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Sediment Transport Model on Estuary and Coastal Engineering

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1. INTRODUCTION

With the economic development in China, the utilization of silty and muddy coasts including the construction of deepwater harbors and channels are being carried out at a fast pace. In these projects, the key technology involved is sediment transport. Due to the complication of sediment problems under the actions of tidal currents and wind waves, physical experiments are necessary in addition to numerical model studies. However, there are some difficulties to simulate two dynamic factors in one model. The main difficulties to conduct such model are firstly, how to coordinate the similarity scales between the tidal currents and waves in a distorted model and, secondly, lack of a suitable formula of concentration summarizing tidal currents and waves actions.

In this paper, the similarity theory of total sediment transport under the joint actions of both tidal currents and waves developed by Dou Guoren is introduced especially for the distorted physical models. According to the similarity condition, the experiment of model of Huanghua coastal region has been summarized. The result shows this theory provides a more reliable technical means for studying sediment problems in estuary and coastal engineering.

2. SIMILARITY THEORY

2.1 Similarity conditions of tidal currents

From the equations of tidal current movement, the conditions of similarity for the tidal currents between model and prototype are expressed as follows:

$$\lambda_u = \lambda_v = \lambda_h^{1/2} \tag{2.1}$$

$$\lambda_\omega = \lambda_u \lambda_h / \lambda_l \tag{2.2}$$

$$\lambda_t = \frac{\lambda_l}{\lambda_u} \tag{2.3}$$

The above equations obtained based on the similarity of scale ratio inertia force and gravity force, are called gravity similarity conditions.

The following equation obtained based on the similarity of scale ratio of inertia force and resistance is regarded as the similarity conditions of resistance.

$$\lambda_c = \left(\frac{\lambda_l}{\lambda_h}\right)^{1/2} \tag{2.4}$$

Where λ is the scale ratio between the value in the model and that in nature, with the footnote representing the relevant value; u and v are the depth-averaged components of velocity. t is the time; h is water depth; l is the length in horizontal plane. c is Chezy coefficient and n is the roughness of seabed.

From the stochastic theory of turbulence developed by Dou Guoren (1987), one can obtain in the rough region

$$c = \frac{2.51}{\sqrt{g}} \ln(11\frac{h}{\Delta}) \tag{2.5}$$

Where $\triangle$ is the roughness height of seabed. When Manning's formula is adopted, the roughness coefficient scale is

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$$\lambda_n = \frac{\lambda_h^{2/3}}{\lambda_l^{1/2}} \qquad (2.6)$$

Therefore, the conditions of basic similarity between flow in the model and that in nature are that the flow must satisfy the similarity of gravity and the similarity of resistance at the same time.

2.2 Similarity conditions of waves

According to the theory of linear wave, the orbital velocity and wave velocity can be written as

$$U_W = \frac{\pi H}{T}\frac{\cosh[2\pi(h_0+z)/L]}{\sinh(2\pi h/L)}\cos\left(2\pi\frac{x}{L} - 2\pi\frac{t}{T}\right) \qquad (2.7)$$

$$W_W = \frac{\pi H}{T}\frac{\cosh[2\pi(h_0+z)/L]}{\sinh(2\pi h/L)}\sin\left(2\pi\frac{x}{L} - 2\pi\frac{t}{T}\right) \qquad (2.8)$$

$$C_W = \sqrt{\frac{gL}{2\pi}\tanh\frac{2\pi h}{L}} \qquad (2.9)$$

$$T = \frac{L}{C_W} \qquad (2.10)$$

where U_w, W_w are horizontal and vertical components of orbital velocity, respectively. H, L, T, C_w are wave height, length, period and velocity. h is water depth; z is ordinate from the mean water level.

