EFFECTS OF HYPERCONCENTRATION-RELATED DRAG REDUCTION ON TIDAL PROPAGATION IN THE QIANTANG ESTUARY

Wei Li, Zhejiang University, lw05@zju.edu.cn
Zhenghua Su, Zhejiang University, zhenghuasu@zju.edu.cn

INTRODUCTION

The Qiantang Estuary (QE) in the east coast of China is famous for its hyperconcentrated tidal bore with the highest sediment concentration up to about 80 kg/m^3 (Pan et al., 2013). Recent research for some European estuaries has indicated that hyperconcentrated environment may affect tidal propagation through hydraulic drag reduction, resulting in an enlarged tidal range and even a regime shift in the estuary (Winterwerp and Wang, 2013). However, this water-sediment interactions have not been considered in the tidal prediction of the Qiantang Estuary in the past. Instead, a bed roughness even smaller than that of glossy glass has often been used to fit the observed tidal data in the mathematical modelling.

Therefore, the present study aims to reveal whether the hyperconcentration-related drag reduction can explain the mechanism of very small bed roughness in the Qiantang Estuary and to what extent it can affect the tidal propagation especially for the tidal range. First, an analytical model is used to predict the tidal range along the QE (from Wenyan to Ganpu stations) for different methods of bed friction. Then, mathematical modelling is conducted to shed light on the processes of tidal wave propagation for the corresponding approaches. The results of the two models are compared together with the field observations to further verify the ability of the analytical model and the significance of the effects of hyperconcentration-related drag reduction.

ANALYTICAL MODEL

The linear analytical model developed by Winterwerp and Wang (2013) has been extended to include the non-linear friction effects and used for tidal range prediction in the QE. The analytical solution of the non-linear friction model can be written as the same form as that of the linear model, which is

$$\kappa_i = 1 \mp \frac{1}{2}\left[2\sqrt{(\Lambda_e - 1)^2 + (\Lambda_e r_*)^2} - 2(\Lambda_e - 1)\right]^{\frac{1}{2}} \qquad (1)$$

where Λ_e is the estuarine convergence number, r_* is the dimensionless friction, κ_i is the dimensionless imaginary wave number. The relative tidal range can be estimated by $e^{\kappa_i x/(2L_b)}$; x is the distance from Ganpu, L_b is the estuarine convergence length. The essential difference between the two models is the flow velocity for estimating r_*, which is equal to $gu/(\omega h C^2)$. The original linear model uses the maximum velocity while the present model uses the mean velocity. Here, we consider three approaches for bed friction estimation:

(1) Traditional clear-water formula for Chézy coefficient (Winterwerp and Wang, 2013):

$$C = 18\log(12h/k_s) \qquad (2)$$

(2) Manning roughness with sediment effects originally developed for the Yellow River (Li et al., 2017):

$$n = \frac{h^{\frac{1}{6}}}{\sqrt{g}} c_n \frac{\delta_*}{h}\left\{0.49\left(\frac{\delta_*}{h}\right)^{0.77} + \frac{3\pi}{8}\left(1 - \frac{\delta_*}{h}\right)\left[\sin\left(\frac{\delta_*}{h}\right)^{0.2}\right]^5\right\}^{-1} \qquad (3)$$

(3) Bed-material dependent constant bed friction value:

$$r_* = \begin{cases} 3\ (silt) \\ 4\ (sandy\ silt) \\ 5\ (gravely\ sand) \end{cases} \qquad (4)$$

As the analytical model assumes an exponential variation of the estuary width, we divide the QE adequately into several sub-reaches to satisfy this assumption when doing the analytical calculation. Because the synchronous observation data for all flow and sediment variables are difficult to obtain, here we use the data of year 2000 for the tidal range and river depth, and the data of year 2007 for the velocity and sediment-related parameters.

MATHEMATICAL MODELLING

Mathematical modelling of the above three friction approaches has been done by our previously developed 2-D depth-averaged morphological model, which has been successfully applied to hyperconcentrated river flow modelling (Li et al., 2017). To be consistent with the analytical model, all simulations are done over a fixed bed. We schematize a symmetrical plan configuration for the Wenyan-Ganpu reach, of which the longitudinal variations of width and depth are the same as those for the analytical model. We impose a periodic water level (T=12.4hr, amplitude=2.286m) at the downstream open boundary (Ganpu) and a constant water level at the upstream end (Wenyan). The initial flow condition is static with the water level equal to the averaged value of the downstream open boundary.

RESULTS

(1) Comparison of linear and non-linear friction effects

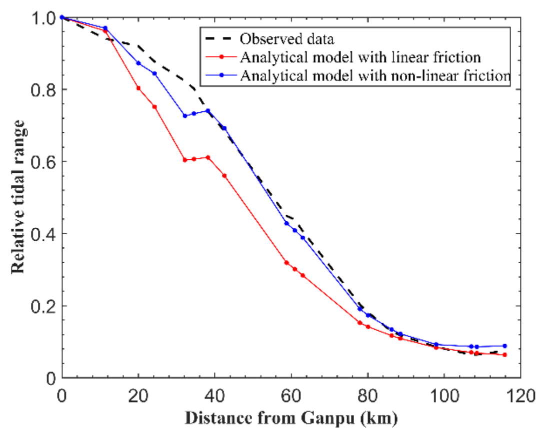

Figure 1 Comparison of linear and non-linear friction model results with observations

Figure 1 shows the comparison of computed relative tidal ranges for the second bed friction method between the linear model and the present model of non-linear friction extension together with the observed data. Both of the two analytical models can predict the general decreasing trend of the tidal range along the QE, while the present model fits better with the observed data when considering the non-linear friction effects. It implies that the use of mean velocity is more appropriate for friction estimation.

