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Development of Generalized Model for Estimation of Sediment Siltation in Coastal Waterways of China

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ABSTRACT

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Coastal sediment siltation has long been a major problem for design and construction of coastal large-scale ports in the world. Silty sediment siltation often occurs in coastal waterways of China especially during storm events, in which silty sediment is stirred up from the seabed and re-suspended into the water column by storm-induced waves, and transported into the waterways by currents in three forms of suspended load, bedload and sheet-flow load. This study is to derive a generalized model for estimation of sediment siltation rates under both non-storm and storm conditions based on 6-year field data collected in the outer navigation channel of Huanghua Harbor. The sediment siltation data were collected by directly measuring the seabed elevation changes along the port navigation channel from 2002 to 2007. In analyzing the field data collected, a semi-empirical model between effective wind energy and sediment siltation rate is also presented, and found that the newly derived model yields satisfactory agreement with the siltation data collected during the coastal storm events.

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ADDITIONAL INDEX WORDS: *silty coast, siltation, sedimentation, navigation channel, storm event.*

INTRODUCTION

Extensive sediment siltation in the navigation channels is found to restrain the development of Chinese coastal ports on the silty coasts. In the most recent years, significant progress has been made to overcome sediment siltation problems in the navigation channels of new coastal ports constructed in Bohai Bay, Laizhou Bay and North Jiangsu Province on the silty coasts of China. Semi-empirical methods were developed to estimate sudden sediment siltation under coastal storm events with different return periods (Ji and Zhang, 2008).

The prediction of sediment siltation in the navigation channel may be divided into two parts, one is sediment deposition inside the port and the other is outside the port of navigation channel. Under the protection of breakwaters or manmade protective structures, hydrodynamic forcing inside the port is often weak, resulting in much less sediment transport. The sediment siltation inside the port is generally caused by sediment re-suspension. Outside the port, however, the port navigation channel, which has no protection of breakwaters or artificially made structures, suffers from sudden siltation during storm events. Moreover, the mechanism of sediment transport is much complex in the open sea, especially during storm events. Several methods have been developed to predict sediment deposition on the silty coasts of China by modifying model parameters of sediment settling velocity or sediment suspended concentration on muddy coasts (Liu, 2004; Luo, 2004). Other sediment transport models on the silty coasts were proposed empirically based on the ratio of suspended sediment load to sediment bedload measured in the field (Cao, Jiao and Zhao , 2004).

Apart from suspended sediment load and bedload on the storm days, there exists a thin layer of high suspended sediment concentrations close to the seabed. The exchange of sediment between the thin sheet-flow layer of high sediment concentration and the seabed is frequent. The thin layer of high sediment concentration, which is in the transitional state from sediment bedload to suspended sediment load, is responsible for a sudden sediment siltation inside the navigation channel (Ji and Zhang , 2008; Yang and Hou , 2004).

METHODS

This study is undertaken to collect long-term field data on silt sediment siltation inside the outer navigation channel of Huanghua Harbor on a silty coast of China, and develop a generalized model for estimation of sediment siltation under both non-storm and storm conditions.The field data on sediment siltation were collected by directly measuring time-series water

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depth of the channel with single beam echo sounder ODOM DF3200MK III. Trimble332 RBN/DGPS receivers were used to determine the positions of the survey boat. An instrumented tripod, which housed ADCP and OBS, was also deployed to collect the field data on waves, currents, and suspended sediment concentrations. Numerical models were also applied to calculate currents and waves in the navigation channel and calibrated with the collected field data.

RESULTS

Total Sediment Load

Based on the recent findings about sediment transport on the silty coast of China (Ji and Zhang, 2008), sediment siltation in a navigation channel may consist of three components, namely suspended load, bedload and sheet-flow load under storm events. Thus, the total siltation volume is expressed as

$$P = P_s + P_b + P_f \ , \quad (1)$$

where P is the total sediment siltation volume per unit area (m^2), P_s and P_b denote the siltation volume per unit area induced by suspended sediment load and sediment bedload respectively, and P_f is the siltation volume per unit area in the thin sheet-flow layer of high sediment concentration close to the seabed.