It can be seen that the wave particle velocity in the model is similar to that in nature only when wave height scale is equal to wave length scale and equal to water depth scale. That is mean wave scale should be taken as an undistorted value. Therefore,

$$\lambda_H = \lambda_L = \lambda_h \qquad (2.11)$$

the scales of orbital velocity and wave velocity will be equal to the scale of flow velocity.

$$\lambda_{u_w} = \lambda_{w_w} = \lambda_{C_W} = \lambda_h^{1/2} = \lambda_v \qquad (2.12)$$

$$\lambda_T = \lambda_L / \lambda_{C_w} = \lambda_h^{1/2} \qquad (2.13)$$

According to Stokes second order wave theory, the mass transport velocity U_T can be written as

$$U_T = \frac{1}{2}\pi^2\left(\frac{H}{L}\right)^2 C_W \frac{\cosh[4\pi(h_0+z)/L]}{\sinh(2\pi h/L)} \qquad (2.14)$$

One can write

$$\lambda_{U_T} = \lambda_{C_w} = \lambda_h^{1/2} \qquad (2.15)$$

that is, the mass transport velocity is equal to the wave velocity.

It can be proved that the wave refraction in the model is similar to that in the prototype. For slight slope beaches, the break wave height and the water depth at which the wave is broken in the model may be similar to those in the prototype. However, in a distorted model the similarity of diffraction cannot be realized because of unequal scales between wave length and horizontal distance. This means the model distortion should be made as small as possible.

2.3 Similarity conditions of suspended load

In estuaries and coastal regions, the seabed scour and siltation is mainly caused by suspended load. Therefore, It has an important meaning to simulate suspend transport in the model. The suspended load transport equations and it's capacity formula of tidal currents and waves developed by Dou Guoren (1995) are as follows:

$$\frac{\partial(hS)}{\partial t} + \frac{\partial[hS(u+u_w)]}{\partial x} + \frac{\partial[hS(v+v_w)]}{\partial y} + \alpha_s\beta_s\omega_s(S-S_*) = 0 \qquad (2.16)$$

$$\gamma_0\frac{\partial\eta_s}{\partial t} = \alpha_s\omega_s\beta_s(S-S_*) \qquad (2.17)$$

$$S_* = 0.023\frac{\gamma\gamma_s}{\gamma_s-\gamma_s}\left(\frac{(\overline{u}^2+\overline{v}^2)^{1/2}}{C_0^2 gh\omega_s} + 0.04 f_w\frac{\overline{H}^2}{h\omega_s\overline{T}}\right) \qquad (2.18)$$

$$\beta = \begin{cases} 1, & when\ \ S \ge S_*; \\ 1, & when\ \ S < S_*\ \ and\ \ V \ge V_C; \\ 0, & when\ \ S < S_*\ \ and\ \ V < V_C; \end{cases}$$

where h is water depth; S is sediment concentration; u, u_w and v, v_w represent the components of the vertical mean velocity of tidal current and the vertical mean velocity of wave particles at x and y directions; α_s is the settling probability (or called settling coefficient); ω_s is the settling velocity of suspended load (or flocculation settling velocity when flocculation occurs); S_* is the sediment transport capacity under the joint action of tidal currents and waves; γ_0 is the dry volume weight of sediment on bed surface; $\partial\eta_s$ is the variation of scour and siltation due to suspended load; $\bar{u}$, $\bar{v}$ are the components of mean depth velocity of tidal currents; f_w is wave friction coefficient; $\overline{H}$ is mean wave height; $\overline{T}$ is mean wave period.

In order to ensure the sediment transport in the model be similar to that in nature, the following similarity condition should be satisfied.

$$\lambda_u = \lambda_v = \lambda_{u_w} = \lambda_{v_w} = \lambda_h^{1/2} \tag{2.19}$$

$$\lambda_\omega = \lambda_u \lambda_h / \lambda_l \tag{2.20}$$

$$\lambda_s = \lambda_{s*} = \frac{\lambda_{\gamma_s}}{\lambda_{(\gamma_s - \gamma)}} \tag{2.21}$$

$$\lambda_{t_s} = \frac{\lambda_{\gamma_0}\lambda_h}{\lambda_s \lambda_\omega} = \frac{\lambda_{\gamma_0}\lambda_l}{\lambda_s \lambda_h^{1/2}} \tag{2.22}$$

In which λ_{t_s} is time scale of seabed deformation caused by suspended load.

