A Numerical Study on the Structure and Dynamics of Turbulence in Oscillatory Bottom Layer Flow over A Flat or Rippled Bed

BAI Yu-chuan (白玉川)\textsuperscript{a,1}, NG Chi-\textsuperscript{u}On (吴朝安)\textsuperscript{a, b} and HUANG Tao (黄涛)\textsuperscript{a}
\textsuperscript{a} Institute of Sediment on River and Coast Engineering, Tianjin University, Tianjin 300072, China
\textsuperscript{b} Department of Mechanical Engineering, The University of Hong Kong, Hong Kong, China

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ABSTRACT

This paper is mainly concerned with the turbulence in oscillatory bottom boundary layers over flat or rippled seabeds. Owing to the strong shear and anisotropy of oscillatory flow, an anisotropic turbulence mathematical model is set up using the finite difference method, and the computational results of the model are verified by comparisons with well-known experiments. Turbulent energy, dissipation and Reynolds stress can all be computed with this mathematical model, and the development processes of a large coherent vortex structure over a rippled bed, such as main flow separation, coherent vortex formation and curling, coherent vortex ejection and breaking up, are successfully simulated.

Key words: oscillatory boundary layer flow; anisotropic turbulence model; sand ripples

1. Introduction

Under the influence of surface waves, sand ripples often appear on beaches. When the amplitude of water oscillation is sufficiently large, vortices are formed on the lee of every sand ripple crest. Among these vortices, the most important are turbulence coherent vortex structures, which are effective in dislodging sand particles and keeping them in suspension, and also contribute to the evolution of the ripples themselves, so the turbulence properties and structures of oscillatory flow are of concern to coastal engineering scientists. The flows above natural ripples are usually coupled to the motion of sand; the theoretical analysis is extremely difficult. Past analyses have been mainly conducted by means of the empirical friction factors, and theoretical research has been mostly related to the laminar flow situation only: see Lyne (1970), Sleath (1987), Uda and Hino (1975), Kaneko and Honji (1979), Tanaka and Shuto (1984), and Hara and Mei (1990), for instance.

Studies of the turbulence in wave boundary flow over flat beds have been conducted, and more findings made available from experimental investigations, such as Bagnold (1946), Jonsson (1963), Obremski and Fejer (1967), Kobashi and Hayakawa (1978), Hino et al. (1983), Sleath (1987), and Jensen et al. (1989). Like the experimental and theoretical studies, a large number of numerical modeling studies have been conducted, such as the mixing-length theory, the time-varying viscosity parameters model, the $k\varepsilon$ model, the $k\omega$ model and the LES model. Many researchers used the mix-

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1 Corresponding author. E-mail: ychbai @tju. edu.cn
ing-length theory, such as Brevik (1981) and Myrhaug (1982). Other researchers adopted different models, such as Nielsen (1985) and Davies (1986) using time-varying viscosity parameters model, Hagatun et al. (1986), Thais et al. (1999) and Sana et al. (2002) using the $k\varepsilon$ model, Fredsøe et al. (1999) using the $k\omega$ model, and Liu et al. (2005) using the LES model.

Despite the achievements of those studies, the complexity of oscillatory flows means that it is very difficult to reflect their overall properties by theoretical or experimental methods. The objective of this study is to present an improved turbulence mathematical model for oscillatory boundary layer flow above flat or rippled beds, and provide a numerical method with which the strong shear and anisotropic properties of turbulence can be thoroughly described.

2. Assumptions and Basic Equations

An improved turbulence mathematical model is needed to aid in the understanding of the mechanics of the oscillatory boundary layer flow, especially for modeling the evolution of strong lee coherent vortices. Oscillatory flows over flat or rippled beds are studied, and, because the bed sediment is mainly picked up by the flow in the vertical plane, the flows are simplified as vertical two-dimensional. As oscillatory flows have isotropic properties, an anisotropic turbulence model to investigate them.