Suspended Sediment Load

There are several prediction models developed to estimate the sediment siltation volume in coastal waterways on the muddy coasts of China. They are also applicable to predict sediment siltation on the silty coasts in this study. The model of Cao (1992), one of the most widely used ones, is adopted in this study to calculate the suspended sediment load P_s in Eq.(1)

$$P_s = \frac{\omega s t}{\rho_1}\left\{k_1\left[1-(\frac{h_1}{h_2})^3\right]\sin\theta + k_2\left[1-\frac{h_1}{2h_2}(1+\frac{h_1}{h_2})\right]\cos\theta\right\} \quad (2)$$

where ρ_1 is the dry density of suspended sediment (kg/m^3), k_1 and k_2 are the empirical coefficients obtained from the field data, but in the absence of the field data, k_1=0.35 and k_2=0.13 may be used, ω is the settling velocity of suspended silty sediment (You, 2005), h_1 and h_2 are the water depths of the shoal and the navigation channel, θ is the angle between the flow and the center line of navigation channel, s denotes the average sediment concentration above the thin sheet-flow layer of high sediment concentration close to the seabed.

Sediment Bedload

The bed shear stress induced by tidal currents on calm days may be not able to move sediments into motion, but the bed shear stress on storm days, which is induced by both wind-waves and currents, is large enough to re-suspend sediment from the seabed into water columns by wind-induced waves, and transported by tidal currents, and deposited in the navigation channel. According to Kong, Cao and Li, (2004) and You (1994) and You (2005), the bedload transport rate under the action of both waves and tides can be expressed as

$$\varphi_{cw} = A(1-\frac{\psi_{e.cw}}{\psi_{cw}})^{\alpha_1}\psi_{cw}^{\alpha_2} \quad (3)$$

with

$$\varphi_{cw} = q_b / (\rho_s \, d \, \omega_b) \text{ and } \Psi_{cw} = \tau_{cw}/[(\rho_s-\rho)\, dg] \quad (4)$$

in which $\alpha_1 = 1.0$ and $\alpha_2 = 1.5$ were determined from the field data (Ji and Zhang, 2008), φ_{cw} is the unit width sediment transport function, ψ_{cw} is the bed sediment transport function,

$$\tau_{cw}/\rho = 0.5 f_{cw} u_{cw}^2, \quad (5)$$

where f_{cw} is the friction coefficient under waves and currents, and u_{cw} is the combined wave-current velocity close to the bed. You (1994, 1995) developed simple model to calculate the bed shear stress uder a combined wave-current flow. Thus, the bedload transport rate can be rewritten as

$$q_b = \alpha_b \frac{\rho_s \rho}{\rho_s - \rho}\frac{\omega_b}{\sqrt{gd}}\left[1-\frac{u_e^2}{u_{cw}^2}\right]\frac{u_{cw}^3}{g} \ , \quad (6)$$

with

$$\alpha_b = A\,(0.5 f_{cw})^{\frac{3}{2}}\,(s-1)^{-0.5} \quad \text{and} \quad s = \frac{\rho_s}{\rho}. \quad (7)$$

Furthermore, it is assumed that all bedload transported into the channel would be all stayed inside the channel, the siltation volume per unit area due to bedload transport can be written as

$$P_b = \beta \frac{\rho}{\rho_2}\frac{\omega_b}{\sqrt{gd}}(1-\frac{u_e^2}{u_{cw}^2})\frac{u_{cw}^3 \sin\theta}{b} t \ , \quad (8)$$

with

$$\beta = \alpha_b \frac{s}{(s-1)g} \quad \text{and} \quad u_{cw} = \sqrt{u_c^2 + u_w^2} \ , \quad (9)$$

in which u_{cw} is the flow velocity under combined waves and currents, β is an empirical coefficient, ρ_s and ρ are the density of sediment and water respectively, ω_b is the settling velocity of sediment, d is the medium diameter of sediment, u_e is the onset velocity of sediment motion, u_c is the velocity induced by currents only, u_w is the bottom orbital velocity of waves, ρ_2 is the dry density of sediment, and b is the channel width.

