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ESTIMATION OF SUSPENDED SEDIMENT CONCENTRATION IN ESTUARY

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ABSTRACT Based on the sediment transport theory and water flow energy equilibrium theory, an expression of semi-tidal period averaged suspended sediment concentration in estuaries is developed for different conditions of water flow, and a case study is conducted for the Yangtze River Estuary. The separation of sediment concentration is helpful to the interpretation of the characteristics of erosion and siltation in estuaries by means of sediment load transported by water flow and suspended sediment from the riverbed. For the Yangtze River Estuary, load transported is the main form of sediment transport and the possibility of silting is large in the flood season, while suspension of sediment from the riverbed is predominant and riverbed erosion is serious in the dry season, i.e. "siltation in the flood season and erosion in the dry season" in the Yangtze River Estuary. The results show that suspended sediment concentration in estuaries consists of sediment load transported by water flow and suspended from the riverbed, and the concentration is also influenced by other dynamical factors such as wind, wave, etc. Besides, the present expression of sediment concentration has laid a foundation for calculating the semi-tidal period averaged sediment-carrying capability for estuaries.

KEYWORDS tidal estuary, flow energy, suspended sediment concentration, correlation analysis

1 Introduction

Suspended sediment concentration in silty estuaries plays a vital role in estuarine geomorphology and change of ecological environment and is also important for estuary regulation engineering, so it is of great significance to research and engineering practice.

Sediment suspended by water flow silts up in estuaries because the water area is broadened and the velocity of water flow is reduced; on the contrary, the sediment of the bed surface is suspended by turbulence of water flow because of the effect of tide movement. Thereby, exact estimation of suspended sediment concentration in estuaries is of significance to the study on the evolution of estuarine geomorphology and of value for exploitation and utilization of estuarine natural resources.

Owing to the action and interaction of the river, tide, wave (current by water wave), salt intrusion density flow, wind induced flow, etc, the estuarine physical environment is very complex, and suspended sediment concentration in estuaries shows randomness, varying with different hydrodynamic conditions. Thus, it is necessary to simplify this unsteady random variable into a steady one, i.e. semi-tidal period averaged concentration, by the application of water flow energy equilibrium theory from the statistics theory.

Based on the sediment transport theory and water flow energy equilibrium theory, an expression of semi-tidal period averaged suspended sediment concentration in estuaries is developed for different conditions of water flow，and a case study is conducted for the Yangtze River Estuary.

2 Suspended Sediment in Water Flow

On the basis of the sediment transportation theory (Chien 1981; Wang 2001), sediment is classified as bed load and suspended sediment according to the forms of its movement, and as bed silt sediment and wash load according to its composition. Bed silt sediment and wash load can contain bed load and suspended sediment at the same time, and in the same way, bed load and suspended sediment can contain bed silt sediment and wash load at the same time. Comparatively, suspended sediment is finer than bed load, and is not considered in bed load study. Bed silt sediment and wash load can change from one form to another under certain conditions.

General speaking, suspended sediment concentration is determined by comparison of sediment buoyant weight to intensity of water flow due to turbulence. When the former is stronger than the latter, suspended sediment goes down to silt up instead of going up to suspend, and the sediment concentration of water flow reduces. On the other hand, when the former is weaker than the latter, the sediment concentration of water flow increases and the bed surface tends to be eroded. If the action of them is equal, the sediment concentration of water flow does not change, neither does the bed surface.

Apparently, as we know, water flow acts on sediment in three ways: transporting bed load, transporting suspended sediment, and suspending or re-suspending sediment. Suspended sediment concentration increases when bed load suspended up by turbulence diffusion of water flow, and reduces when turbulence diffusion of water flow is weaker than sediment buoyant weight and thus, suspended sediment settle down. The two situations exist at the same time in suspended sediment transportation.

3 Water Flow Energy

Sediment concentration is affected by flow intensity, and flow intensity is represented by water flow energy.

So far as per unit water column is concerned, the energy provided by the water column in unit time, 'Ep', is defined as (Bagnold, 1966; Yalin, 1977; Deng, 1989)

$$E_p = \int_0^D \gamma uJdz = \gamma JD \frac{1}{D}\int_0^D udz = \gamma JDV \tag{1}$$

where ã=weight of water D=water depth J=water flow energy slope V=depth-averaged velocity of water column.

