ANALYSIS OF WAVE PROPERTY ON TYPICAL MUDDY COAST AND ITS EFFECT ON SEDIMENT-TAKING LIANYUNGANG (CHINA) AS EXAMPLE

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ABSTRACT: This paper aims to discuss the relationship among the wave height, wind speed and water depth on muddy coast, to establish the temporal relationship between the on-way loss of the wave power and the vertical power of the suspension sediment on the muddy coast, and to try to prove the significance of wave-induced current on muddy coast and its remarkable influence on local fluid state. Taking Lianyungang(China)as example, the works have been done as follows: First, the notable relationship between two dimensionless quantities, relative wave height and relative wind speed, is studied through theoretical analysis and verifying base on observation data. And then, the process of the wave power on-way loss was calculated trough the mathematical wave model at Lianyungang in Typhoon Wipha(2007). Both the observation data and the model result show that the process of wave power on-way loss lags behind that of wave height and is in good agreement with the process of suspension sediment concentration.

Keywords: Muddy coast, relative wave height, typhoon, loss of wave power, sediment concentration, Lianyungang

INTRODUCTION

Wave and tidal current are both elementary hydrodynamic factors on sediment transport investigation for muddy coast. It is difficult to represent the hydrodynamics situations on muddy coast by physical model because of the gently slope. So the field observation becomes important to the researchers. With the accumulation of the observational data and the development of observation technology, more and more insight to hydraulic mechanism on muddy bench was got. Tubman et al. (1977), Zhao et al. (1993) presented that the energy lost to the bottom by the waves at muddy coast was found to be at least an order of magnitude greater than that resulting from the processes of percolation or that caused by normal frictional effects. Gong et al. (1983) calibrated the friction roughness of the muddy bottom by comparing a series wave simulation results to the data, and it was supported by the Huhe et al. (1994). Zhang et al. (2000) discussed the wave damping on the muddy coast by reviewing the recent research result. Xiao(2006) studied the wave transformation and breaking on gentle slope by the method of combination of numerical analysis and experiment, and she showed limiting gradient that the wave may not break when the wave energy lose so much caused by bottom friction.

Lianyungang is a typical muddy coast in China. During the time typhoon Wipha passed Lianyungang ,China in 2007, a combine observation of currents, wave and suspended sediment concentration (SSC) was held. It got so many valuable data. Basing on such date, more and more researchers paid their attention to numerical analysis on the muddy coast. Zhao(2007) and Zhang et al. (2012) use different mathematical model to reappear the currents, wave and sediment states in observation time, and noted a desynchronize between the wave progress and SSC one. Although some made their try to get a believable explanation to such lag, a common conclusion is still absent.

This paper aims to discuss the relationship among the wave height, wind speed and water depth on muddy coast, and try to establish the temporal relationship basing on the observation data and numerical analysis on muddy coast. This paper is divided into three parts. In the first part, the notable relationship between two dimensionless quantities, relative wave height and relative wind speed, is studied through theoretical analysis and verifying base on observation data. Besides, the process of the wave power on-way loss was calculated trough the mathematical wave model at Lianyungang in Typhoon Wipha, and makes cooperation among the progresses of wave height, wave power on-way loss and SSC to fine their relationship.

ANALYSIS OF WIND AND WAVE ON GENTLE SLOPE

According to the 44 years historical summary in Lianyungang (fig.1), an empirical relationship between the wave height and wind speed was established by the former as below:

\[
H_{1/10}=0.0179U_{10}^{1.62}
\]  

(1)

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Where $H_{1/10}$ is one—tenth highest wave and $U_{10}$ is wind speed at 10m above the surface.

Fig.1 the empirical relationship between the wave height, $H_{1/10}$ (Y-axis), and wind speed, $U_{10}$ (X-axis), which is similar to exponential one.

This relationship provide an available approach to estimate the wave height under given wind speed at the observation point, which, however, is also a shortage to its use as a apply limitation of the place. The reason of that is that the wind speed and wave height used in the relationship are both dimensional quantities, as well as the relationship does not considering the influence of water depth, bottom slope, bottom matter etc. to the wave height.

