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Mean Current Profile over Rippled-Beds in the Presence of Non-Breaking Waves and Analysis of Its Influencing Factors

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Abstract: Classical eddy viscosity model deviates from the actual mean current profiles, when calculating the mean current profiles over rippled-beds in the presence of non-breaking waves, owing to the neglect of the enhancement of the wave boundary layer thickness by ripples and the wave-induced shear stress (the radiation stress and the wave Reynolds stress). Considering these shortcomings, a semi-empirical one-dimensional vertical (1DV) model is presented in this study. The present model was obtained using the two-dimensional Navier–Stokes equations and eddy viscosity assumptions, which differ from those of previous researchers, while a top-to-bottom sequence was adopted to calculate the mean current profiles. Empirical formulae were derived from the laboratory measurements and used in the present model to accurately predict the wave boundary layer thickness and bed roughness. The present model is in satisfactory agreement with the data from laboratory experiments. The factors influencing the mean current profiles were analyzed also. The wave-induced second-order shear stresses were found to be the principal reason for the deviations of the mean current profiles in the near-surface layer; as the influencing factors of wave-induced shear stress, the intensity of the wave relative to the current, the angle between the wave and current, and the size of ripples can also have a non-negligible effect on the mean current profiles.

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Keywords: one-dimensional vertical model; rippled-bed; mean current profile; laboratory measurements; wave-induced shear stress

1. Introduction

Fluid motion in combined wave and current conditions is a predominant dynamic driving force of sediment movement in estuarine and coastal areas [1,2]. The wave boundary layer (WBL) is a thin layer where waves, currents, and the bed interact, and the fluid motion within the layer governs sediment resuspension, transport, and the evolution of the bed forms [3]. Therefore, the study of the hydrodynamic characteristics near the bottom in combined wave-current conditions is of great significance for the study of sediment transport; moreover, the shifting of coastline and beach profile evolution has received wide attention from researchers [4–6].

Bed forms and bed roughness have significant effects on bed shear stress, flow structure and sediment concentration in the vicinity of the bed. Flat beds and rippled beds are two common bed forms in combined wave-current flows, and they transform into each other under different dynamic conditions. Ripples appear when dynamic conditions are relatively weaker, and these ripples will be eroded with increased dynamics, resulting in the formation of flat beds, which present a high-intensity sheet flow [7]. Physical bed roughness, k_s (equivalent Nikuradse roughness or briefly the hydraulic roughness) is directly defined as the roughness, which is determined from the structure of a purely steady flow over the bed [8]. In Van Rijn [9], k_s is determined by fitting a logarithmic distribution to the near-bed flow velocities measured under current alone conditions, and the values of k_s were found to be approximately 3–7 times the ripple height. The presence of waves leads to an intensified near-bottom turbulence effect, which can be characterized by introducing an

“apparent” bed roughness, k_a ; this can be exhibited by the current velocity profile outside the wave boundary layer [10]. Apparent bed roughness is similar to an enhanced physical bed roughness. The existence of such enhanced roughness was confirmed in several prior studies [10–13].

Laboratory experiments are the primary means of studying hydrodynamic properties and sediment transport within and outside the WBL; however, the data provided by laboratory experimental measurements are limited and need to be supplemented by mathematical models. In recent decades, many one-dimensional vertical (1DV) wave-current boundary layer models have been developed, and these models can be classified into theoretical and numerical models. Theoretical models, also called zero-equation models or eddy viscosity models, use assumed eddy viscosity to close the fluid momentum equation, including models that use time-invariant eddy viscosities and time-variant eddy viscosities. Models using time-invariant eddy viscosities such as Grant and Madsen [14] (hereinafter GM model), Christoffersen and Jonsson [15] (hereinafter CJ model), Styles and Glenn [16,17] (hereinafter SG2000 and SG2017 model), and You [18] (hereinafter You model) and models using time-variant eddy viscosities such as Trowbridge and Madsen [19], and Foster et al. [20]. Time-variant eddy viscosity models allow for manifold vertical modes that simulate more realistic flows in association with real waves. However, the above two models did not investigate the combined flow conditions because of the assumption of the dominance of wave on current [21]. Numerical models include one-equation and two-equation models. One-equation models, also called mixing length models, use the turbulence kinetic energy and dynamic mixing length to represent the eddy viscosity, as in Davies et al. [22], and Soulsby et al. [23]. Two-equation models, including k - ε models and k - ω models, use the turbulent kinetic energy and turbulent kinetic energy dissipation rate to represent the eddy viscosity, as in [24–27]. Among these, [27] used the k - ε model to study the characteristics of hydrodynamics and sediments in flat beds and rippled-beds, and proposed toe-shaped wave eddy viscosities based on the results of the 1DV model.

To study the hydrodynamic characteristics in a combined wave-current flow, it is simpler to use a zero-equation model to close the fluid momentum equation because the one-equation and two-equation models require complex iterations and calculations. There are several problems with the classical time-invariant eddy viscosity models: (1) It has been found that the presence of ripple-beds leads to an enhanced wave boundary layer thickness [13]. However, the GM, CJ, SG2000, SG2017 and You models do not consider this effect, resulting in the predicted values of the wave boundary layer thickness being significantly smaller than the estimated values obtained from the laboratory experimental measurements; (2) GM, CJ, SG2000, SG2017 models all assume that eddy viscosities felt by waves and currents within the WBL are the same. However, You et al. [28] derived the expressions of eddy viscosities felt by waves and currents, which were qualitatively analyzed and concluded that the magnitude and vertical distribution of the eddy viscosity felt by waves and currents should not be the same; (3) GM, CJ, SG2000 and SG2017 models neglect the effects of the radiation stress and the wave Reynolds stress. Therefore, in order to modify the shortcomings of the above 1DV models, new 1DV models need to be researched and developed.