2.1 Two-Dimensional Reynolds Averaged Navier-Stokes (RANS) Equations in Vertical Plane

When $U$ and $W$ represent the velocity in the horizontal ($x$-coordinate) and vertical ($z$-coordinate) directions, and $P$ represents the pressure, the Reynolds decompositions are as follows:

\[
\begin{align*}
U &= \overline{u} + u' \\
W &= \overline{w} + w' \\
P &= \overline{p} + p'
\end{align*}
\]

where $\overline{u}$, $\overline{w}$, and $\overline{p}$ are the ensemble-averaged velocities, and $u'$, $w'$ and $p'$ are the fluctuating velocities of turbulence. Substituting Eq. (1) into the Navier-Stokes equations, taking an ensemble-average for them, and replacing the two-dimensional Reynolds correlation quantities matrix with terms $A$, $B$, and $C$ as follows:

\[
\begin{bmatrix}
\frac{u'}{u'} & \frac{w'}{w'}
\end{bmatrix}
= \begin{bmatrix}
A & B \\
B & C
\end{bmatrix}
\]

one has the RANS equations:

\[
\begin{align*}
\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{w}}{\partial z} &= 0; \\
\frac{\partial u}{\partial t} + \frac{\partial (\overline{u}u)}{\partial x} + \frac{\partial (\overline{uw})}{\partial x} &= - \frac{1}{\rho} \frac{\partial \overline{p}}{\partial x} + \nu \left( \frac{\partial^2 \overline{u}}{\partial x^2} + \frac{\partial^2 \overline{u}}{\partial z^2} \right) + \frac{1}{\rho} \left[ \frac{\partial \overline{\omega}}{\partial x} (- \rho A) + \frac{\partial \overline{\omega}}{\partial z} (- \rho B) \right] ; \\
\frac{\partial w}{\partial t} + \frac{\partial (\overline{uw})}{\partial x} + \frac{\partial (\overline{w} w)}{\partial z} &= - \frac{1}{\rho} \frac{\partial \overline{p}}{\partial x} + \nu \left( \frac{\partial^2 \overline{w}}{\partial x^2} + \frac{\partial^2 \overline{w}}{\partial z^2} \right) + \frac{1}{\rho} \left[ \frac{\partial \overline{\omega}}{\partial x} (- \rho B) + \frac{\partial \overline{\omega}}{\partial z} (- \rho C) \right] - g.
\end{align*}
\]

2.2 Turbulence Model Equations

The majority of natural flows are fully or partially turbulent, where the Reynolds number is rela-
tively high, the turbulence structures cannot be resolved numerically by computer, and many computational fluid mechanics researchers use the Reynolds-averaged Navier-Stokes equations. In this framework, the turbulence modeling is one of the most critical aspects of accurate prediction of natural flows. The first turbulence model was the Boussinesq method, which used eddy viscosity coefficients to simulate the Reynolds stress. Then, many kinds of turbulence models were developed, such as the zero-equation model (eddy viscosity coefficients model), the one-equation model (ε-equation model, see Wilcox, 2002), the k-equation model, (see Bradshaw, 1977), the two-equation models, such as the well-known k-ε model, and the multiple-equation models, such as the Reynolds stress model. Among those turbulence models, the k-ε model is very popular for its economy and accuracy in a wide range of flows. However, it performs poorly when used to deal with the nonequilibrium and anisotropic turbulence of boundary layer problems (Menter, 1993), and tends to predict the onset of separation too late and to underpredict the amount of separation. Oscillatory boundary layer flows are precisely that type of situation. Thus, to overcome the difficulties of the strong shear properties in the oscillatory boundary and overcome the deficiencies of turbulence models, we use an anisotropic Reynolds stress transport model. The anisotropic turbulence stress transport model can be written in general as:

$$\frac{D}{Dt} \left[ \begin{array}{c} u' \, u' \, k \\ \epsilon 
\end{array} \right] = \left[ \begin{array}{c} \frac{\partial u'}{\partial x_i} \left[ C_k \, k \, \frac{u'}{u} \, \frac{\partial u'}{\partial x_k} \right] + \frac{\partial}{\partial x_i} \left[ \nu \, \frac{\partial u'}{\partial x_i} \right] + Q_{ij} - \frac{2}{3} \rho \, \frac{\partial \epsilon}{\partial x_j} \\ \frac{\partial}{\partial x_i} \left[ \frac{\partial u'}{\partial x_j} \right] + \frac{\partial}{\partial x_j} \left[ \nu \, \frac{\partial u'}{\partial x_k} \right] + Q_{ij} - \epsilon 
\end{array} \right];$$