The coefficient β in Eq.(9), which is related to coastal hydrodynamics and sediment property, needs to be determined from the field data. Based on the field observations undertaken in the ports of both Weifang and Huanghua, for example, β =0.000845 and β=0.00477 were obtained (Ji and Zhang, 2008).

Sheet-Flow Load

The sediment siltation volume P_f due to the high sediment concentration in the thin layer of sheet flow is estimated by applying the formula of suspended sediment. The concept of the model is generally derived in combined wave-current flow. The sediment transport rate in sheet flow close to the bed per unit width is estimated as

$$q_s = h_f \, u_f \, s_f \, , \quad (10)$$

in which h_f , u_f and s_f are the layer thickness of sheet flow, the flow velocity, and the sediment concentration, respectively.

Eq.(10) is derived under the assumption that all sediments in sheet flow are spread out evenly in the flow path when they are transported into the channel obliquely. Thus, the sediment siltation volume in the sheet flow layer is estimated as

$$P_f = \frac{h_f u_f S_f \sin\theta}{\rho_1 b} t \ , \tag{11}$$

which is combined with Eq.(10) and the length of the flow path is equal to $b/sin\theta$. For convenience of engineering applications, it is assumed that all sediments inside the sheet flow layer transported into the navigation channel are all deposited within the channel. Thus, Eq.(11) can be further simplified as

$$P_f = \frac{h_\mathrm{f} u_\mathrm{f} S_\mathrm{f} \sin\theta}{\rho_1 b} = \alpha_\mathrm{f} \frac{\omega_\mathrm{f} S_\mathrm{f}}{\rho_1} \eta_\mathrm{f} \ , \tag{12}$$

where α_f is the probability of sediment deposition in the layer of sheet flow, and η_f is the sediment deposition coefficient in sheet flow. When sediment in the thin layer of sheet flow is completely deposited into the navigation channel, $\alpha_f = 1$ and $\eta_f = 1$, and thus substituting Eq.(12) into Eq.(11) leads to

$$P_f = \frac{\omega_\mathrm{f} S_\mathrm{f}}{\rho_1} t \ . \tag{13}$$

In Eq.(13), the settling velocity ω_f is a key parameter for estimating the sediment siltation volume in the port navigation channel. Sediment with median diameter d_{50} less than 0.03mm is flocculated in the seawater, and the sediment falling velocity of this type is $\omega_f = 0.04\sim0.05cm/s$. The effect of suspended sediment concentration on the settling velocity of cohesive sediment was experimentally investigated by You (2004). In contrast, sediment with d_{50}>0.03mm is not flocculated, and the sediment falling velocity can be estimated as a single sediment particle. In this study, the settling velocity of silty sediment is calculated with weighted average settling velocity of different grain size classes, $\omega_f = \sum p_i \omega_i$, where p_i is the percentage of each grain size class of sediment, ω_i is the settling velocity of sediment in the *i*th class.

Sudden Sediment Siltation

The silty sediment siltation in the coastal waterways is caused by a combination of waves and currents, especially by coastal storm-induced waves. The energy transformation from the wind to the sea is thorough wind shear stress acting on the sea surface. The energy imported from wind is expressed as

$$E_\mathrm{w} = \tau_\mathrm{w} u = \left(\rho_a f_w w^2\right) u \ , \tag{14}$$

where the flow velocity induced by wind is estimated as $u = \alpha_v w$, α_v is an empirical coefficient ranging from 0.02~0.03 determined from the experimental data, ρ_a is the density of air, f_w is the wind friction coefficient, and w is the wind speed. Considering the storm duration t, the effective energy imported to the sea is estimated from Eq.(14) as

$$E_\mathrm{w} = \alpha_\mathrm{v} f_\mathrm{w} \rho_\mathrm{a} w^3 t \ . \tag{15}$$