In this study, considering the problems of the above classical models, a semi-empirical 1DV model is presented to calculate the mean current profile over the rippled beds in the presence of non-breaking waves while considering the wave-induced shear stress term. The wave boundary layer thickness, physical bed roughness, and apparent bed roughness for the proposed model are discussed. The present model and available measurement data were found to be in good agreement. Moreover, the present model was found to be more accurate than the SG2017 model. Finally, the influencing factors of the mean current profile over the rippled beds in the presence of non-breaking waves were studied by analyzing the data from the laboratory experimental measurements.

2. Materials and Methods

2.1. Governing Equations

Neglecting the effects of Coriolis force and kinematic viscosity (the kinematic viscosity of water is relatively small), and assuming the fluid is homogeneous in the horizontal direction and incompressible, the Navier–Stokes equations for the horizontal and vertical velocities are as follows:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial x} \quad (1)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial z} - g \quad (2)$$

The continuity equation reads:

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \quad (3)$$

where u and w both are the instantaneous velocities in the horizontal and vertical directions, respectively; P is the pressure; ρ is the fluid density; and g is the gravity constant.

Using the continuity equation, the momentum equations can be derived from the Navier–Stokes equations:

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uw}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial x} \quad (4)$$

$$\frac{\partial w}{\partial t} + \frac{\partial wu}{\partial x} + \frac{\partial w^2}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial z} - g \quad (5)$$

Suppose (x, z) is a right-angle coordinate system located at the bottom, the x -axis is the direction of wave propagation and the z -axis is vertically upward. The velocities $u(x, z, t)$, $w(x, z, t)$, and pressure $P(x, z, t)$ are divided into three parts, namely the steady, periodic, and turbulent components, respectively:

$$u(x, z, t) = \bar{u}(x, z) + \tilde{u}(x, z, t) + u'(x, z, t) \quad (6)$$

$$w(x, z, t) = \bar{w}(x, z) + \tilde{w}(x, z, t) + w'(x, z, t) \quad (7)$$

$$P(x, z, t) = \bar{P}(x, z) + \tilde{P}(x, z, t) + P'(x, z, t) \quad (8)$$

According to [8], the steady, periodic, and turbulent components in Equations (6)–(8) can be defined restively as:

$$\bar{\xi}(x, z) = \lim_{t \rightarrow \infty} \frac{1}{t} \int_0^t \xi(x, z, t) dt \quad (9)$$

$$\tilde{\xi}(x, z, t) = \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N [\xi_i(x, z, t + iT) - \bar{\xi}(x, z)] \quad (10)$$

$$\xi'(x, z, t) = \xi(x, z, t) - \bar{\xi}(x, z) - \tilde{\xi}(x, z, t) \quad (11)$$

where T is the wave period, t is the time, N is the number of waves, and ξ can be substituted with u , w , and P . According to [8], if any two components of u , w , P are represented by f and g , the relationship between f and g is satisfied as follows:

$$\overline{f'g} = \overline{f'g} = \overline{fg'} = \overline{fg'} = 0 \quad \overline{f} = \bar{f} \quad (12)$$

$$\widetilde{f'g} = \widetilde{f'g} = \widetilde{fg'} = \widetilde{fg'} = 0 \quad \widetilde{f} = \tilde{f} \quad (13)$$

The time-averaged momentum equations in the horizontal and vertical directions can be obtained by substituting Equations (6)–(8) into Equations (4) and (5), respectively, and by using Equation (9), that is, the definition of time averaging and Equation (12).

$$\frac{\partial(\overline{u^2} + \overline{u'^2})}{\partial x} + \frac{\partial(\overline{u\tilde{w}} + \overline{u'w'})}{\partial z} = -\frac{1}{\rho} \frac{\partial \bar{P}}{\partial x} \quad (14)$$

$$\frac{\partial(\overline{u\tilde{w}} + \overline{u'w'})}{\partial x} + \frac{\partial(\overline{w^2} + \overline{w'^2})}{\partial z} = -\frac{1}{\rho} \frac{\partial \bar{P}}{\partial z} - g \quad (15)$$

where $\partial \bar{u} / \partial x = 0$, $\bar{w} = 0$, according to the assumption of homogeneity of the fluid [29]. Assuming that the first term is much smaller than the second term and can be neglected, the time-averaged pressure at an arbitrary level can be derived from Equation (15):

$$-\frac{1}{\rho} \bar{P} = g(h + \bar{\eta} + z) + (\overline{w^2} + \overline{w'^2}) \quad (16)$$

where $\bar{P}|_{z=0} = \rho g(h + \bar{\eta})$, according to the hydrostatic approximation. Where $\bar{P}|_{z=0}$ is the time-averaged pressure at the bed, h is the local mean depth, $\bar{\eta}$ is the mean surface elevation. Substituting Equation (16) into Equation (14), the following Equation (17) can be obtained:

$$-\frac{\partial(\bar{\tau}_{xz})}{\partial z} = \frac{\partial[(\overline{u^2} - \overline{w^2}) + (\overline{u'^2} - \overline{w'^2})]}{\partial x} + g \frac{\partial \bar{\eta}}{\partial x} \quad (17)$$

where the total shear force per unit cross-sectional area $\bar{\tau}_{xz}$ is defined as:

$$\bar{\tau}_{xz} = -\rho(\overline{u\tilde{w}} + \overline{u'w'}) \quad (18)$$

Based on the lab measurements from [30], $(\overline{u'^2} - \overline{w'^2})$ is typically much smaller than $(\overline{u^2} - \overline{w^2})$ and can be neglected in Equation (17). Thus, Equation (19) can be derived from Equation (17) as:

$$-\overline{u'w'} = g \frac{\partial \bar{\eta}}{\partial x} z + \frac{1}{\rho} \bar{\tau}_0 + \int_0^z \frac{\partial(\overline{u^2} - \overline{w^2})}{\partial x} dz + \overline{u\tilde{w}} \quad (19)$$

where $\bar{\tau}_0 = \bar{\tau}_{xz}|_{z=0}$ represents the mean bed shear stress. The effects of wind and the second-order terms caused by the radiation stress in the direction of wave propagation are ignored. $\bar{\tau}_0$ can be determined from Equation (20) on the basis of [31]:

$$\bar{\tau}_0 = -\rho g h \frac{\partial \bar{\eta}}{\partial x} \quad (20)$$

In addition, $\bar{\tau}_0$ can be expressed in terms of u_{*c} [29], where u_{*c} represents the current shear velocity.