(6)

$$\frac{Dk}{Dt} = \left[ \begin{array}{c} \frac{\partial}{\partial x_i} \left[ C_k \, k \, \frac{u'}{u} \, \frac{\partial k}{\partial x_i} \right] + \frac{\partial}{\partial x_i} \left[ \nu \, \frac{\partial k}{\partial x_i} \right] + Q_{ik} - \epsilon 
\end{array} \right];$$

(7)

$$\frac{DE}{Dt} = \left[ \begin{array}{c} \frac{\partial}{\partial x_i} \left[ D \, \epsilon \, k \, \frac{u'}{u} \, \frac{\partial \epsilon}{\partial x_i} \right] + \frac{\partial}{\partial x_i} \left[ \nu \, \frac{\partial \epsilon}{\partial x_i} \right] - G_1 \, \frac{\partial u'}{\partial x_i} \, \frac{\partial \epsilon}{\partial x_i} - G_2 \, \frac{\partial u'}{\partial x_i} \, \frac{\partial \epsilon}{\partial x_i} 
\end{array} \right];$$

(8)

where the parameters are determined as $C_k = 0.01$, $C_1 = 2.3$, $C_2 = 0.4$, $G = 0.07$, $G_1 = 1.44$ and $G_2 = 1.92$, as have been proposed for shear flows (Rodi, 1984; Shima, 1988). The differences between other turbulence models and the isotropic models are mainly in the first terms to the right of the equal-signs, which are the turbulence diffusion terms. The diffusion parameters are related to the turbulence characteristics in every direction of flow, namely $G \, k \, \frac{u'}{u} \, \frac{\partial \epsilon}{\partial x_i}$, and not $G \, k^2 \, \epsilon$ as in isotropic models. $Q_{ij}$ represents the turbulence production, and can be written as:

$$Q_{ij} = - \left[ \frac{\partial u'}{\partial x_i} \, \frac{\partial \epsilon}{\partial x_k} + \frac{\partial u'}{\partial x_k} \, \frac{\partial \epsilon}{\partial x_i} \right];$$

(9)

As $i$, $j$, and $k$ take the values of 1 and 2, and $u' = \bar{u}$, $u' = \bar{w}$, $u' = \bar{u}$, $u' = \bar{w}$, we have the two-dimensional turbulence stresses ($A$, $B$, $C$) transport equations and two-dimensional turbulence energy and dissipation $k$-ε transport equations.
3. Model Validations and Numerical Study on the Structure and Dynamics of Turbulence

3.1 Experiments Chosen for Model Validation

A variety of methods have been used to validate the numerical model and generate confidence in the accuracy of numerical experiments. These fall into four categories: (1) comparison with analytical solutions, (2) internal consistency checks, such as the conservation of mass, momentum, and energy, (3) comparison with experiments, and (4) check against resolution criteria. In relation to the first form of validation, analytical solutions are impossible here due to the complexity of our problem, which is turbulence in oscillatory flow. In relation to the second and fourth forms of validation, our numerical schemes have been applied to the simulation of wave breaking and other oscillatory flows (Bai et al., 2001; Bai and Ng, 2002a, b; Bai et al., 2005), so meeting these two criteria can be guaranteed.

To validate our mathematical model, we choose the third form of validation, namely, comparison with experiments. The experiments of Hayashi and Ohashi (1982), Sleath (1987), and Jensen et al. (1989) for oscillatory bottom boundary flows over flat beds, and of Fredsoe et al. (1999) for oscillatory boundary flow over a ripple-covered bed are selected for the comparison. The situations of the bottom boundary layers are simplified as shown in Fig. 2.