As the storm wind speed varies with time, the effective wind energy can be further expressed as

$$E_\mathrm{w} = \alpha_\mathrm{v} f_\mathrm{w} \rho_\mathrm{a} \sum w^3 t \ , \tag{16}$$

in which the storm wind speeds are grouped into different speed classes, and each speed class with its duration t. The sudden siltation will occur in the coastal waterway when the wind speed and duration (w, t) exceed a certain value. Under such storm conditions, the wind energy is defined as the "effective wind energy". For instance, according to the field observation in Huanghua Port, the navigation channel was silted when the wind speed exceeded 10.8m/s and the wind duration was large than 2 hours (Yang and Hou, 2004). Therefore, the "effective wind energy" causing sudden sediment siltation in the waterways may be estimated as

$$E'_\mathrm{w} = \alpha_\mathrm{v} f_\mathrm{w} \rho_\mathrm{a} \left(w_6^{\ 3} t_6 + w_7^{\ 3} t_7 + w_8^{\ 3} t_8 + w_9^{\ 3} t_9 - w_6^{\ 3} t_0 \right), \tag{17}$$

in which w_6=10.8~13.8m/s,w_7=13.9~17.1cm/s, w_8=17.2~20.7m/s, and w_9=20.8~24.4cm/s are different classes of wind speeds, and t_6, t_7, t_8 and t_9 are the durations of the corresponding wind speed classes, and t_0 is the critical wind duration taken as 2 hours. The data on wind speed and duration were collected at Huanghua Port. Note that the empirical coefficients in Eq.(17) need to be revised at different sites on the silty coasts of China.

Extensive silty sediment siltation often occurs during storm events due to wind-induced waves. Sediment is suspended from the seabed by wind-waves, transported by tidal currents, and deposited into deep and wide navigation channel. Thus, the energy E_s required for sediment transport comes from wave energy that originates from winds E_w,

$$E_\mathrm{s} = \alpha_\mathrm{sw} E_\mathrm{w} \ , \tag{18}$$

in which α_sw is the energy transfer coefficient. If the total energy E_s of sediment transport is assumed to be proportional to the kinetic energy E_s1 of suspended sediment load

$$E_\mathrm{s} = \alpha_\mathrm{s} E_\mathrm{s1} \ , \tag{19}$$

where α_s is constant and $\alpha_s < 1$. The energy, which keeps sediment in suspension, may be expressed as

$$E_{s1} = \alpha_{s1} \omega_s C h t_1 \ , \tag{20}$$

in which α_{s1} is an empirical constant, C is the suspended sediment concentration, h is the water depth, ω_s is the settling velocity of sediment, and t_1 is the time keeping sediment in suspension.

If α_p is a deposition ratio of suspended load P_s1 to the total load P, the total sediment siltation volume can be expressed as,

$$P = \alpha_p P_{s1}, \tag{21}$$

with

$$P_\mathrm{s1} = \frac{\alpha \omega_\mathrm{s} C t_2}{g \rho_\mathrm{c}} \eta = \frac{\alpha \eta t_2}{\alpha_\mathrm{s1} g \rho_\mathrm{c} h t_1} E_\mathrm{s1} \ , \tag{22}$$

where α is the settling coefficient, t_2 is the time of sediment setting, ρ_c is the density of deposited sediment, and η is the sediment deposition rate. Based on Eqs.(14)-(22), we can obtain

$$P = \frac{\alpha_\mathrm{sw} \alpha_\mathrm{v} \alpha_\mathrm{p} \alpha \eta \rho_\mathrm{a} f_\mathrm{w} t_2}{\alpha_\mathrm{s} \alpha_\mathrm{s1} g \rho_\mathrm{c} h t_1} \sum w^3 t = \frac{\alpha_\mathrm{pw}}{h} \sum w^3 t \ , \tag{23}$$

with

$$\alpha_{pw} = \frac{\alpha_{sw}\alpha_v\alpha_p\alpha\eta\rho_a f_w t_2}{\alpha_s\alpha_{s1} g\rho_c t_1}, \quad (24)$$