$$\bar{\tau}_0 = \rho u_{*c}^2 \quad (21)$$

The last two terms in Equation (19) are the wave-induced second-order stress terms. Based on the linear wave theory,

$$\tilde{u} = \frac{\pi H}{T} \frac{\cosh(kz)}{\sinh(kh)} \cos(kx - \omega t) \tilde{w} = \frac{\pi H}{T} \frac{\sinh(kz)}{\sinh(kh)} \sin(kx - \omega t) \quad (22)$$

$$\int_0^z \frac{\partial(\overline{u^2} - \overline{w^2})}{\partial x} dz = \int_0^z \frac{\partial H}{\partial x} \frac{H \omega^2}{4 \sinh^2(kh)} dz = -S_1 z \quad (23)$$

where H is the wave height, T is the wave period, k is the wave number, and ω is the radian frequency. S_1 is a constant that is always positive. Term $\overline{u'w'}$ in Equation (19) is the wave Reynolds stress. Several studies have focused on investigating the vertical distribution of the wave Reynolds stress by numerical simulation and lab measurements [29,32–34]. By analyzing the lab measurements, [29] found that the vertical distribution of $\overline{u'w'}$ is approximately linear, and $\overline{u'w'}$ can be represented by

$$\overline{u'w'} = -S_2 z \quad (24)$$

In which, S_2 is a constant that is always positive. Therefore, the wave-induced stress in Equation (19) can be rewritten as

$$\int_0^z \frac{\partial (\overline{u'^2} - \overline{w'^2})}{\partial x} dz + \overline{u'w'} = -Sz \quad (25)$$

where $S = S_1 + S_2$, $-Sz$ represents the wave-induced second-order stress.

Substituting Equations (20), (21), (25) to Equation (19), becomes

$$-\overline{u'w'} = u_{*c} |u_{*c}| (1 - z/h) - Sz \quad (26)$$

Turbulent Reynolds stresses are expressed as the product of an isotropic current eddy viscosity [8]:

$$-\overline{u'w'} = K_c \frac{\partial \overline{u}}{\partial z} \quad (27)$$

where K_c is the current eddy viscosity. By substituting Equation (26) into Equation (27), Equation (27) can be rewritten as

$$\frac{\partial \overline{u}}{\partial z} = \frac{1}{K_c} [u_{*c}^2 (1 - z/h) - Sz] \quad (28)$$

2.2. Bed Form and the Bed Roughness

The momentum transfer of fluid and associated sediment dynamics in the near-bed layer are dominated by periodic vortex structures over ripple beds; above this layer, the periodic vortex structures collapse and are replaced by random turbulence [35,36]. It has been suggested by [35] that the height of the vortex layer is approximately twice the ripple height. It was pointed out in [8,37] that the vertical structure of wave velocity is similar to laminar flow in considerably rough flows, such as over a ripple bed. Therefore, the wave eddy viscosity over the rippled-beds can be set to a constant value. The flow in the combined wave-current motion over ripple beds is shown in Figure 1. The physical bed roughness k_s and apparent bed roughness k_a in the presence of ripples are discussed in Section 3.2. Ripples wash out in strong flows. [38] showed that a significant concentrated near-bed sediment layer develops over rippled-beds in strong flows and increases the value of k_s . However, this effect is negligible in moderate flows and was not considered in the present model.

Figure 1. Physical conceptual diagram of flow in combined wave-current motion over ripples (after [39]).

2.3. Eddy Viscosities

Assuming current eddy viscosity and wave eddy viscosity are different. Based on the pseudo-laminar eddy viscosity model introduced in [39], the wave eddy viscosity K_w can be represented as

$$K_w = 180 \frac{\eta^4}{\lambda^2 T} \quad (29)$$

To determine the current velocity distribution within and outside the wave boundary layer, there are three type of current eddy viscosities:

$$K_c = \kappa u_{*cw} z \left(1 - \frac{z}{h}\right) \quad z > \delta_1 \quad (30)$$

$$K_c = \frac{1}{m} \kappa u_{*cw} \delta_1 \quad \delta < z \leq \delta_1 \quad (31)$$

$$K_c = \frac{1}{m} \kappa u_{*cw} z \quad z \leq \delta \quad (32)$$

where u_{*cw} is the characteristic shear velocity within the wave boundary layer and reflects the combination of the maximum shear stress for the wave and current [14]. In order to make the current velocity profile continuous, a scaling parameter m was added. δ is the thickness of the wave boundary layer and the value of δ will be discussed in Section 3.1. δ_1 represents the height of the transition layer. According to [17], the relationship between δ_1 and δ is as follows:

$$\frac{\delta}{\delta_1} = 1 + \beta \frac{k_b}{A_b} \quad (33)$$

where, k_b is the bed roughness in the presence of waves over ripple beds, which equals to 6.4η . A_b is the semi-excursion amplitude. $\beta = 0.3$ is an empirical coefficient. The distributions of the wave and current eddy viscosities are shown in Figure 2.

Figure 2. The distributions of the eddy viscosities (a) Wave eddy viscosity; (b) Current eddy viscosity.