2.4 Similarity conditions of bed load

Based on the same principle of energy conservation as suspended load movement, Dou Guoren derived the sediment transport formula under joint action of currents and waves:

$$\frac{\partial(hN)}{\partial t} + \frac{\partial(hN(u+u_w))}{\partial x} + \frac{\partial(hN(v+v_w))}{\partial y} + \alpha_b \omega_b (N - N_*) = 0 \tag{2.23}$$

By dividing it in wave period,

$$\frac{\partial(hN)}{\partial t} + \frac{\partial(hNu)}{\partial x} + \frac{\partial(hNv)}{\partial y} + \alpha_b \omega_b (N - N_*) = 0 \tag{2.24}$$

The scour and siltation formula of bed due to bed load is:

$$\gamma_0 \frac{\partial \eta_b}{\partial t} = \alpha_b \omega_b (N - N_*) \tag{2.25}$$

where N and N_* are the values of the bed load transport volume and the carrying capacity at the discussed point; u, u_w and v, v_w are the components of the mean velocity of tidal current and the mean velocity of wave particle at x and y directions respectively; α_b is settling coefficient of bed load; ω_b is settling velocity of bed load; γ_0 is the dry volume weight of bed material; $\partial\eta_b$ is the variation of scour and siltation due to bed load. Based on the definition of N and N_*, one should have

$$N = q_b / q, \quad N_* = q_{b*} / q \tag{2.26}$$

where unit charge $q = h\sqrt{u^2 + v^2}$.

$$q_{b*} = \frac{\rho}{\rho_s - \rho} \gamma_s \left(\frac{k_F}{C_0^2} \frac{U^3}{g\omega} + k_W f_W \frac{H^2}{\omega T} \right) (U - U_c) \tag{2.27}$$

the following relationship can be obtained for the similarity of bed load transport under the action of tidal currents and waves:

$$\frac{\lambda_N \lambda_h}{\lambda_t} = \frac{\lambda_h \lambda_N \lambda_u}{\lambda_l} \tag{2.28}$$

$$\lambda_N = \lambda_{N*} \tag{2.29}$$

$$\frac{\lambda_h \lambda_N \lambda_u}{\lambda_\ell} = \lambda_{\omega_b} \lambda_N \tag{2.30}$$

$$\lambda_{\gamma_0} \frac{\lambda_h}{\lambda_{t_b}} = \lambda_{\omega_b} \lambda_N \tag{2.31}$$

From equation(2.30), the settling velocity scale of bed load is

$$\lambda_{\omega b} = \lambda_u \lambda_h / \lambda_\ell = \lambda_h^{3/2} / \lambda_\ell \tag{2.32}$$

that is the same as the settling velocity scale of suspended load and the tide velocity in vertical direction.

From equation (2.32), the time scale of scour and siltation caused by bed load is

$$\lambda_{t_b} = \lambda_{\gamma_0} \frac{\lambda_h}{\lambda_N \lambda_{\omega b}} = \lambda_{\gamma_0} \frac{\lambda}{\lambda_{\gamma_s}} \lambda_t \tag{2.33}$$

It can be seen the sameness between the time scale of scour and siltation caused by suspended load and bed load. Therefore total sediment, suspended and bed loads, can be experimented in one model.

Besides the similarity conditions mensioned above, the similarity of incipient velocity and settling velocity must be satisfied in order to achieve the similarity of suspend load and bed load transport in deed. Only when the sediment (suspended load and bed load) incipient velocity of tidal currents and waves are satified respectively, the similarity of sediment incipient has been obtained. The settling velocity scale of suspended load is same as that of bed load. The settling velocity can be calculated by formula.

3. The Huanghua physical model

3.1 The nature situation

The Huanghua port, the second largest sea-port in China constructed for transporting coal from western China to the east, was to be built in Huanghua coastal region. It lies in southwest bank of Bohai Sea Gulf and nearby the estuary of Dakouhe River where Zhangweixin River and Xuanhui River converge(fig.1). The bed slope is about 1/2400. The median diameter of bed materials in Huanghua coastal region is from 0.002 to 0.071mm and suspended from 0.002 to 0.063mm.The measure data show the sea bed is basically balance.

