Study of Roughness Effect on Waves And Currents Combined Flow

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Abstract

In this paper, An analytical and experimental models will be presented, to study the effect of waves and currents interaction phenomena. In this experiments we will consider the viscosity effect and sea bed roughness. This model has been driven by using the general form of the so called (N-S) Equations of motions, and shear stress calculations which are a Combinations of theory and experiments in this field. Our major concern will be to define and express the governing dimensionless parameters in such complicated phenomena. The results of experiments data will be good compared by Brevik of Ass¹ (1980), van rijn³ (1993) and Jonsson⁵ (1976). Finally the experimental analysis shows that, the dimensionless parameter developed in present study, have essentially reasonable agreement with the theory.

Key words: Sea Waves, Currents, Interaction, Roughness, Dimensionless Parameter

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Introduction

Interaction of waves, currents and sea bed roughness is a complicated phenomena in fluid dynamics. Study and analysis of this combined flow is very important, in true dealing with sediment transport, approach channels, platforms, sea bed pipe line, and forces on the coastal structures. The friction at the seabed gives rise to erosion and transportation of sea bed sediments, determines the dispersion of pollutants, and influences the forces on structures on the bed. For example, when waves interface with a tidal current, the wave and current boundary layers interact in such a way that the time mean bed shear stress is larger than that the same depth averaged current in the absence of waves. A number of theories of wave-current combined flow have been proposed in the last two and a half decades, listed for example by Kamphius and Soulsby (1988), which mostly consider wave-dominated cases, or a current dominated of the real sea but in this experiment, we will study the effect of different roughness patterns on the wave parameters such as wave height ($H$), wave length, wave period ($T$), wave direction ($\phi$), and waves celerity ($C$), as well as the current velocity ($U$), to drive the nondimensional parameters of the combined flow.

Theory

To demonstrate the importance of the various parameters in waves, currents and roughness system, the general form of (N-S) Equations, have been considered as follows:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial \rho}{\partial x} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} \right)
\]  

\[
\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial \rho}{\partial z} + \nu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial z^2} \right)
\]

\[
\frac{\partial u}{\partial x} + u \frac{\partial w}{\partial z} = 0
\]

Let us discuss now the interaction between a regular linear wave train and a steady shear current with arbitrary profile in two dimensional plane (Fig:1), the surface elevation $\xi(x,t)$ is sinusoidal, i.e: 

\[
\xi(x,t) = a \cos(kx - \omega t)
\]

$u_s(z) = \frac{u_s}{k} \ln \left( \frac{z}{z_0} \right)$

$\omega_t = \omega_0 + ku \cos(\phi - \phi_0)$
By placing the operator \( \frac{\partial}{\partial t} \) by \(-C \frac{\partial}{\partial x}\), and elimination the pressure terms, from equations (1), (2), and nonviscous term, and also\[ u \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} \leq \left| \frac{\partial u}{\partial t} + U \frac{\partial u}{\partial x} \right|, \]then we obtain the combined flow equations as follows.

\[
\frac{d^2 w}{dz^2} - \left[ k^2 - \frac{k}{w - ku_i} \cdot \frac{d^2 u}{dz^2} \right] w = 0 \quad (10)
\]

However, the system of equation (10) cannot be solved analytically for arbitrary wave number \( K \) and frequency \( \omega \) unless the current velocity varies linearly with depth, Equ(5), for special case, it is necessary to solve the equation in non-dimensional form, and experimentally measured value of wave length, velocity profile, and roughness patterns, will help us, to determine the value of parameters. The velocity profile due to waves and currents is as follows:

\[
U(z) = \frac{u_{sc}}{K} \cdot \frac{1}{u_{sc} + u_{sw}} \cdot \ln \left( \frac{z}{K_s/30} \right). \quad (11)
\]

Fig (1): Definition of Waves + Currents + Roughness System

Which \( K_s \) is grain size diameter, \( u_{sc} \) Current shear velocity, \( u_{sw} \) waves shear velocity, \( K = 0.4 \) Von Karman Coefficient, and \( u(z) \) is the real current velocity due to waves and currents combined flow. In experimental analysis \( u_{sw} \) and \( \delta_w \) waves boundary layer thickness calculated by Jonsson and Sleath (1976),

\[
(12) \delta_w = \left( \frac{\pi v T}{4} \right)^{\frac{1}{2}} \quad u_{sw} = \frac{\omega \delta_w}{4k}
\]

In our experiments we found new expression of equation (11) during the tests by different roughness patterns.
\[ U(\cdot) = \frac{u_w}{k} \left( \frac{u_{w} + u_w}{k + u_w} \right) \left( \frac{z}{k} \right) \left( \frac{1}{\nu} \right) \left( \frac{u_{b} D_{e50}}{\nu} \right)^{0.02} \]  