Xiao(2006), as mentioned above, shows that the bottom friction dissipation would has a major place in wave energy loss, just like breaking may disappear when the slope is less than a limit value. Fig.1 tell us the relationship between $H_{1/10}$ and $U_{10}$, is distinct at Lianyungang. It also describes a balance between the bottom friction output and wind energy input may exist on sufficient space caused by the gentle slope on muddy coast. The wind power on unit area is:

$$P_{\text{wind}} = C_d \rho \omega C U_{10}^3$$  \hspace{1cm} (2)

And the wave power on per unit width profile is:

$$P_{\text{wave}} = \frac{1}{8} \rho g H^2 c_s$$  \hspace{1cm} (3)

Assuming there is a positive correlation between the surface wave power and the average of profile one and a balance between the energy input and output:

$$P_{\text{surface}} = \frac{1}{8} \rho g H^2 c_s = \beta P_{\text{wind}}$$  \hspace{1cm} (4)

After folding the constant term, (4) turns to:

$$\frac{\alpha' \rho g H^2 c_s}{h} = \rho_w U_{10}^3$$  \hspace{1cm} (5)

And (5) could be written in another style as below:

$$f(\rho, \rho_w, g, H, h, c_s, U_{10}) = 0$$  \hspace{1cm} (6)

Applying $\pi$ theorem, (6) could turn to a combination of three dimensionless qualities as below:

$$f(\frac{\rho}{\rho_w}, \frac{g H}{c_s}, \frac{U_{10}}{c_s}) = 0$$  \hspace{1cm} (7)

So following (7), (5) is presented as below:

$$\alpha' \frac{\rho g H^2}{c_s} = \rho_w \frac{U_{10}}{c_s}^3$$  \hspace{1cm} (8)

The density ratio of water to air can be treated as a constant. According to the linear wave theory, the expression of wave speed, $c_s$, in shallow water is as following:

$$c_s = c = \sqrt{gh}$$  \hspace{1cm} (9)

Substituting (9) into (8), the following expression is got:

$$\frac{H}{h} = \alpha'' \left(\frac{U_{10}}{\sqrt{gh}}\right)^3$$  \hspace{1cm} (10)

(11) shows that relative wave height, $H/h$, is proportional to 1.5 power of the relative wind speed, $U_{10}/\sqrt{gh}$. Of which the index of the left term, 1.5, is close to that of the empirical one (1). 1.62.

Combining with (1), the years cumulative statistics regression results at Daxishan, Lianyungang, the formula (11) shows consistent results with good adaptability in the shallow water. On the other hand, with respect to the formula (1), formula (11) is a dimensionless quantization, which means can be further extended to other water depth point at the shallow beach.

After the formula form’s derivation, calibrating formula parameter, $a''$, with measured data is necessary. Here two different sets of observations are used in the parameter calibration: one is original observations for years at the Daxishan measured station, Lianyungang, which is shown in Fig.1 as scatter. The other is the data from a combination field observation of Typhoon Wipha in 2007, which includes the wind, wave, flow and sediment observations. This observation was held by Tianjin Research institute for Water Transport Engineering. Measured scatter and their fitting are shown in Fig.2 as below.
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Fig. 2 the relationship between relative wave height and relative wind speed at Lianyungang, which accords (11). It also illustrates a significantly correlation between the relative wave height and 1.5 power of relative wind speed. The rhombic points are the P1 data, the square point are P2 data, and the triangle points are the years OB data from Fig.1. The x-axis is the right side of (11) without α”, and the y-axis is the left side.

According to fitting results in Fig.2, alpha” ≈ 0.092, while the correlation coefficient is greater than 0.8 that means significantly correlated. Fig.2 also shows a good adaptation of the formula (11) in Lianyungang waters. Of course, this conclusion needs more wind and the wave field data for a further step rich and validation.