2.4. Solutions of $\bar{u}(z)$ and $\tilde{u}(z)$

2.4.1. Solution of $\bar{u}(z)$

By combining Equations (28) and (30) and using boundary conditions, the current velocity distribution outside the transition layer can be obtained:

$$\bar{u} = \frac{u_{*c}}{\kappa} \ln \frac{z}{z_{0a}} + \int_{z_{0a}}^z \frac{-Sz}{\kappa u_{*c} z (1 - z/h)} dz \quad (34)$$

where $z_{0a} = k_a/30$. Assuming $z_{0a} \ll h$, Equation (34) can be rewritten as:

$$\bar{u} = \frac{u_{*c}}{\kappa} \ln \frac{z}{z_{0a}} + \frac{Sh}{\kappa u_{*c}} \ln(1 - z/h) \quad z > \delta_1 \quad (35)$$

The current velocity distribution within the transition layer and the wave boundary layer can be obtained by combining Equations (28) and (31), (32) and using boundary conditions:

$$\bar{u} = m \left[\frac{u_{*c}^2}{\kappa u_{*cw}} \ln \left(\frac{z}{z_0} \right) - \frac{\frac{u_{*c}^2}{h} + S}{\kappa u_{*cw}} (z - z_0) \right] \quad z_0 \leq z \leq \delta \quad (36)$$

$$\bar{u} = m \left[\frac{u_{*c}^2}{\kappa u_{*cw} \delta} (z - \delta) - \frac{\frac{u_{*c}^2}{h} + S}{2\kappa u_{*cw} \delta} (z^2 - \delta^2) \right] + \bar{u}(\delta) \quad \delta \leq z \leq \delta_1 \quad (37)$$

where $z_0 = k_s/30$, and $\kappa = 0.4$ is the Von Kármán number. The formulae for z_0 and z_{0a} are presented in Section 3.2.

By adopting the top-to-bottom calculation sequence, the current distribution above the transition layer can first be calculated using Equation (35). The value of the scaling parameter, m , can be calculated by substituting $z = \delta_1$ into Equations (35) and (37) respectively, and making $\bar{u}$ calculated by Equations (35) and (37) equal. Further, the current velocity distribution within the transition layer and the wave boundary layer can be calculated using Equations (36) and (37).

Based on [29], the value of S in Equation (35) can be established by a reference current velocity $\bar{u}_r$ and a reference height z_r where $\bar{u}_r$ is located:

$$S = \frac{\kappa u_{*c} (\bar{u}_r - \frac{u_{*c}}{\kappa} \ln \frac{z_r}{z_{0a}})}{h \ln(1 - z_r/h)} \quad (38)$$

2.4.2. Solution of $\tilde{u}(z)$

The solution of $\tilde{u}(z)$ is analogous to the solution of velocity in the laminar boundary layer:

$$\tilde{u} = \left(1 - e^{-(1+i)z/\delta'}\right) u_b e^{i\omega t} \quad (39)$$

where u_b is the free-stream wave orbital velocity, $\delta' = \sqrt{2K_w/\omega}$, K_w can be calculated using Equation (29).

2.5. Shear Velocities and Wave Friction Factor

See equation below:

$$\tau_{wm} = u_{*wm}^2 = \frac{1}{2} f_w C_R \rho u_b^2 \quad (40)$$

where f_w is the wave friction factor, C_R is a parameter that indicates the enhancement of the currents by waves. The relationship between u_{*cw} and wave shear velocity u_{*wm} can be established by C_R :

$$u_{*cw}^2 = C_R u_{*wm}^2 \quad (41)$$

where C_R can be expressed as

$$C_R = \left[1 + 2 \left(\frac{u_{*c}}{u_{*wm}} \right)^2 \cos \varphi_{cw} + \left(\frac{u_{*c}}{u_{*wm}} \right)^4 \right]^{\frac{1}{2}} \quad (42)$$

where $\varphi_{cw} (0^\circ \leq \varphi_{cw} \leq 90^\circ)$ is the angle between the mean current and wave.

The maximum shear stress for wave τ_{wm} can also be expressed as

$$\frac{\tau_{wm}}{\rho} = u_{*wm}^2 = K_w \frac{\partial \tilde{u}}{\partial z} = K_w \frac{u_b}{\eta} \Gamma_{ws} \quad (43)$$

where Γ_{ws} is the dimensionless wave shear. On the basis of Equation (39), Γ_{ws} can be represented as

$$\Gamma_{ws} = \frac{\eta}{u_b} \frac{\partial \tilde{u}}{\partial z} = \eta \left| e^{-(1+i)z/\delta'} \cdot \frac{1+i}{\delta'} e^{i\omega t} \right| \quad (44)$$

The expression of wave friction factor f_w can be obtained by combining Equations (40), (43) and (44):

$$f_w = \frac{K_w}{\eta} \tau_{ws} \frac{C_R}{u_b} \quad (45)$$

2.6. Solution Procedure

To calculate the mean current profile, the input parameters of the present model used are as follows: λ , η , u_b , a_b , u_c , $\bar{u}_r$, z_r , and a set of estimates for u_{*c} and u_{*cw} . The solution procedure was similar to that in [16].

1. The initial C_R was equal to 1. The value of u_{*wm} can be calculated by Equation (40), then a new value of C_R can be obtained by substituting u_{*c} and u_{*wm} into Equation (42). The value of u_{*cw} can be derived by substituting C_R and u_{*wm} into Equation (41).
2. Repeat step (1) until u_{*cw} converges. This is the inner loop.
3. Calculate the mean current profile using Equations (35)–(37). If the calculated value of $\bar{u}(z_r) \neq \bar{u}_r$, then the process from step (1) is repeated with a new u_{*c} until the calculated $\bar{u}(z_r)$ is equal to $\bar{u}_r$. This is the outer loop.

The value of u_{*c} can be corrected iteratively by the secant method, and the value of S can be derived by substituting the estimate of u_{*c} , $\bar{u}_r$, z_r into Equation (38). Figure 3 shows the diagram of the solution procedure.

Figure 3. Diagram of the solution procedure.