The first experimental study we selected for a smooth flat bed was conducted by Hayashi and Ohashi (1982). Measurements of velocities in the purely oscillatory layer over a horizontal wall were made in a large oscillating water tunnel. In the simulation we used the procedure of periodic ensemble averaging, modified by the application of a finite Fourier series for the estimation of the most probable value of the periodic averages, which gave the separation of periodic components and the turbulence fluctuations. From the decomposed data we obtained the vertical profiles and the time variations, of mean velocities, Reynolds stresses and turbulent energy. We conducted four groups of experiments and selected a complete group from the literature for computational validation. The experimental conditions are given in Table 1.

<table>
<thead>
<tr>
<th>Test</th>
<th>T (s)</th>
<th>$U_0$ (cm/s)</th>
<th>$\omega$ (1/s)</th>
<th>$\lambda$</th>
<th>$\delta$ (cm)</th>
<th>$a$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>9.8</td>
<td>59.0</td>
<td>0.63</td>
<td>439</td>
<td>0.213</td>
<td>93.7</td>
</tr>
</tbody>
</table>

In Table 1, $T$ is the period of oscillatory motion, $U_0$ is the free stream velocity amplitude, $\omega$ is the radian frequency, $\lambda$ is the Stokes parameter and $\lambda = (U_0/2) (2\nu/\omega)^{1/2}/\nu$, $\delta$ is the Stokes-layer thickness and $\delta = (2\nu/\omega)^{1/2}$, and $a$ is the free steam amplitude.

The second experimental study we selected for rough flau beds was conducted by Sleath (1987). In his experiment, velocity measurements were presented for turbulent oscillatory flow over rough beds in an oscillatory-flow water tunnel. Two components of velocity were measured with a laser Doppler anemometer, and the rough beds consisted of a single layer of sand, gravel or pebbles on a flat sur-
face. Nineteen groups of experiments were conducted, and turbulence intensities and Reynolds stress were obtained. We selected some relatively complete data groups for our computational validation. The experimental conditions are given in Table 2.

<table>
<thead>
<tr>
<th>Test</th>
<th>T (s)</th>
<th>(U_0) (cm/s)</th>
<th>(v \times 10^6) (m²/s)</th>
<th>(a/ k_s)</th>
<th>(h_s) (cm)</th>
<th>(h_s/ u_3)</th>
<th>(f_w)</th>
<th>(\delta) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4.54</td>
<td>68.6</td>
<td>1.21</td>
<td>151</td>
<td>2.26</td>
<td>1.73</td>
<td>0.0161</td>
<td>2.35</td>
</tr>
<tr>
<td>4</td>
<td>4.58</td>
<td>61.7</td>
<td>1.193</td>
<td>138</td>
<td>2.13</td>
<td>1.66</td>
<td>0.0158</td>
<td>2.35</td>
</tr>
</tbody>
</table>

In Table 2, \(v\) is the kinematic viscosity, \(k_s\) is the Nikuradse roughness size, \(f_w\) is the friction coefficient, \(u_3\) is the friction velocity, \(h_s\) is the amplitude of friction velocity, \(T\) is the period of oscillation, \(U_0\) is the free stream velocity amplitude, \(\delta\) is the Stokes layer thickness, and \(a\) is the free stream amplitude.

The third experiment we selected for rough flat beds was conducted by Jensen et al. (1989). Their experiment dealt with turbulent oscillatory boundary-layer flows over both smooth and rough flat beds. The free-stream flow was a purely oscillating flow with sinusoidal velocity variation. Mean and turbulent properties were measured mainly in two directions, streamwise and perpendicular to the bed. Some measurements were also made in the transverse direction. The measurements were carried out up to \(Re = 6 \times 10^6\) over a mirror-shine smooth bed and over rough beds with various values of the parameter \(a/ k_s\), from approximately 400 to 3700. The experiments were carried out in a U-shaped oscillatory-flow water tunnel. We select four groups of experiment data for the validation of our computational model; two groups for smooth beds and two for rough beds. The experiment conditions are given in Table 3.