3.1.1 Wind

In this region, the prevailing wind direction is SSW and the frequency is 11.7%. The sub-prevailing direction is SW and the frequency is 10.5%. The strong direction is ENE and the frequency is 7.3%. In one year, the wind scale that is greater than 5 is 11.6%, the out-shoreward wind is 50.5% and the shoreward that is the strongest direction is 33%. The largest wind speed is 31m/s in direction of ENE.

3.1.2 Wave

The measured values show that the wave is principally wind deduce wave(66.8%) and secondly swell wave (27.1%). The prevailing wave direction is E and the frequency is 10.06%. The sub-prevailing direction is ENE and the frequency is 9.38%. The strong wave direction is NE and the largest wave height measured in the filed is $H_{1/10}$=3.8m.

3.1.3 Tide

The *tide in the region belongs to non-regular* semi-diurnal tide. There are two high tides and two low tides during every tidal day and the inequality of tidal diurnal is remarkable. The highest high-water level is 5.71m and the lowest low water level is 0.26m. The mean high tide is 3.58m and the mean low water is 1.26m. The mean sea level is 2.4m.

The tidal current is anti-clockwise flow outside the estuary but it is to-and fro flow in the estuary. According to the measured data between June and July,1987, the flow direction is in 216°-273°and the ebb direction is in 35°-97°. The mean largest velocity in depth 0.58m/s during flow and 0.53m/s during ebb. The largest velocity is 1.0m/s during flow and 0.74m/s during ebb. The mean velocity of spring tide in tidal day is 0.41m/s during flow and 0.24m/s during ebb.

During 1983 to 1987, measurements of sediment concentration were done after wind in the field. The high concentration existed near shore which exceeded 0.8kg/m^3 inside the −1.0m seabed elevation. From −1.0m to −6.0m seabed elevation the concentration decreased from 0.8kg/m^3 to 0.27kg/m^3. The concentration was not exceeded 0.27kg/m^3 outside −6.0m seabed elevation. The lift action of waves to sediment can be seen obviously near shore.

3.2 The model design

Based on the similarity theory, a physical model of total sediment transport under the joint action of tidal currents and waves was designed in 1995 to study the sediment siltation of Huanghua Port.

According to the analyze of similarity and the condition of testing hall, the horizontal scale was 625 and the vertical one was 100. The mobile-bed materials and suspended sediments in the model were bakelite powders with different diameters. Tide time scale is 62.5 and one tidal day is 23'49" in the model. The detail scales are shown in Table 1.

Table 1. Scale Values of Huanghua coastal region model

Scales		Values
Horizontal	λ_l	625
Vertical	λ_h	100
Flow velocity	λ_V	10
Roughness	λ_n	0.86
Tide time	λ_t	62.5
ave height	λ_H	100
Wave length	λ_L	100
Wave period	λ_T	10
Orbital velocity	λ_{u_w}	10
Wave velocity	λ_{C_w}	10
Littoral velocity	λ_{V_l}	10
Settling velocity	λ_ω	1.6
Particle diameter	λ_d	0.68
Sediment concentration	λ_S	0.52
Sediment transport capacity	λ_{S*}	0.52
Dry unit weight	λ_{γ_0}	1.46
Incipient velocity of current	λ_{V_c}	7~11
Incipient velocity of wave	$\lambda_{V_{wc}}$	8~12
Bed load discharge	λ_{q_b}	520
Bed deformation time	$\lambda_{t_s}=\lambda_{t_b}=\lambda_{t_l}$	180

The mean diameter of bed materials is 0.015mm and floc diameter is 0.0305mm. The roughness of sea bed is about 0.016-0.019. In the model the bakelite powders that the median diameter is 0.045mm is used as mobile-bed materials. The mean diameter of suspended materials is 0.0096mm and the floc velocity is 0.0004m/s. The median diameter of bakelite powders of suspended load is 0.031mm which can be obtained from the formula of settling velocity.

3.3 The model layout and experiment

The testing hall is 50m in length and 32m in width. The model simulated 18km along the coastal and 31.3km from the land to the sea and 500m^2 mobile-bed in prototype. Tidal and wave generator were lied in –8m seabed elevation. Four two-way pumps were used to generate tidal currents.