and finally, the total sediment siltation volume is estimated as

$$Q = \frac{\alpha_{Qw} bl}{h}\sum w^3 t, \quad (25)$$

in which α_{Qw} is the sedimentation coefficient, l is the total channel length, b is the channel width, h is the average water depth. For engineering application purposes, Eq.(25) is further simplified as

$$Q = k\left[w_6^3(t_6 - t_0) + w_7^3 t_7 + w_8^3 t_8 + w_9^3 t_9\right] + Q_0 \text{ with } k = \frac{\alpha_{Qw} bl}{h}, \quad (26)$$

where Q_0 is the time-averaged sediment deposition and accounts for a small proportion of the total volume of sediment deposition. The parameters Q_0 and α_{Qw} in Eq.(26) needs to be determined from the field data before it can be used.

DISCUSSIONS

The sediment deposition rate in the navigation channel is separated into two components: one is deposited in non-storm conditions and the other under storms. On no-storm days, the sediment deposition results from sediment suspension, Eq.(2) is used to calculate the deposition rate. However, on storm days, there exists the thin sheet-flow layer of high sediment concentration close to the seafloor (You and Yin, 2006), the deposition rate in the navigation channel is the summation of the deposition rates calculated from Eqs.(2), (8) and (11). Thus, the total sediment siltation in the navigation channel is the sum of the sediment deposition rates occurred over the non-storm and storm days. When the navigation channel is quite long and with variable water depth, it is divided into n computation sections, and each section has a constant water depth, and the deposition rate for each section can be then calculated.

The proportion of sediment bedload, sediment suspended load, and sediment sheet-flow load is determined by sediment properties, coastal forcing, meteorological conditions and other factors. Based on the most recent field data collected in the navigation channel of Huanghua Port, the percentage of the three loads, namely, suspended sediment load, sediment bedload, and sheet-flow sediment load, was found to be 18%, 26%, and 56%, respectively (Ji and Zhang, 2008), the sheet-flow sediment load is the main contributor to silty sediment siltation in the port navigation channel. It was also found that the submerged breakwaters had reduced sediment deposition inside the ports of Huanghua, Jingtang and Weifang.

The field siltation data, which are used to compare with the generalized model in Eq.(1) together with Eqs.(2), (9) and (14), were collected in the navigation channel of Huanghua Port from 2002 to 2007. The physical dimensions of the navigation channel were increased to expand the port loading capacity. From 2006 to 2011, the length of navigation channel was increased from 30km to 43.5km, the width from 170m to 270m, the depth from 12.7m to 14m, while the channel slope was always maintained to be 1:5. The transects of water depth were surveyed 100m apart in the direction perpendicular to the navigation center line. For each transect surveyed, the water depth data were collected every 30m at sampling rate of 5Hz, and the position of the survey boat was measured at sampling rate of 1Hz. The time interval between the surveys is about 10 days during no-storm conditions, but the surveying frequency was increased before and after the storms. The field data on water depths, which were collected at different phases of tides, were all adjusted relative to the lowest tidal level at Huanghua Port. The effects of the survey boat's motions on the field data were also removed.

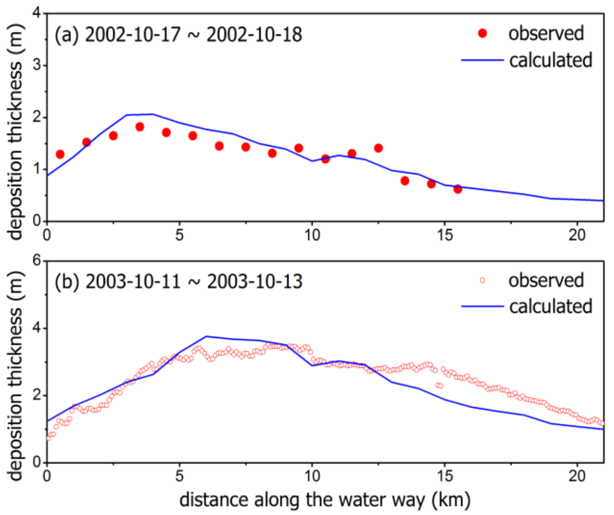

Figure1 Comparisons between the measured and calculated siltation thickness in the navigation channel of Huanghua Harbor.