3. Predictions of Boundary Layer Thickness and Bed Roughness

3.1. Thickness of the Wave Boundary Layer

The thickness of the wave boundary layer is one of the most significant characteristics that a model to be predicted. The classical GM, CJ, SG2000, SG2017, and You models fail to accurately predict this parameter when disposing of large roughness elements, such as ripples and dunes. Regarding the wave boundary layer thickness δ , Sleath [40] proposed a classical definition, where δ is the distance between the mean bed level and the level at which the velocity defect should be 5% of the free-stream wave orbital velocity u_b . In the lab experiments by [40], the rough beds were composed of a single layer of sand and gravel on a flat bed, which differs from the ripple beds. Hence it is questionable whether the definition of [40] can accurately predict the thickness of the wave boundary layer in the present model. Based on the findings by [39], the proportion of velocity defects to u_b is denoted by A and δ can be expressed as:

$$\delta = B\sqrt{2K_w/\omega} \quad (46)$$

where B is the factor to be determined. The relationship between A and B can be obtained by combining Equations (39) and (46), where the imaginary parts in Equation (46) are ignored.

$$e^{-B} = A \quad (47)$$

To study the characteristics of fluid motion and bed roughness in combined wave-current flows over ripples, laboratory experiments have been conducted by several studies [10,41–43]. The experiments conditions and estimates of the wave boundary layer thickness obtained visually from the experimental velocity amplitude profiles are shown in Table 1, where $A = 1\%, 2\%, 3\%, 4\%, 5\%$ and the values of the corresponding B can be obtained by Equation (47). As shown in Figure 4, Equation (46) best fits the data when $A = 2\%$, that is, $B = 3.91$. Hence, the wave boundary layer thickness in combined wave-current flows over ripple beds can be accurately predicted using Equation (46) with $B = 3.91$. The wave boundary layer thickness δ is shown in Figure 5.

Table 1. Experiments conditions and estimates of δ .

Exp.	Experimental δ /(cm)	η /(cm)	λ /(cm)
a ¹	6.0	1.5	10
b ¹	7.2	1.5	10
c ¹	7.0	1.5	10
n ¹	3.5	1.5	20
165-02 ²	2.7	0.7	5
PWO ³	7.3	1.5	10
WC1 ⁴	15.9	3.5	22

¹ the experiments in [41], ² the experiment in [42]. ³ the experiment in [43]. ⁴ the experiment in [10].

Figure 4. δ as a function of $\sqrt{2K_w/\omega}$. **Figure 5.** Wave boundary layer thickness δ .

3.2. Physical Bed Roughness and Apparent Bed Roughness

To study the physical bed roughness and apparent bed roughness with ripples, several researchers have performed laboratory sink experiments [10,12,13,44–47]. The experiments conditions are listed in Table 2. Many researchers have derived empirical formulae for k_s [8,10,48]. However, they did not consider the ripple steepness as the dividing line, hence, different empirical formulae can be used to express the physical bed roughness for small and large ripple steepness. As shown in Figure 6a, the ripple steepness of the data above the dot-and-dash line is greater than 0.13 and less than 0.13 for data below the dot-and-dash line, data with $\eta/\lambda > 0.13$ and $\eta/\lambda \leq 0.13$ can be summarized as two different empirical

formulae. The findings of [12], which indicates a large ripple steepness = $0.28 > 0.13$, but a small k_s , —is an exception. This is due to its particularly small value of η .

$$k_s = 34.24 \eta^2 / \lambda \quad \eta / \lambda > 0.13 \text{ and } \eta > 0.8 \text{ cm} \quad (48)$$

$$k_s = 10.85 \eta^2 / \lambda \quad \eta / \lambda \ll 0.13 \quad (49)$$

Table 2. Experiments conditions. The legends in the table are applicable to Figure 6a–d.

Author	Legend	φ_{cw}	H/h	a_b/k_s	h/k_s	η/λ	$\eta(\text{cm})$
Kemp [12]	×	0°	0.11–0.23	0.5–0.9	10	0.28	0.50
Havinga [46]	●	$60^\circ, 90^\circ$	0.16–0.33	4.6–94.9	17.5–506	0.07–0.13	0.6–1.3
Nieuwjaar [44]	◆	0°	0.15–0.30	0.7–2.3	3.7–10.3	0.10–0.18	1.5–1.9
Mathisen [47]	◀	0°	0.19–0.29	0.2–0.4	3.0	0.15	1.50
Mathisen [47]	◀	0°	0.26	0.3–0.6	2.5–5	0.075	1.50
Fredsøe [10]	■	0°	0.313	1.2	4.9	0.16	3.50
Van Kampen [45]	★	0°	0.15–0.30	0.5–2.8	4.2–12.4	0.13–0.15	0.8–1.5

Figure 6. Experimental k_s , k_a and linear regression. (a) k_s as a function of η^2/λ ; (b) experimental k_a/k_s , where the data in Havinga [46] are divided into those with $\varphi_{cw} = 60^\circ$ and those with $\varphi_{cw} = 90^\circ$; (c) k_a/k_s as a function of u_b/u_c ; (d) linear regression between experimental z_{0a} and calculated z_{0a} .

The values of apparent bed roughness k_a were determined from the mean current profiles measured in the laboratory experiments are shown in Figure 6b, and the following conclusions can be drawn from Figure 6b.

1. There is a distinct trend where k_a/k_s increase with u_b/u_c , where u_c is the depth-averaged current velocity. When u_b/u_c is positive, $u_b/u_c > 1$. These conclusions are similar to those summarized in [10].
2. For a given u_b/u_c , k_a/k_s increase with H/h , that is, the higher the waves, the larger the apparent bed roughness.
3. For a given u_b/u_c , φ_{cw} is supposed to be a potential impact factor for k_a/k_s . Unfortunately, no exact effect of φ_{cw} on u_b/u_c can be identified. In addition, when $u_b/u_c > 1$, k_a/k_s will be smaller with increasing φ_{cw} . This may be because φ_{cw} has little effect on k_a/k_s .