<table>
<thead>
<tr>
<th>Test</th>
<th>T (s)</th>
<th>(U_0) (cm/s)</th>
<th>(a) (m)</th>
<th>(v \times 10^6) (m²/s)</th>
<th>(a/ k_s)</th>
<th>(Re = aU_0/\nu)</th>
<th>(u_3) (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>9.72</td>
<td>102</td>
<td>1.58</td>
<td>1.14</td>
<td>-</td>
<td>1.6 \times 10^6</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9.72</td>
<td>200</td>
<td>3.10</td>
<td>1.14</td>
<td>-</td>
<td>6 \times 10^6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test</th>
<th>T (s)</th>
<th>(U_0) (cm/s)</th>
<th>(a) (m)</th>
<th>(v \times 10^6) (m²/s)</th>
<th>(a/ k_s)</th>
<th>(Re = aU_0/\nu)</th>
<th>(u_3) (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14</td>
<td>8.12</td>
<td>87.0</td>
<td>1.13</td>
<td>1.14</td>
<td>435</td>
<td>9.0 \times 10^6</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>8.12</td>
<td>210</td>
<td>2.71</td>
<td>1.14</td>
<td>730</td>
<td>5.2 \times 10^6</td>
</tr>
</tbody>
</table>

The fourth experiment we selected for a ripple-covered bed was conducted by Fredsøe et al. (1999). The experiment, which concerned the combined wave and current boundary layer flow over a rippled bed, comprised laser Doppler anemometry velocity and turbulence measurements, and a flow
visualization study in the laboratory with ripples, 22 cm in length, and 3.5 cm in height. One wave-alone, three current-alone, and three waves and a current combined tests were conducted. The experiments were carried out in a wave flume, the bed of which was covered with ripples. We select the wave-alone case and the waves and current combined case for the studied with our present numerical model. The experimental conditions are given in Table 4.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Test conditions for the fourth fundamental case, the wave-alone case</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>$D_h = 42$, water depth measured from ripple crest (cm)</td>
</tr>
<tr>
<td></td>
<td>$U_0 = 24.2$, $a = 9.6$</td>
</tr>
<tr>
<td>WC1</td>
<td>$D_h = 41.5$, water depth measured from ripple crest (cm)</td>
</tr>
</tbody>
</table>

3.2 Structure and Dynamics of Turbulence Oscillatory Boundary Layer Flow over Flat Beds

3.2.1 Definition of Wave Bottom Boundary Layer

The definition of the wave bottom boundary layer over a smooth bed is given in Fig. 1a and that of the wave bottom boundary layer over a rough bed in Fig. 1b. The wave boundary layer is generally simplified as an oscillatory boundary layer for theoretical analysis, so the outer stream flow is also seen as a periodic oscillatory flow. For the rough bed, the theoretical bed position is generally set at $z_0 = k_s/30$, where $k_s$ is Nikuradse’s equivalent sand roughness and generally $k_s = 2.5D$, $D$ being the diameter of the bed sediment.

3.2.2 Characteristic Values of the Wave Bottom Boundary Layer

To study the wave boundary layer motion, we mainly use the following characteristic values: $U_m$, the oscillatory flow velocity; $T$, the periodic time of oscillation; $k_s$, Nikuradse’s equivalent roughness; $\nu$, fluid viscosity; and $U_c$, the unidirectional current velocity in the wave and current combined.

There are two basic values in the above five: the time and spatial scale values. The amplitude of fluid particles can define the character length $a = U_m T/ (\Pi)$. In the wave-alone situation three parameters can be used for description, such as the Reynolds number $Re_a = aU_m/\nu$, water depth $h$ and equivalent roughness $k_s$. When full turbulence has been developed, the effect of the Reynolds number is no longer important; if the wave and current combined situation is considered, $U_c / U_m$ should be used instead to reflect the intensity of water current.
Fig. 1a. Oscillatory flow over a smooth flat bed (Hayashi and Ohashi, 1982).

Fig. 1b. Oscillatory flow over a rough flat bed (Sleath, 1987; Jensen et al., 1989).

3.2.3 Numerical Model Validation for A Flat Bed

1) The model results for the smooth flat bed are compared with the experiments conducted by Hayashi and Ohashi (1982), as shown in Fig. 2a.

2) The model results are compared with Sleath’s (1987) experiments, as shown in Fig. 2b. The computed velocities and the experimental velocities basically agree with each other in the acceleration and deceleration phases.

3) The model results are compared with those of Jensen et al.’s (1989) experiments, as shown in Fig. 2c.