(2) Comparison of different friction methods for analytical model

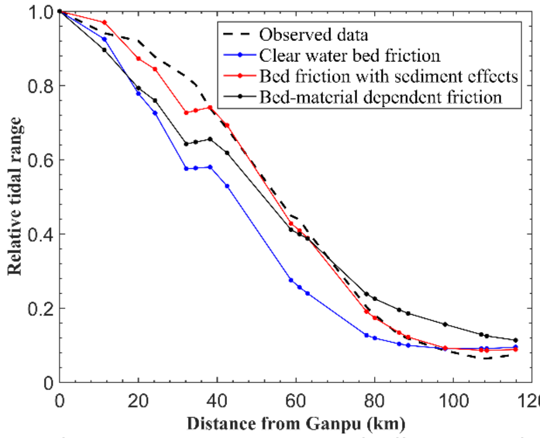

Figure 2 Analytical model results of different bed friction methods against the observations

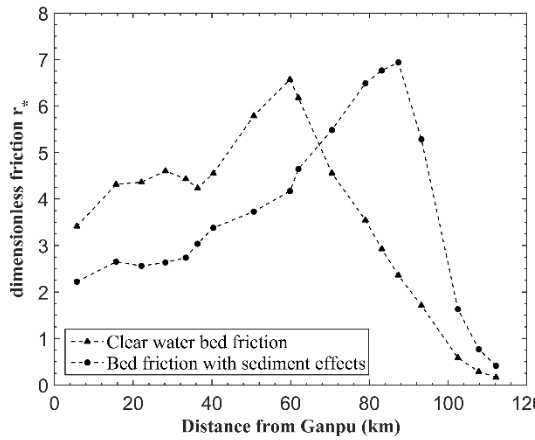

Figure 3 Dimensionless bed friction for clear water and sediment effect approaches respectively

The analytical results (Fig. 2) show that the general trend of the tidal range variation along the QE can be well predicted by the present analytical model with the three bed friction approaches. When considering the sediment effects on the bed roughness, the predicted tidal range show good agreement with the field data. While the tidal range is underpredicted by the other two friction approaches. Moreover, Figure 3 shows that the dimensionless bed friction is much smaller when considering sediment effects on the bed roughness than that of clear-water formula in the hyperconcentrated reach (0-60 km) of the Qiantang Estuary. It implies that the hyperconcentration-related drag reduction can explain the very small bed friction in the QE and plays a significant role in the tidal range variations.

(3) Comparison of analytical prediction and mathematical modelling

Figure 4 shows the analytical and numerical results of the second bed friction method against the observed data. The analytical and numerical solutions agree well with each other in most parts of the QE though there exist some discrepancy near the upstream end. The underprediction of the tidal range by the mathematical modelling may be caused by the constant water level imposed at the upstream boundary. The agreement of the analytical and numerical results with the observations demonstrates the accuracy and applicability of the present analytical model for the QE. It also implies the successful extension of the bed friction formula of sediment effects for the silt-dominated Yellow River to the estuarine environment possessing silt to sandy silt sediments.

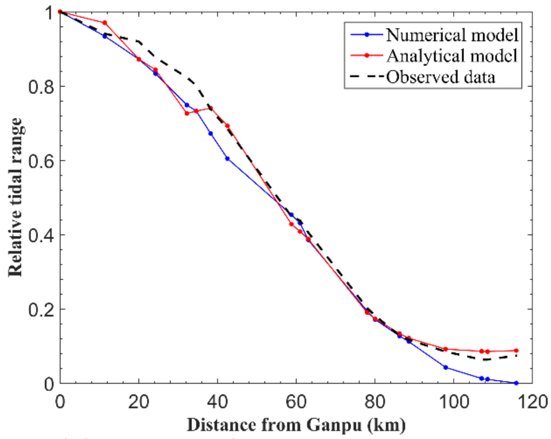

Figure 4 Comparison of the analytical and numerical results of the second bed friction method against the observations

CONCLUSIONS

The tidal propagation along the Qiantang Estuary has been investigated by a combination of analytical framework and mathematical modelling. Conclusions can be drawn as follows:

For the analytical prediction of tidal range variations, non-linear bed friction using mean flow velocity is more appropriate than linear bed friction with the maximum velocity.

For sediment-laden flow, especially the hyperconcentrated estuarine environments like the Qiantang Estuary, the hyperconcentration-related drag reduction can explain the extremely small bed friction calibrated in many numerical models and provides a more reasonable way for the accurate prediction of the tidal range variations from a physical point of view.

The bed friction formula with sediment effects, which is originally developed for the silt-dominated Yellow River, shows successful extension in application to the Qiantang Estuary.

REFERENCES

Li, Su, van Maren, Wang, and de Vriend (2017): Mechanisms of hyperconcentrated flood propagation in a dynamic channel-floodplain system, Advances in Water Resources, vol. 107, pp. 470-489.
Pan, Zeng, Tang et al (2013): A study of sediment characteristics and riverbed erosion/deposition in Qiantang Estuary, Hydro-Science and Engineering, iss. 1, pp. 1-6 (in Chinese).
Winterwerp and Wang (2013): Man-induced regime shifts in small estuaries-I: theory, Ocean Dynamics, vol. 63, pp. 1279-1292.