Analysis of Wave power on way loss and SSC
Analysis of Wave power loss in propagation

On the muddy coast, wave is main source of energy of sediment suspended. The role of it can be represented by the square of the wave height in sediment-carrying capacity formula. According to the observation data in Typhoon Wipha at -3m(P1) and -5m(P2) depth contour point(Fig.3) shown as Fig.4, the progress of square of wave height, vertical average sediment concentration and near-bottom sediment concentration process were out of phase. It can be seen from the figure 3 that both wave height and sediment concentration have two peak time during the progress, which the latter lag behind the former from 0.5 to 1.0 hours. This shows that the actual sediment concentration lags behind the wave height and wave energy process.

Fig. 3 the sketch diagram of the point and profile.

Light is P1(-3 m) and right is P2(-5m)

Fig. 4 the progress of the wave power and SSC at -3m (p1,a) and -5m(p2,b) point in Lianyungang during typhoon Wipha, 2007. The scatters are the square of wave height, H^2. The solid line is the vertical average SSC and the star line is the SSC at bottom.

Fig. 5 the progress of the wave height at -3m and -5m point and their difference. The solid is wave height at -5m point(P2) and the star line is wave height at -3m point(P1). The dash is the difference value between P1 and P2.

Fig. 5 illustrates a wave height difference between P1 and P2, which is the existence of wave energy dissemination in the propagation caused by bottom friction and wave breaking. Based on linear wave theory, wave energy on-way loss at per unit width section in a wave period can be expressed as:

\[
\frac{\partial E}{\partial x} = \frac{1}{4} \rho g H^2 \frac{\partial H}{\partial x}
\]

(12)

Assume that the loss of bottom friction along the slope is constant for a certain value. Thus the decay rate of the wave height between P1 and P2 can be approximately expressed as the ratio of wave height difference to distance:

\[
\frac{\partial H}{\partial x} \approx \frac{H_{3} - H_{5}}{\Delta x}
\]

(13)
Substituting (13) to (12) at P1 and P2, the following is get:
\[
\frac{\partial E}{\partial x}|_{x=-s} = \rho g H_s (H_s - H_p) \frac{1}{4Ax} \quad (14)
\]
\[
\frac{\partial E}{\partial x}|_{x=s} = \rho g H_s (H_s - H_p) \frac{1}{4\Delta x} \quad (15)
\]

From (14) and (15), it is known that the progress of wave energy on-way loss rate at each point is effected by the combination of wave height(H) and wave height difference (ΔH) between two point. Fig.4 shows that there are two wave peak time around the early in the morning and 9:00 at Sep. 20th. Figure 3 illustrates that H reached the peak for two points at 1:00, but the peak of ΔH appeared 1 hour later; At 9:00, wave high two points reached achieve peak at the same time while he peak of wave height difference lagged two hours later than that. This shows that ΔH lags behind H in progress. Taking into account numerically determination of power on-way loss at both two point (14) (15), it may be inferred that a phase gap exists between \( \frac{\partial E}{\partial x} \) and H, which former lags the latter.

Establish, verification and calculation of Wave model in Lianyungang

Typhoon field data is difficult to obtain. So for a further talk the feature of \( \frac{\partial E}{\partial x} \) mentioned above, a mathematical model was established during the Weipa Typhoon at Lianyungang, which provides wave power cross-profile distribution in surf zone, inverts the wave energy on-way loss at P1 and P2, and then lays the groundwork for the subsequent analysis. A wave model based on dynamic spectral energy conservation equation is used because the large beach area:

\[
\frac{\partial}{\partial t} N + \frac{\partial}{\partial x} C_x N + \frac{\partial}{\partial y} C_y N + \frac{\partial}{\partial \sigma} C_\sigma N + \frac{\partial}{\partial \theta} C_\theta N = \frac{S}{\sigma} \quad (16)
\]

Which N is the dynamic spectral energy density, \( \sigma \) is the relative wave frequency (frequency) under the coordinate system with the water movement observed \( \theta \) is the wave direction of \( C_x, C_y \) is propagation speed along the travelling direction, \( C_\sigma, C_\theta \) is the propagation velocity under the coordinates consisted by \( \sigma, \theta \). S is the source and sinks terms as (17)

\[
S=S_w+S_{nl}+S_{fl}+S_{bot}+S_{surf} \quad (17)
\]

In (17), \( S_w \) is the wind entry; the \( S_{nl} \) is nonlinear wave - wave interactions energy transfer; the \( S_{fl} \) is wave energy loss caused by Whitecaps dissipation; \( S_{bot} \) is the energy loss caused by the bottom friction; \( S_{surf} \) is energy loss caused by wave breaking.