Which will describe the effect of roughness nominal diameter \( D_{e50} \), and viscosity effect in sea bed, \( U_b \) is the sea bed orbital velocity due to combined flow, which is calculated by:

\[ U_b = \frac{\omega H}{2} \left( \frac{1}{\sinh(kh)} \right) \]  

In which, waves frequency \( \omega \) should be calculated by using equation (6). New dimensionless parameters is somehow roughness Reynolds number \( R_{er} = \frac{u_{b} D_{e50}}{\nu} \) (15)

Which describes the types of flow near the sea bed in shallow water regions. In this experiment, we have used different shapes of roughness elements, which will produce turbulent flow near the bed.

Fig: (2): Different roughness patterns

Due to different geometry of the roughness, various roughness Reynolds numbers can be defined, which will present in another paper in the very near future. Another important problem in the derivation of the (N-S) equations is to define the stream line governing equations. In the case of pure waves the stream lines equation on the viscous form are as follows:

\[ \frac{\partial u}{\partial t} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + \nu \nabla^2 u \]  

\[ \frac{\partial w}{\partial t} = -\frac{1}{\rho} \frac{\partial P}{\partial z} + \nu \nabla^2 w - g \]  

\[ u = -\frac{\partial \Psi}{\partial z}, w = \frac{\partial \Psi}{\partial x} \]  

By eliminating pressure gradients parameters, we will have,

\[ (19) \left( \frac{\partial}{\partial t} \left( \nabla^2 \Psi \right) = \gamma \left( \nabla^4 \Psi \right) \right) \]
To find the stream line functions for combined flow we have used the equation (10), and substitute \( \frac{\partial \Psi}{\partial z}, w = \frac{\partial \Psi}{\partial x} \) as follows:

\[
\begin{align*}
\frac{k}{\omega - ku_1} \frac{\partial^3 \Psi}{\partial x \partial z^2} + \frac{\partial^3 \Psi}{\partial x \partial z^2} + \left[ k^2 \frac{u_* z_0}{\omega - ku_1} \right] \frac{\partial \Psi}{\partial x} &= 0 \\
\text{If} \omega = KC, K &= \frac{2\pi}{L}, C = \frac{L}{T}, \omega^2 \equiv gK \tanh(kh) \\
\text{then}, \text{we will have} \\
\frac{\partial^4 \Psi}{\partial x \partial z^3} + (C - U) \frac{\partial^3 \Psi}{\partial x \partial z^2} - \left[ k^2 (C - U) \right] \frac{u_* z_0}{k} \frac{\partial \Psi}{\partial x} &= 0 
\end{align*}
\]

In equation (21), we will see the stream lines are in the 4th order of \( \Psi \), which cannot be solved analytically, but by injection of some dyes the path lines can be measured experimentally in the combined flow.

**Applied Formulas**

Near the sea bed the effect of inertia and neglected with those of friction can be defined on the form quadratic friction law.

\[
(22) \tau_0 = \rho c_d U^2
\]

This formula is only for pure currents + roughness, in which \( c_d \) is the drag coefficient

\[
(23) c_d = \left[ \frac{K}{0.71 + \ln \left( \frac{z_0}{h} \right)} \right]
\]

\[
(24) z_0 = \frac{k}{30} + \frac{v}{9u_*} \text{ In which}
\]

But, when waves are present, the shear stress cannot be calculated by using the equation (23). In this experiment we have received a new formula after Bijker\(^1\) (1967). To calculate the shear stress due to waves of currents (Morovvat\(^8\), 2000)

\[
\tau_0 = \frac{\rho g}{\sqrt{2\pi c}} \sqrt{h} \sqrt{f_w U} \quad (25)
\]

In which \( C \) in the chezy coefficient in coastal area, and can be calculated by this formula

\[
(26) C = 18 \log \frac{12h}{D_{n50} + D_{s90}}
\]

Which is presented by the writer for coastal shallow water, as a results of numerous tests over different roughness patterns. Another friction term which is considered in combined flow, is the eddy viscosity terms which appears in the equation of motion in the form of

\[
A_x \frac{\partial^2 u}{\partial x^2}, A_x \frac{\partial^2 u}{\partial z^2}, A_x \frac{\partial^2 w}{\partial z^2}, and A_x \frac{\partial^2 w}{\partial x^2}, Which A_x and A_z
\]
Are $A_x \equiv U \cdot L$ And $A_x = \frac{UH^2}{L}$ In dimensionless forms. By a dimensional Analysis of all the governing parameters, which are in these functions are as follows:

$$(27) f \left( H, T, L, h, u, w, a_b, u_b, U, \cdot, z_0, \nu, \rho, \mu, k, D_{n50}, D_{n90}, C, n, A_x, A_x, \Delta \rho, g, \ldots \right) = 0$$