If Ep is divided by gD, the rate of energy per unit weight of water is also defined by Yang (1972, 1996), called unit stream power, with which he gained much satisfactory achievement in river sediment research. In fact, this is only another expression of water flow energy.

By use of the Chezy formula $V=C(RJ)^{0.5}$(R=hydraulic radius and R=D for actual wide shallow river or estuarine and coastal shallow waters; C=Chezy coefficient), Ep can be expressed as

$$E_p = \gamma \frac{V^3}{C^2} \tag{2}$$

As is explained earlier, water flow energy Ep provides energy for the transport of bed load and suspended sediment and to suspend sediment, including the energy to overcome the bed resistance due to water flow. In fact, measured water flow energy slope and depth-averaged velocity have included these four factors.

4 Expression of Suspended Sediment Concentration

Based on the above discussion, suspended sediment concentration is composed of suspended sediment through water column and sediment suspended from bed surface. Both of them consume water flow energy.

Suspended sediment through water column S_1 can be written as (Deng 1989)

$$S_1 = K_1 \frac{V^2}{gD} + b_1 \tag{3}$$

Sediment suspended by flow from bed surface S_2 in unit area is given by (Dou 1995)

$$S_2 = K_2 \frac{V^3}{gD\omega} + b_2 \tag{4}$$

where g is gravitational acceleration, w is the settling velocity of the suspended sediment.

In these two equations, K_1 and K_2 are coefficients (including efficiency coefficient and energy dissipated rate etc), and b_1 and b_2 are related to the influence of other hydrodynamical factors (such as wind-induced flow, current due to breaking wave, etc) on semi-tidal period averaged suspended sediment concentration in estuaries and all can be obtained from field data.

Thereby, we obtain a new expression to estimate the suspended sediment concentration in estuarine waters, that is

$$S = S_1 + S_2 = K_1 \frac{V^2}{gD} + K_2 \frac{V^3}{gD\omega} + b \tag{5}$$

where b is sediment concentration caused by exceptional hydrodynamical factors. K_1, K_2 and b should be determined from field data.

So it is not appropriate to calculate semi-tidal period averaged suspended sediment concentration in estuaries equation with (3) or (4) or any extended form of them.

5 Application and Comparison

Suspended sediment concentration is calculated with equations (3), (4), and (5), respectively based on the data measured from 1996 September (flood season) to 1997 February (dry season) at the Yangtze River Estuary. The results are different, as shown below.

Using equation (3) we obtain (see Fig.1)

$$S = 36.96 \frac{V^2}{gD} + 0.153 \quad \text{(flood season, r=0.5997)} \tag{7}$$

$$S = 29.40 \frac{V^2}{gD} + 0.385 \quad \text{(dry season, r=0.4802)} \tag{8}$$

With equation (4) we find (see Fig.2)

$$S = 7.284 \times 10^{-3} \frac{V^3}{gD\omega} + 0.36 \quad \text{(flood season, r=0.5253)} \tag{9}$$

$$S = 5.54 \times 10^{-3}\frac{V^3}{gD\,\omega} + 0.52$$ （dry season, r=0.373） （10）

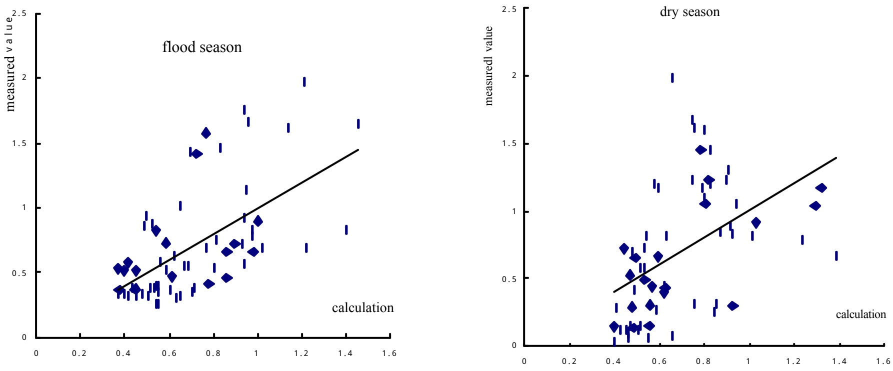

Figure1. Correlation between calculated sediment concentrations with equation (3) and measured data