Ignoring the effect of φ_{cw} , k_a/k_s can be expressed as a function of u_b/u_c , as shown in Figure 6c.

$$\frac{k_a}{k_s} = 3.04 \frac{u_b}{u_c} + 1 \quad (50)$$

By substituting Equations (48) and (49) to Equation (50), $z_{0a} = k_a/30$ can be expressed as

$$z_{0a} = 1.14 \frac{\eta^2}{\lambda} (3.04 \frac{u_b}{u_c} + 1) \quad \eta/\lambda > 0.13 \text{ and } \eta > 0.8 \text{ cm} \quad (51)$$

$$z_{0a} = 0.36 \frac{\eta^2}{\lambda} (3.04 \frac{u_b}{u_c} + 1) \quad \eta/\lambda \ll 0.13 \quad (52)$$

[9,49] derived classical empirical formulae for the apparent bed roughness. These two empirical formulae and Equations (51) and (52) were selected, and the mean absolute error (MAE), the mean absolute percentage error (MAPE), root-mean-square error (RMSE), and index of agreement (d) were used to compare the calculated results with the experimental z_{0a} . Based on [50], the MAE, MAPE, RMSE, and d can be represented as

$$MAE = \sum_{i=1}^N |x_i^c - x_i^m| / N \quad (53)$$

$$MAPE = \sum_{i=1}^N |(x_i^c - x_i^m) / x_i^m| \cdot 100\% / N \quad (54)$$

$$RMSE = \sqrt{\sum_{i=1}^N (x_i^c - x_i^m)^2 / N} \quad (55)$$

$$d = 1 - \sum_{i=1}^N (x_i^c - x_i^m)^2 / \sum_{i=1}^N (|x_i^c - \bar{x}| + |x_i^m - \bar{x}|)^2 \quad (56)$$

where x_i^c represents the calculated values, x_i^m represents the values estimated from the mean current profiles measured in laboratory experiments, $\bar{x}$ represents the average of x_i^m , and N represents the total number of data and there are 48 sets of data. The calculated results are presented in Table 3. From the established data sample and the index of agreement d , the values of MAE, RMSE of result calculated from Equations (51) and (52) are all the smallest, those obtained from the formula proposed by Van Rijn [9] are the second largest, those obtained from the formula proposed by Sleath [49] are the largest, and the value of d of result calculated from Equations (51) and (52) are all the largest. Hence, Equations (51) and (52) has have improved the accuracy of the prediction of k_a compared with the existing formulae. The linear regression between experimental z_{0a} and calculated z_{0a} is shown in Figure 6d.

Table 3. Comparison between calculated and experimental z_{0a} of different formulae.

Author	Formula	MAE	RMSE	d
Sleath	$z_{0a} = z_0(1 + 0.19(u_b/u_{*c})(A_b/k_s)^{0.5})$	0.738	1.15	0.750
Van Rijn	$z_{0a} = z_0 \exp(\gamma u_b/u_c)$	0.638	0.893	0.906
	Equations (51) and (52)	0.345	0.626	0.961

4. Results

In order to examine the accuracy of the present model, the calculated results of the present model and the SG2017 model [17] were compared with the laboratory measurements of Havinga [46] and van der Kaaij and Nieuwjaar [44], as shown in Figure 7. It can be demonstrated that the present model is in good agreement with laboratory measurements. The mean absolute percentage error (MAPE), the mean absolute error (MAE), root-mean-square error (RMSE), and index of agreement (d) were used to compare the present model and the SG2017 model with the laboratory measurements, as shown in Table 4. As seen in Table 4, the accuracy of the present model is significantly better than that of the SG2017 model. Although the accuracy of the present model is slightly less than that of the SG2017 model in cases T14 30-90, T7.5 40-0, and T12 10-0, the shape and trend of the current profiles calculated by the present model are in better agreement with the laboratory measurements.

Figure 7. Cont.

Figure 7. Comparison of the present model, the SG2017 model, and the laboratory measurements. For example, T7 10-90 represents a laboratory experiment with a wave height of approximately 7 cm, a current velocity of approximately 10 cm/s and $\varphi_{cw} = 90^\circ$. Scatters are the laboratory measurements in combined wave-current flows, the straight lines represent the calculated results of the present model, the dot-and-dash lines represent the calculated results of the SG2017 model, and the dashed lines are the lab measurement in pure currents. (a–d) Comparison of the present model with Havinga [46]; (e,f) comparison of the present model with van der Kaaij and Nieuwjaar [44].

Table 4. Comparison of accuracy of the present model and the SG2017 model in calculating current velocity.

EXP.	The Present Model				SG2017			
	MAPE	MAE	RMSE	d	MAPE	MAE	RMSE	d
T7 10-90	6.44%	0.444	0.589	0.986	10.44%	0.815	0.966	0.969
T7 20-90	4.25%	0.768	0.952	0.989	6.32%	1.091	1.481	0.980
T7 30-90	1.30%	0.294	0.410	0.999	5.25%	1.188	1.565	0.985
T14 10-90	5.10%	0.395	0.525	0.993	8.36%	0.847	0.934	0.982
T14 20-90	5.09%	0.812	1.147	0.988	9.41%	1.589	2.173	0.971
T14 30-90	6.50%	1.311	1.787	0.980	6.23%	1.375	1.618	0.988
T7 10-60	4.79%	0.527	0.685	0.966	12.57%	1.186	1.605	0.898
T7 20-60	2.52%	0.485	0.574	0.996	6.63%	1.050	1.656	0.975
T7 30-60	0.96%	0.282	0.497	0.998	8.41%	1.861	2.448	0.960
T14 10-60	1.49%	0.165	0.287	0.993	22.32%	2.319	2.719	0.760
T14 20-60	4.50%	0.807	1.009	0.984	6.66%	1.243	1.423	0.977
T14 30-60	4.26%	1.003	1.154	0.988	7.66%	1.610	2.291	0.967
T7.5 10-0	6.12%	0.390	0.495	0.993	6.43%	0.406	0.567	0.993
T7.5 20-0	7.95%	1.089	1.372	0.986	9.62%	1.407	1.808	0.977
T7.5 40-0	6.04%	1.929	2.408	0.980	4.58%	1.449	1.997	0.990
T12 10-0	12.87%	0.774	0.964	0.976	20.38%	1.481	1.659	0.939
T12 10-0	11.06%	1.437	1.931	0.979	9.18%	1.420	1.659	0.986
T12 10-0	7.08%	2.442	2.740	0.972	9.90%	3.335	3.895	0.959