After the analysis, the dimensionless numbers of combined flow have been driven in the forms of Froude numbers and Reynolds numbers:

$$R_{eb} = \frac{u_b a_b}{\nu} \quad (28)$$

$$R_{ca} = \frac{u_b L_a}{\nu} \quad (29)$$

$$R_{ed} = \frac{u_b D_{n50}}{\nu} \quad (30)$$

$$R_{ed} = \frac{(c - u)L}{\nu} \quad (31)$$

Another very important dimensionless parameters are $\pi_1, \pi_2, \pi_3$ which are defined as follows, that describe the relations between viscosity, nominal roughness diameter, current velocity $U$ and waves parameters:

$$\pi_1 = \frac{\omega H^2}{\nu} \quad (29)$$

$$\pi_2 = \frac{\omega H^2 \cdot \nu}{D_{n50} (c - u)^2} \quad (30)$$

$$\pi_3 = \frac{XH^2}{D_{n50} \cdot \nu} \quad (31)$$

$\pi_1$ Express the waves parameters and viscousity effect relation, by increasing the viscosity of fluid, the wave height decreases. $\pi_2$ express the relations between wave height, roughness elements and current velocity $U$, in the following direction, $\pi_3$ is a very special number of this experiment, which satisfies wave height decrement, due to current velocity in decreasing, and also it explains a logical relations between the waves, currents and roughness complicated phenomena.

**EXPERIMENT AND DATA ANALYSIS**

Experiments were carried out in the wave – current flume as shown in (Fig. 3) and also use the results some special bed roughness data analysis. From (Morovvati, 1995), the flume is 30m long, 1m high, and 1m wide, and also some experiment in a special tilting flume (L = 10m, h = 45cm, w = 30 cm, m = 15/1000). It is equipped with a piston type random wave generator at one end and a wave absorbing beach at the other end. The beach has a slope of about 1/2.2 and also a wave absorber by a net of 1/5 in meshes. Currents can be generated by pumping the water through the pipe under – near the flume.
as shown in (Fig:3) , many experiments have been done by waves and currents in the following and opposite directions. Measurements of wave height, wave period, and current velocity were performed from a carriage moving over rails above the flume, water level variation were measured by three resistance probe and velocities by propeller and pito-tube current meters in different depth.

In order to have better understanding of the complex system, we have done many tests in a wave and currents over different roughness patterns. Dominant parameters are \((H, T, h, C, n, L)\), and the following experimental arrangements have been done:

- Water depth \(20 < h < 40\) (cm)
- Wave height \(7 < H < 15\) (cm)
- Wave period \(0.7 < T < 1.4\) (cm)
- Current velocity \(10 < U < 120\) (cm/sec)
- Roughness elements (Ripples, Sand, Gravels, 5*3*2 cm concrete block)
- Roughness patterns (regular, irregular, 4 spots, 5 spots)....
- Dye injection of crystal of \((k_2 MnO_4)\), of organics of \((k_2 Cr O_4)\) and \((k_2 Cr O_7)\) and fluorescent \(C_2OH_12O_5\) which gives good fluorescent to the water, eaimm sulfide which is dissolve in cold water, and has very good fluorescent by \(P \equiv 10^{30}\), for path line observation. The test program and basic hydrodynamic data are given in tables. Detailed of waves, currents, and roughness the presented by the writer (1990)

**EXPERIMENTAL RESULTS**

The results of each tests gives the wave height before and after the roughness area \((H_1\) and \(H_2)\), the roughness pattern characteristics \((C, Lr, \Lambda, a, Ks)\), ratio of wave height changes, waves excursion \((ao)\), and important parameter as the ration \((C/ao)\), the wave length for \(T = 10.4\) sec wave measured. All tests results can be found in tables 1-4.

By using the results of four typical roughness patterns \((C/a = 3.33, 6.66, 13.33, 26.66)\), on Fig 5, it can be seen that, wave height decrements in the case of semi close arrangement \((C/a = 6.66)\) is higher than the other case.

In the case of waves + currents \((0.1 < u_c < 1)\) m/s, and sea bed roughness (Ripple bed, Sand bed, Gravel bed) which can be shown in fig: 5, 6, and 7, the effect of waves on velocity profiles has been analyzed. It can seen that the presence of waves, appears in the form of wave eddy viscosity friction, and effect on the velocity distribution, the superposition of wave motion on a uniform current helps of the turbulence boundary layer.
condition which can be seen on (Fig: 5, 6, 7), which are good comparable by the other experiments.