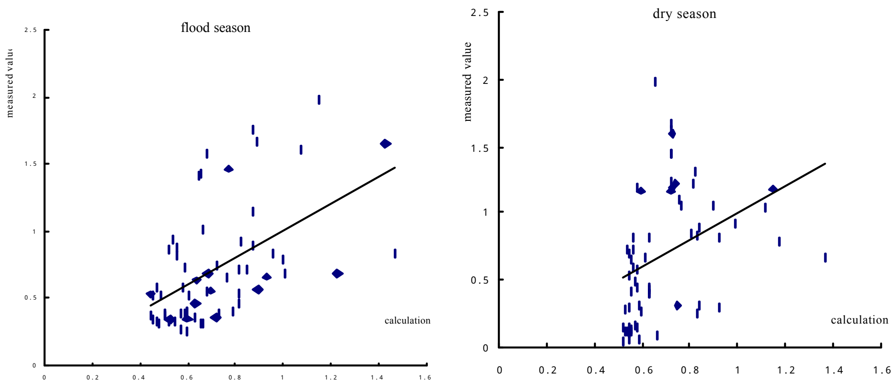

Figure2. Correlation between calculated sediment concentrations with equation (4) and measured data

Equation (5) gives (see Fig.3)

$$S = 26.36\frac{V^2}{gD} + 0.0038\frac{V^3}{gD\omega} + 0.2114$$ （flood season, r=0.753） （11）

$$S = 8.50\frac{V^2}{gD} + 0.0146\frac{V^3}{gD\omega} + 0.3385$$ （dry season, r=0.756） （12）

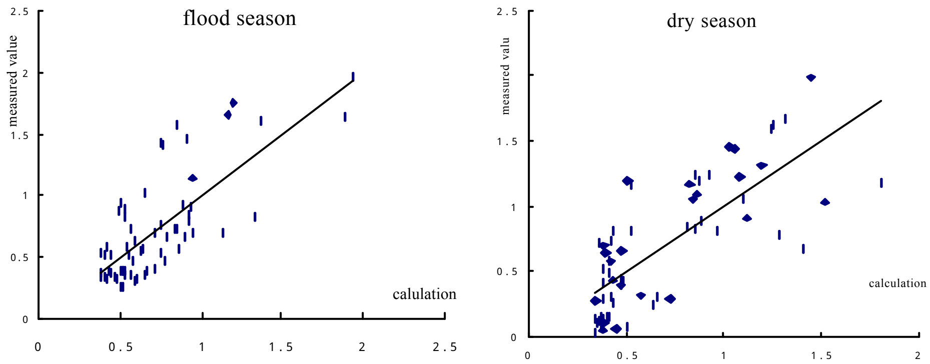

Figure3. Correlation between calculated sediment concentrations with equation (5) and measured data

From the above expressions and figures, it could be found that the results from the present equation (5) are the most accurate and the correlation coefficients (r) are the best; the results from equation (3) occupy the second place; and the results from equation (4) are poor. Another meaning of equation (5) is to separate sediment concentration in estuaries reasonably into two parts: suspended sediment transported and sediment suspended, and this helps to interpret the characteristics of erosion or siltation in estuaries. In the case of the Yangtze River Estuary, equation (11) means that suspended sediment transport is the main form of transport and the possibility of silting is large in the flood season, while equation (12) means that suspension of sediment from the bed is predominant and the possibility of river bed erosion is large in the dry season, i.e. “siltation in the flood season and erosion in the dry season” in the Yangtze River Estuary. At the same time, based on them, one can derive a formula of the semi-tidal period averaged sediment-carrying capability for estuaries.

Finally the present equation is compared with Ren’s expression (Ren etal 1981) through the calculation of sediment-carrying capability of the Yangtze River Estuary, as shown below.

$$S = \left(5.195 \frac{V}{\sqrt{gD}} + 0.189 \right)^2 \quad \text{(flood season, r=0.616)} \qquad (13)$$

$$S = \left(4.708 \frac{V}{\sqrt{gD}} + 0.327 \right)^2 \quad \text{(dry season, r=0.590)} \qquad (14)$$

The results show that Ren’s expression is better than equation (3) or (4), but is not better than equation (5).

6 Conclusion

Analyses and application indicate that suspended sediment concentration in estuaries consists of sediment transported by water flow and sediment suspended from the bed surface, and the concentration is also influenced by other hydrodynamic factors such as wind-induced flow, water wave, etc. The present formula considers the characters of sediment in the Yangtze River Estuary and the results from it are satisfactory. This formula could be applied to estuary research and engineering practice. However, further research is needed for extensive applications of the present formula.

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