Fig. 2a. Comparisons of the computed results of velocity profiles in the acceleration or deceleration phases with those of Hayashi and Ohashi (1982).

3.2.4 Dynamics of Turbulence in Oscillatory Boundary Layer Flow over Flat Beds

To verify the turbulence model, we also compared the computed results and measured values of the turbulence properties in oscillatory flows; however, due to space limitations, we only compare the results with those of Hayashi and Ohashi (1982).
Fig. 2b. Comparisons of the computed results of the velocity profiles in the acceleration or deceleration phases with the Sleath (1987) experimental results.

Fig. 2c. Comparison of the computed results of velocity in the acceleration or deceleration phase with those of Jensen et al. (1989).
Fig. 3 compares the computed results of the turbulent energy in different phases with those of Hayashi and Ohashi (1982). Fig. 4 compares the computed results of the turbulent shear stresses in different phases with those of the same study. The comparisons of these groups of computed results with the experimental results indicate good consistency between them, which also proves that the present numerical model can forecast and reflect the configurations of oscillatory bottom boundary layer flows.

**Fig. 3.** Comparisons of the computed results of turbulent energy in different phase with those of Hayashi and Ohashi (1982).

### 3.3 Structure and Dynamics of Turbulence in Oscillatory Boundary Layer Flow over Rippled Beds

#### 3.3.1 Rippled Bed Shapes in Waves or Oscillatory Flows

Under the effects of oscillatory flow, there are many configurations and multifarious equilibrium sections and scales of sand ripples, and these characteristics of sand ripples can transform each other in some regions. However, they can be reduced to two kinds of typical sand ripples: rolling ripples, which exist in the initial stage of formation and are very unstable, and vortex ripples, also called orbital ripples by Bagnold (1946) because the ripple wavelength is a function of the particle orbital motion. The sectional figure of a vortex ripple appears as a triangle, with two very smooth side slopes. The flow characteristics surrounding the vortex ripple are determined by the intensity of the eddy pr-
duced on the lee of the sand ripple and the sediment transport is realized as the sand particles roll from one side to the other side, making the sand ripple move ahead constantly. Vortex ripples exist in seashore areas, and decide the bed resistance and wave attenuation.

The flow structures over sand ripples are very complex and include the entire process of the surrounding flow such as flow separation, eddy production and evolution and breaking up. For this reason, understanding the structures of flow around the ripples is of utmost importance in studying the formation of vortex sand ripples. To understand these subtle flow structures, theoretical methods are inadequate; they must be investigated through experimental methods or refined turbulence models. In this paper, we use the inverse method.

3. 3. 2 Oscillatory Flow or Wave Boundary Layer Flow over Sand Ripples

For the investigation of the bottom layer dynamics, it is necessary to analyze the characteristic quantities of sand ripples under the wave or oscillatory flow. As Fig. 2(c) shows, the following quantities must be considered: \( \lambda \), the wavelength of the sand ripple; \( H \), the height of the sand ripple; \( h \), the water depth.

There are two basic dimensions in the above quantities: the time and spatial scales. The amplitude of fluid particles is the characteristic length \( a = U_m T / (2\pi) \), and the sand ripples can be characterized by \( \lambda / a \) and \( H / \lambda \). The following parameters are used to describe different situations such as flat beds or waves alone: the Reynolds number \( R_{ca} = a U_m / \nu \), water depth \( h \), equivalent roughness \( k_s \), and characteristic values of sand ripples \( \lambda / a \) and \( H / \lambda \). When full turbulence has been developed, the effect of the Reynolds number is no longer important. If we consider the situation of wave and current combined, the parameters \( U_c / U_m \) and \( h / a \) should be included to reflect the intensities of water current and waves, respectively.

3. 3. 3 Model Validations for Oscillatory Boundary Layer Flow over Rippled Beds

To validate the numerical model for flow over rippled sand beds, we compare the numerical re-
sults with those of Fredsoe et al. (1999), the conditions of which can be found in Table 4. The experiments were carried out in a wave flume of 0.6 m in width, 0.8 m in depth and 28 m in length. The bed of the flume was covered with ripples. The experiments were carried out for three situations: (1) current-alone experiment, (2) wave-alone experiment, and (3) wave and current combined experiment. We selected various situations for simulation; the velocity measurements were carried out at four vertical sections on the centerline of the flume, as shown in Fig. 5b. For the present problem, we choose three sand ripples as the length of the computational domain (see Fig. 5a), which is larger than that reported by Fredsoe et al. (1999), so our simulation should produce much better results.