This wave model used an unstructured triangular grid as shown in Fig.6. Blue line is the coast while the red and green is open boundary treated as lateral ones. Wind and tide data used in model is from observation point at Daxishan, Lianyungang. The bottom friction coefficient values \( k_n \) is 0.01 as introduced by Gong Chong-zhun et al. The indicator of wave breaking follows Ruessink (2004). The wave spectrum used in the model is JOSWAP. Model validation takes return period wave on the majority direction NE as certification basis. The model results and comparison are listed in Tab.1.

Tab.1 illustrates that the wave mathematical model established here is in a good agreement with the observation data at different return period conditions, and thus it can be used for a further calculations during Typhoon Wipha.

![Fig. 6 the range and the mesh of wave model](image)

<table>
<thead>
<tr>
<th>Return period</th>
<th>Observation Da Xishan</th>
<th>Deep water</th>
<th>Model result Da Xishan</th>
<th>Deep water</th>
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<td>T/s</td>
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<td>6.3</td>
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</table>

As the calculated parameters for the Typhoon Wipha, the time step is 30 sec, and the model calculates period is from Sep.15th to 21th, 2007, focusing on from 18:00 at 18th to 12:00 on the 20th, which is main wave process during the storm. The wind and tide data is from the local field data during the storm, and interaction between currents and wave is omitted. The verification of the typhoon model is illustrated by the comparison of wave height data and model result at P1 and P2 as Fig.7. It shows that the calculated wave height meets the
measured value and the process of change tend of both are consistent.

Thus it proves capability of the wave model during Typhoon Wipha period, and proves that this model can be a basis for further research and analysis for wave power loss distribution.

$$\frac{\partial P}{\partial x} \approx \Delta P / \Delta x$$

$$P_{ssc} = (1 - \rho_s/\rho)ghS\omega$$

In the above equation, $\omega_s$ is the settling velocity, $S$ is the vertical average sediment concentration, $\rho_s$ is the density of sediment particle and water, and $h$ means that the water depth.

The simulation of $\partial P / \partial x$ is on the basis of the model result of Typhoon Wipha, and that of $P_{ssc}$ take the real-time sediment data at P1 and P2.

![Diagram](image)

Fig. 8 the relationship between the on-way wave power loss and the work of suspended sediment. (a) is at P1, and (b) is at P2. The dashed line is the $P_{ssc}$, and the solid line is $\partial P / \partial x$.

The unit of y-axis is W/m², and the x-axis is time.

By analysis of the results (Figure 8) to the following conclusion can be got that the variation of wave power on-way loss on the muddy beach, which lags behind the variation of wave height as mentioned above, can relatively reflect the sediment concentration changes, which is represented as $P_{ssc}$. Peak and valley moment of $\partial P / \partial x$ and $P_{ssc}$ are synchronous, and there is no phase gap between two progress, which is different from the asynchronous between the wave power and $P_{ssc}$ shown in Fig.4. Fig.8 also shows a feasible though of prediction of SSC progress by the wave on-way power loss, which exist time relativity.

CONCLUSION

1) Both the theoretical analysis and measured data show that the muddy coast beaches relative wave height and relative wind speed is proportional to the power of 1.5, in Lianyungang, and scale factor $\alpha'' = 0.092$.

2) Measured data indicate that, under typhoon conditions, the muddy coast at a point wave energy power loss variation process lags behind the wave height change process. Although the results of the measured data and numerical models there are subtle differences in the lag time, but the same characteristics, showed hysteresis.

3) Under the conditions of a windy day, muddy coast wave power along loss change process to the apparent spatial and temporal correspondence relationship with the sediment concentration change process, which the hysteresis phenomenon does not exist.

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