The verifications included tidal level, velocities and directions of tide, sediment concentrations and seabed variations were carried. The velocities and directions of 11 points and tidal levels of 3 points measured in the model were compared to that data in the filed measured on June 26-27, 1987. In this year several times measurements of sediment concentration on-the-spot had been carried on under different wave heights. In the model, the distributions of sediment concentration under the action of tidal currents and waves were reproduced. The comparisons of concentration between the model and prototype are presented in Fig.1. The verification of seabed scouring and silting was done according to the measured topographic drawing from May,1985 to July,1987 and to Septemeber,1992. The comparison results also showed that the beach variation in the model is in good agreement with that in the prototype (see Fig.2 and Fig.3).

Table 2. The intensities of siltation in different schemes

seabed elevation	Berthing Area	Basin	Inner Passage	Outer Passage
-2.0m	2.54m	1.45m	4.02m	1.0
-2.5m	1.64m	1.22m	1.87m	0.88
-3.0m	1.12m	1.09m	1.61m	0.71
-4.0m	0.92m	0.82m	1.38	0.64

After the verifications, some schemes that the positions of basin doorway are in –2m, –2.5m, –3m and –4m seabed elevation have been studied especially. The intensities of siltation in the berthing area, basin, inner passage and outer passage will decrease obviously with the doorway stretching to the deepwater area. The range of siltation reduction is the most remarkable when the doorway is from –2m to –3m seabed elevation. The siltation experiments of different position of doorway show that the doorway in –2.5m seabed elevation is more suitable.

4. CONCLUSION

In estuaries and coastal regions, it is uneasy to do undistorted model because the simulated area is very large. The more practical way is to use distorted model. In order to solve the problem of sediment transport under the joint action of tidal currents and waves, Dou Guoren has systematically studied the similarity of sediment transport physical model both theoretically and experimentally. The research show that tidal currents, waves, suspended and bed load can be simultaneously reproduced in one model when the gravity similarity and the resistance similarity condition can be satisfied by tidal currents and waves. By using this model, the sedimentation problems of Huanghua Harbor and its navigational channel were studied, and the layout schemes of this project were experimented.

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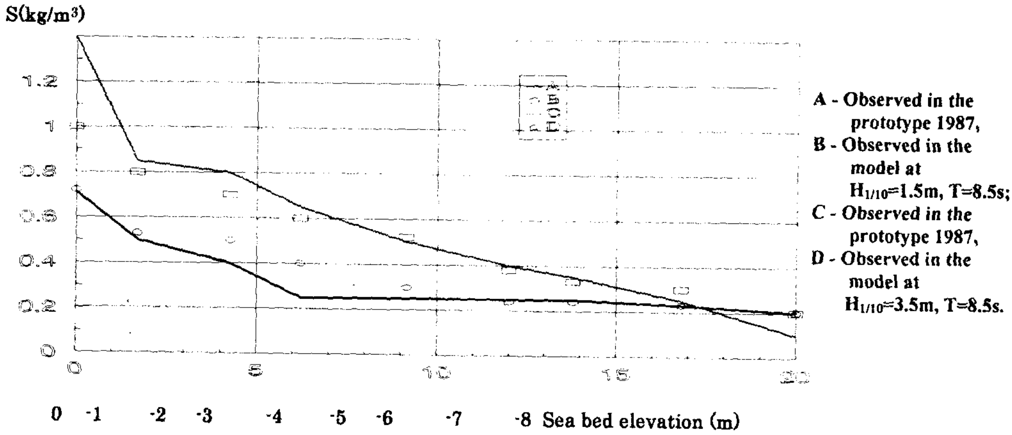

Fig. 1. Comparison of sediment concentration under the action of tidal currents and waves.