Fig. 5. a) Computational area for flow over sand ripples. b) Measurement sections.

Using the data in Tables 4a and 4b, we conducted numerical simulation studies for the flow structures of the current-alone and wave-alone situations. Fig. 6 compare the results of the measured velocity and numerical velocity profiles for pure currents. All the numerical velocity profiles agree well with the measured profiles for the four typical experimental sections.

These comparisons show that, for all the cases, the numerical and experimental data agree with each other well, except for the small difference for a certain water depth during some phases. Hence, the present numerical model can be used to study the characteristics of flow close-by rippled sand beds under oscillatory or unidirectional currents.

3. 3. 4 Oscillatory Boundary Layer Flow over Rippled Beds Under Wave and Current Combined

The flow structure around a sand ripple is more complex under waves and currents. Fig. 7 shows the flow fields and vortices, where the velocity ratio of current to wave is $U_c / U_m = 1:2$. In the first half of the period, the velocity directions of the wave and current are consistent, so a strong flow will form in the outer layer and there will be large eddies; but in the second half of the period, the velocity directions of the wave and current are opposite, so the combined flow will diminish, and the vortex will form but it will be weaker than that in the wave-alone case. In the time of flow reversal, all of these vortices will move across the sand ripple, enter the main flow zone, and then break and disappear.

A sequence of photographs from Fredsoe et al. (1999) that illustrate the motion of the lee-wake vortex during approximately one wave period are shown in Fig. 8. The flow field and vortex contour lines shown in Fig. 7 are found to agree very well with the corresponding ones shown in Fig. 8. Therefore, the experimental and numerical flow field and vortex development processes are basically consis-
Fig. 6. Comparisons of numerical and measured results under current alone.

4. Conclusions

A numerical model for oscillatory boundary layer flow over a flat or rippled bed has been set up by introducing an anisotropic turbulence stress transport model, the effectiveness and reliability of which have been verified by comparison with experiments. The turbulence and vortex in flows over flat or rippled beds have been studied in detail.

Owing to the strong shear and flow separation in an oscillatory boundary layer flow, the anisotropic turbulence stress transport model may be more appropriate than other turbulence models in simulating the oscillatory flow. Our modeling results also show the process of vortex development as a function of
Fig. 7. Comparison of computational flow field and vortex in the wave and current combined situation with those of the Fredsoe et al. (1999), unit: 2 cm.
The flow over sand ripples will separate as it moves over the ripple crest. With the increasing velocity of the outer layer, the vortex structure produced due to separation will expand rapidly, and its maximum structure will not correspond to the maximum velocity of the outer free stream.

The whole process of the formation, evolution, and disappearance of the vortex takes place during one wave period, and can be described as follows. With an increase in the oscillatory flow velocity, strong rotation is produced after the flow moves over the ripple crest, then the separation vortex grows gradually from the ripple crest and reaches its maximum value shortly after the free stream begins to decelerate, when the oscillation phase is about $\omega t = 150^\circ$. During this time, even though the outer flow begins to decelerate, the separation of the vortex still expands and it is transported to the next ripple. After a while, the vortex curls up into the main flow, but it maintains the strong rotation. As the outer flow reverses, the separation vortex is lifted away from the ripple crest, and then ejected into the outer flow where it becomes a large free vortex; this vortex is thereby called a coherent vortex. Then, the next flow separation begins on the lee side of the ripple; at the same time, the former ejected vortex breaks up gradually in the outer flow.

The computational modeling shows that the effect of unidirectional current on the boundary layer is related to the velocity ratio of the free stream flow to the maximum oscillatory flow; however, when the ratio is smaller than 0.25, such as $U_c/Um < 0.25$, the flow structure for the combined wave and current is similar to that for the wave alone.

References