5. Discussion

The problem of the classical eddy viscosity models underestimating the wave boundary layer thickness was explained in detail in [47,51]. Madsen and Salles [51] introduced a scaling factor to represent the effect of the presence of ripples on the increase in the wave boundary layer thickness. However, the classical eddy viscosity models GM, CJ, SG2000, SG2017 and You ignored this increasing effect. As shown in Figure 7, the SG2017 model fails to have a good agreement with the laboratory measurements, mainly reflected by the small calculated values of the current velocity in the near-bed layer ($z/h < 0.2$) and the absence of deviations in the near-surface layer ($z/h > 0.6$) of current profiles. The former phenomenon may be due to the inappropriate assumption of the current and wave eddy viscosity within the wave boundary layer, and the latter may be due to the neglect of the wave-induced shear stresses. Moreover, the effect of the presence of waves on the mean current profile can be seen in Figure 7 as follows:

1. In the near-bed layer ($z/h < 0.2$) and near-surface layer ($z/h > 0.6$), the presence of waves leads to a reduction in the current velocities, and an enhancement in the middle layer.
2. The deviation of the current velocity profile caused by the presence of waves is relatively notable when the free stream wave orbital velocity, u_b , is relatively large with respect to the depth-averaged current velocity u_c .
3. For a given u_b and u_c , the smaller the ϕ_{cw} , the lower is the level at which the current velocities begin to decrease.

The first two findings were similar to those in [9]. Equation (34) qualitatively explains the deviation of the current velocity distribution in the near-surface layer from the logarithmic distribution as a result of the wave-induced second-order shear stress. Physically, the deviation is due to the combination of the wave-induced second-order shear stress ($-S_z$) and the shear stress induced by bottom friction. The magnitude of the shear stress induced by bottom friction reaches its maximum on the bed and gradually decreases from the bed to the surface, and the value of the shear stress induced by the bottom friction is positive. The magnitude of the wave-induced second-order shear stress, $-S_z$, increases linearly from the bed upward and $-S_z < 0$. Therefore, the wave-induced second-order shear stress $-S_z$ and the shear stress induced by bottom friction are superimposed to form a “z” type shape. The magnitude of the combined shear stress reaches its maximum at the bed, decreases from the bed upward, and becomes zero at a certain level, then increases

upwards. That is, the combined shear stress changes from positive to negative from the bed to the surface, and the current velocity decreases upwards above the level at which the combined shear stress becomes zero. This indicates that the level at which the current velocities begin to decrease can reflect the magnitude of $-S_z$ relative to the magnitude of the shear stress induced by bottom friction. For a larger $-S_z$, the combined shear stress will reduce to zero at a lower level. Denote the level at which the current velocities begin to decrease with z_d . It is clear from finding 2 that for a given φ_{cw} , the stronger the waves are relative to the currents, the greater is the influence of $-S_z$. Hence, the wave parameters and the intensity of the wave relative to the current are both the influencing factors of $-S_z$, as mentioned in [29].

According to [52], the wave height attenuation $\partial H/\partial x$ and the bed slope are both influencing factors of the wave Reynolds stress $\overline{u'w'}$ in Equation (25). Moreover, $\partial H/\partial x$ is the primary influencing factor of $\int_0^z \partial(\overline{u'^2} - \overline{w'^2})/\partial x \, dz$ in Equation (25). Hence $\partial H/\partial x$ is an influencing factor of $-S_z$ when the bed slope is ignored. From Equations (40) and (45), it can be found that large η and η/λ potentially lead to large bottom stresses, which results in a large wave height attenuation $\partial H/\partial x$. The laboratory measurements of current velocities in combined wave-current flows and current only in van der Kaaij and Nieuwjaar [44] and Nap and Van Kampen [45] are shown in Figure 8. As shown in Figure 8, for similar wave-current conditions, z_d is smaller for a large size of the ripples (the larger size of the ripples means that the ripple height is larger than others when the ripple steepness are approximately the same). Hence, the size of the ripples is also an influencing factor of $-S_z$. As can be seen in Figure 8a, z_d in van der Kaaij and Nieuwjaar [44] and those in Nap and Van Kampen [45] are nearly the same, which may be due to the differences in ripple size being too small or the presence of differences in current conditions in the two laboratory experiments.

Figure 8. Laboratory measurements of $\bar{u}$ in two similar wave-current conditions in ripples of different sizes. $\varphi_{cw} = 0^\circ$ in all the experiments. For example, T7.5-20 represents a lab experiment with a wave height of approximately 7.5 cm, a current velocity of approximately 20 cm/s. The short horizontal lines represent z_d . (a) $\eta = 1.5$ cm and $\lambda = 9.9$ cm in van der Kaaij and Nieuwjaar [44], and $\eta = 1.27$ cm and $\lambda = 8.44$ cm in Van Kampen [45]; (b) $\eta = 1.8$ cm and $\lambda = 10$ cm in van der Kaaij and Nieuwjaar, and $\eta = 0.86$ cm and $\lambda = 6.47$ cm in Van Kampen; (c) $\eta = 1.6$ cm and $\lambda = 11.1$ cm in van der Kaaij and Nieuwjaar, and $\eta = 1.1$ cm and $\lambda = 7.79$ cm in Van Kampen.