The comparison of the generalized model with the field data is shown in Figure 1, where Eq.(1) together with Eqs.(2), (8) and (13) are used to estimate the sediment siltation in the navigation channel of Huanghua Port. The generalized model is shown to agree well with the siltation data collected from the port entrance seawards. The maximum of sediment siltation is shown to occur at a distance from the port entrance, where currents and waves are expected to interact extensively with the protective port breakwater, resulting in the sediment siltation maximum in the region of the port entrance. The sediment siltation thickness in Figure 1a is shown to be smaller than that in Figure 1b, and the distance at which the maximum siltation occurs is also shown to be shorter mainly because the storm conditions in Figure 1a were weaker than those in Figure 1b.

There are also several storm-induced sediment siltation events observed in the outer navigation channel of Huanghua Port from 2004 to 2007 (see Table.1), from which the parameters (k, Q_0) in Eq.(26) are determined as $k = 4.04 \times 10^{-9}$ (m^3 sec m^{-1} hour) and $Q_0 = 45$ (m^3). The good correlation between the effective wind energy E'_w and the deposition volume P is shown in Figure 2, where the error in estimating the siltation volume via Eq.(26) is generally less than 6% as shown in Table.1.

Table 1 *Sediment deposition volumes measured in the outer navigation channel of Huanghua Port are compared with those from Eq.(26).*

Storm Date	E_w' (10^9 J)	Measured ($10^4 m^3$)	Predicted ($10^4 m^3$)	Error (%)
10/03/2005	0.50	67	65	3
10/03/2006	0.70	71	73	-3
20/09/2005	0.90	80	81	-2
08/08/2005	1.20	93	94	-1
22/12/2004	1.41	98	102	-4
21/10/2005	1.97	130	125	4
24/11/2004	2.70	161	154	4
08/05/2007	2.70	164	154	6
04/03/2017	4.50	220	227	-3

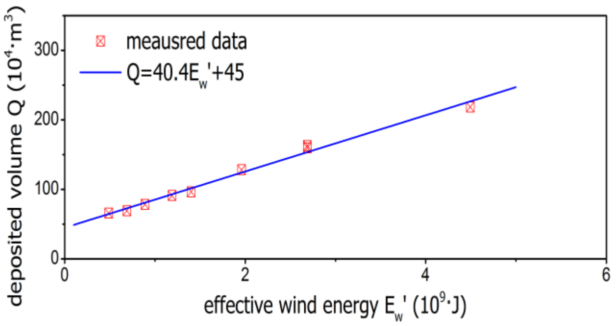

Figure 2 Relationship between effective wind energy and sediment siltation volume measured in the navigation channel of Huanghua Port.

CONCLUSION

Sediment siltation often occurs in the coastal navigation channels of China during storm events. Silty sediment is stirred up from the seabed and suspended into the water column by storm-induced waves, and then transported to the navigation channel by tidal currents. Under non-storm conditions, silty sediment is transported mainly in two forms of suspended sediment load and bedload, while under coastal storms, silty sediment is transported in three forms, namely. suspended load (18%), bedload (26%) and sheet-flow induced load (56%). The sheet-flow load is found to be about twice larger than the sediment bedload, and three times larger than the suspended load based on the field data collected in the outer navigation channel of Huanghua Port.

In analyzing the siltation data collected in Huanghua Port from 2004 to 2007, the generalized model in Eq.(1) or the semi-empirical model in Eq.(26) are found to agree well with the field data. This newly developed model has been also applied to estimate the sediment deposition rates in the coastal navigation channels of Weifang Port, Binzhou Port and other ports that were built on the silty coasts of China, and found to agree well with the field data collected. The model derived from the effective wind energy has provided a convenient and effective way for estimation of storm-induced sediment siltation in the coastal waterways of China and possible other coastal navigation channels in the world.

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