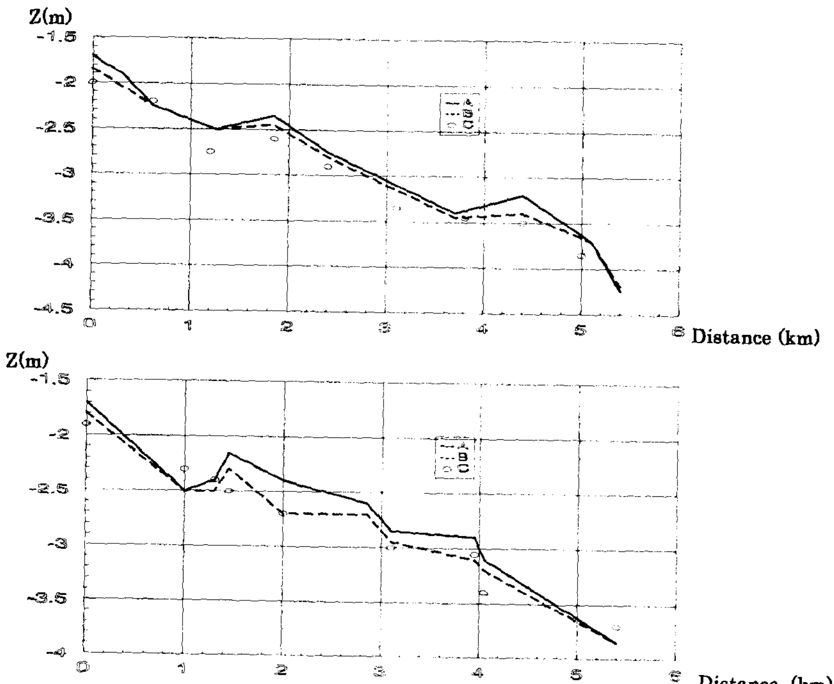

Fig. 2. Verification tests of bed deformation for 1985~1986
A – The beach profile of 1985
B - The beach profile of 1986
C – Predicted by the model for 1986.

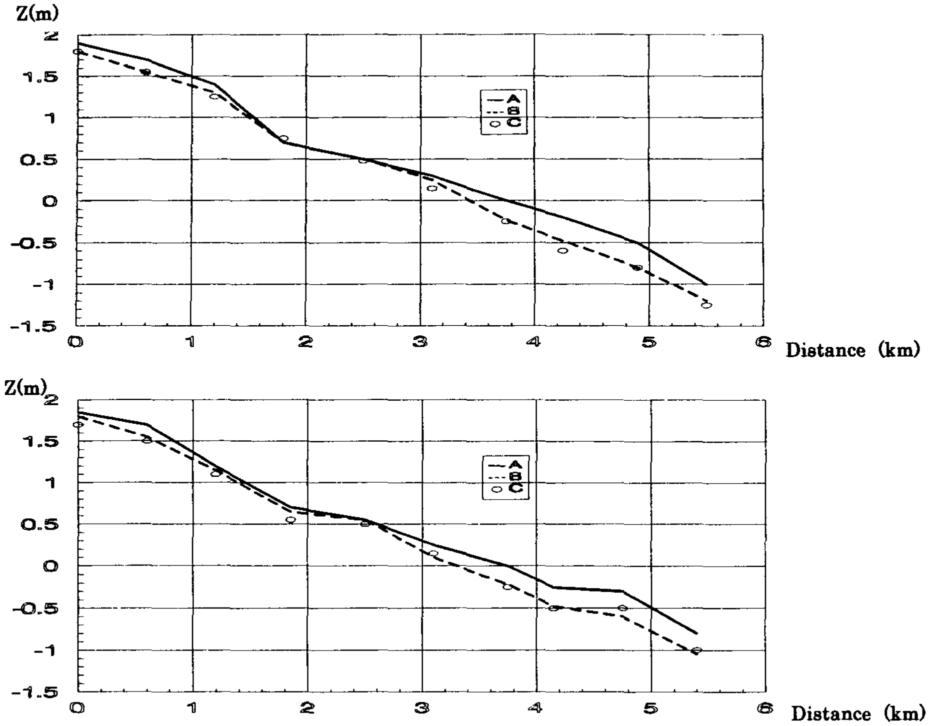

Fig. 3. Verification tests of bed deformation for 1989~1990
A – The beach profile of 1989
B - The beach profile of 1990
C – Predicted by the model for 1990.