The findings revealed that the φ_{cw} may be an influencing factor of $-S_z$. By using Equation (38), the values of S estimated from the laboratory experiments of van der Kaaij and Nieuwjaar [44] and Havinga [46] are shown in Figure 9a. As shown in Figure 9a, $S/u_b^2\kappa$ is a linear function of u_{*c}/u_b and the values of $S/u_b^2\kappa$ are divided into three segments owing to different φ_{cw} ; for a given u_{*c}/u_b , lower the φ_{cw} , larger is the $S/u_b^2\kappa$. In [29], You also mentioned that $S/u_b^2\kappa$ can be a linear function of u_{*c}/u_b , however, You [29] only discussed the cases of currents following the waves and opposing the waves.

The appropriate values of S from Equation (38) depend on the precision of the chosen reference current velocity $\bar{u}_r$ and on the assumed eddy viscosity in Equation (30). To obtain the empirical expression for the gradient S with an arbitrary φ_{cw} , an angle-dependent correction factor $\gamma = 1 + 2.1\cos\varphi_{cw}$ is introduced. As shown in Figure 9b, the gradient S in which $0^\circ \leq \varphi_{cw} \leq 90^\circ$ can be expressed as:

$$S = \gamma \kappa u_b^2 (0.002 \frac{u_{*c}}{u_b} + 0.00003) \quad (57)$$

Figure 9. Gradient S evaluated from Equation (21) in lab experiments of van der Kaaij and Nieuwjaar [44] and Havinga [46]. (a) $S/u_b^2 \kappa \gamma$ as a function of u_{*c}/u_b ; (b) $S/u_b^2 \kappa \gamma$ as a function of u_{*c}/u_b .

6. Conclusions

In order to improve the shortcomings of the classical eddy viscosity models, a new semi-empirical 1DV model is proposed in this study. Based on the two-dimensional Navier–Stokes equations and new assumed wave and current eddy viscosities, the present model can calculate the mean current profiles by a top-to-bottom sequence. The present model is in good agreement with available laboratory experimental measurements and the present model is significantly more accurate than the previous eddy viscosity model SG2017.

By the comparison with the measured values of the thickness of the wave boundary layer, an accurate empirical formula for predicting the wave boundary layer thickness was derived. In the present model, the thickness of the wave boundary layer is defined as the distance between the mean bed level and the level at which the velocity defect should be 2% of the free-stream wave orbital velocity u_b . In the presence of ripples, both the physical bed roughness and apparent bed roughness in case of $\eta/\lambda \geq 0.13$ and $\eta/\lambda < 0.13$ can be calculated using two different empirical formulae separately.

Through the analysis of the present model calculation results and the laboratory measurements, the deviations of the mean current profiles in the near-surface layer ($z/h > 0.6$) were attributed to the wave-induced second-order shear stress $-S_z$. These deviations decrease as the intensity of the wave relative to the current decreases and the angle between the wave and current increases. In addition to the above factors, the size of the ripples was found to influence S , that is, when the ripple steepness and other conditions are almost the same, the higher the ripples, the larger values of the gradient S . The gradient S of the wave-induced shear stress can be represented as a function of the wave parameters, the current strength, and the angle between the wave and current. Moreover, an angle-dependent correction factor γ was introduced that allows the values of S to be calculated using an empirical formula with an arbitrary angle between the wave and current.

The variables used in this paper are shown in Table 5.

Table 5. List of variables.

A	Ratio of velocity defect to free-stream wave orbital velocity	A_b	Semi-excursion amplitude	B	Empirical coefficients related to the thickness of WBL
C_R	A parameter that indicates the enhancement of the currents by waves.	d	Index of agreement	f_w	Wave friction factor
g	Gravitational acceleration	h	Water depth	H	Wave height
k	Wave number	k_a	Apparent bed roughness	k_b	Bed roughness in the presence of waves over ripple beds
K_c	Current eddy viscosity	k_s	Physical bed roughness	K_w	Wave eddy viscosity
m	Scaling parameter	MAE	Mean absolute error	$MAPE$	Mean absolute percentage error
$RMSE$	Root-mean-square error	N	Number of waves	$\bar{P}$	Time-averaged pressure
$-S_z$	Wave-induced second-order stress	S	Gradient of wave-induced second-order stress	S_1	Gradient of radiant stress
S_2	Gradient of the wave Reynolds stress	T	Wave period	u	Instantaneous horizontal velocity
$\bar{u}$	Mean horizontal velocity	$\tilde{u}$	Periodic horizontal velocity	u_b	Free-stream wave orbital velocity
u_c	Mean current velocity	$\bar{u}_r$	Reference current velocity	u_{*c}	Current shear velocity.
u_{*wm}	Wave shear velocity	u_{*cw}	Characteristic shear velocity within the WBL	WBL	Wave boundary layer
x_i^c	The calculated value	x_i^m	Values estimated from the mean current profiles measured in laboratory experiments	$\bar{x}$	The average of x_i^m
z_0	The height where velocity is zero	z_{0a}	Apparent hydraulic roughness	z_r	Reference height
z_d	Level at which the current velocities begin to decrease	$\bar{\tau}_{xz}$	Total shear force per unit cross-sectional area	$\bar{\tau}_0$	Mean bed shear stress
τ_{wm}	Maximum shear stress for wave	Γ_{ws}	Dimensionless wave shear	ρ	Water density
η	Ripple height	$\bar{\eta}$	Mean surface elevation	λ	Ripple length
δ	Thickness of WBL	δ_1	Height of the transition layer	β	=0.3, an empirical coefficient
κ	=0.4, Von Kármán number	ω	Radian frequency	φ_{cw}	Angle between the mean current and wave
γ	= $1 + 2.1\cos\varphi_{cw}$, angle-dependent correction factor				

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