-term morphological development of the Feiyun Estuary (Fig.1) in Zhejiang, China, has been set up. The model has been calibrated using hydrographic field data as well as data on historical morphological changes. After the calibration the model has been applied to investigate the impact of the change of river discharge regime due to the construction of reservoirs in the upstream river, and of a land-reclamation / bend cut-off project (Fig.1) in the estuary.

The morphological development in the Feiyun Estuary appears to be strongly influenced by the upstream river discharge. An increase of the river discharge will cause erosion and a decrease of the river discharge causes sedimentation in the estuary. A systematic decrease of the river discharge due to e.g. the diversion from the Zhoushandu reservoir will cause sedimentation in the estuary. The model results indicate that the sedimentation process does not establish a new equilibrium and the sedimentation rate seems to be increasing in the first 30 years. The mechanism behind this is that sedimentation in the estuary cause a decrease of the tidal intrusion which in turn causes more sedimentation. This means that in such estuaries a diversion of river discharge can cause much more serious sedimentation problem than one would expect in the first instance.

According to the model results the considered land reclamation and bend cut-off will cause sedimentation downstream of the project site due to decrease of the tidal volume. Upstream of the project site sedimentation occurs in case of land reclamation and erosion in case of bend cut-off. The morphological change upstream is related to the change of the water levels and has a much smaller magnitude than the response downstream of the project site. It is noticed that the morphological response to the bend cut-off in the considered estuary is quite different than in case of a bend cut-off in a non-tidal river: the sedimentation downstream is much stronger and will be permanent whereas the erosion upstream is much less. The morphological responses of the estuary to both considered cases involve multiple morphological time scales with their corresponding spatial length scales. The smallest time scale related to the local changes at the project site has the order of magnitude of only about one year. The estuary under consideration is thus morphologically very quick.

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