### Table 1: Pure Waves + Roughness (C/a = 3.33, h = 35 cm, T = 0.9 sec)

<table>
<thead>
<tr>
<th>H_1</th>
<th>H_2</th>
<th>ΔH</th>
<th>ΔH/H</th>
<th>a_o</th>
<th>C/a_o</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.10</td>
<td>5.85</td>
<td>1.25</td>
<td>0.16</td>
<td>2.37</td>
<td>4.22</td>
</tr>
<tr>
<td>9.30</td>
<td>7.53</td>
<td>1.77</td>
<td>0.19</td>
<td>3.10</td>
<td>3.25</td>
</tr>
<tr>
<td>10.38</td>
<td>8.50</td>
<td>1.88</td>
<td>0.18</td>
<td>3.95</td>
<td>2.90</td>
</tr>
<tr>
<td>12.96</td>
<td>10.76</td>
<td>2.20</td>
<td>0.17</td>
<td>4.32</td>
<td>2.31</td>
</tr>
</tbody>
</table>

### Table 2: Pure Waves + Roughness (C/a = 6.66)

<table>
<thead>
<tr>
<th>H_1</th>
<th>H_2</th>
<th>ΔH</th>
<th>ΔH/H</th>
<th>a_o</th>
<th>C/a_o</th>
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</thead>
<tbody>
<tr>
<td>7.10</td>
<td>5.79</td>
<td>1.31</td>
<td>0.184</td>
<td>2.37</td>
<td>8.44</td>
</tr>
<tr>
<td>9.30</td>
<td>7.46</td>
<td>1.84</td>
<td>0.197</td>
<td>3.10</td>
<td>6.50</td>
</tr>
<tr>
<td>10.38</td>
<td>8.41</td>
<td>1.97</td>
<td>0.489</td>
<td>3.45</td>
<td>5.80</td>
</tr>
<tr>
<td>12.96</td>
<td>10.70</td>
<td>2.26</td>
<td>0.174</td>
<td>4.32</td>
<td>4.62</td>
</tr>
</tbody>
</table>

### Table 3: Velocity profile due to waves & currents (ripple bed)

<table>
<thead>
<tr>
<th>h(cm)</th>
<th>Z</th>
<th>Z/h</th>
<th>U/u_c</th>
<th>U/u_{cw}</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0</td>
<td>0</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
<td>0.25</td>
<td>0.9</td>
<td>0.98</td>
<td>0.01</td>
</tr>
<tr>
<td>40</td>
<td>20</td>
<td>1.10</td>
<td>1.07</td>
<td>0.01</td>
<td>40</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
<td>0.75</td>
<td>0.95</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>1</td>
<td>0.80</td>
<td>0.75</td>
<td>0.01</td>
</tr>
</tbody>
</table>

### Table 4: Velocity profile due to waves & currents (sand bed)

<table>
<thead>
<tr>
<th>h(cm)</th>
<th>Z</th>
<th>Z/h</th>
<th>U/u_c</th>
<th>U/u_{cw}</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>≈0</td>
<td>≈0</td>
<td>0.008</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>40</td>
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<td>1.10</td>
<td>1.25</td>
<td>0.02</td>
</tr>
<tr>
<td>40</td>
<td>20</td>
<td>0.50</td>
<td>1.30</td>
<td>1.22</td>
<td>0.02</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
<td>0.75</td>
<td>1.07</td>
<td>1</td>
<td>0.02</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>1</td>
<td>0.90</td>
<td>0.80</td>
<td>0.02</td>
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### Table 5: Velocity profile due to waves & currents (gravel bed)

<table>
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<th>Z</th>
<th>Z/h</th>
<th>U/u_c</th>
<th>U/u_{cw}</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
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<td>0</td>
<td>0.0</td>
<td>0.09</td>
<td>0.03</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
<td>0.25</td>
<td>1.22</td>
<td>1.30</td>
<td>0.03</td>
</tr>
<tr>
<td>40</td>
<td>20</td>
<td>0.50</td>
<td>1.37</td>
<td>1.26</td>
<td>0.03</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
<td>0.75</td>
<td>1.20</td>
<td>1.10</td>
<td>0.03</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>1.0</td>
<td>1.07</td>
<td>0.90</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Fig. 5: Mean Current velocity Profiles as modified by waves and ripple bed

Fig. 6: Mean current velocity profiles as modified by waves and sand bed.

Fig. 7: Mean current velocity profiles as modified by waves and gravel bed
CONCLUSIONS
From the analysis with the experiment data, the following conclusions can be made:

1. Waves & currents in the following or opposite directions, affect each other, the currents modifies on waves parameters, such as wave height, wave period, wave length, wave direction and waves geometry.

2. The presence of roughness has a little effect on waves than on a current, but, in a waves + current + roughness system, the effect of waves on current are much sever than the sea bed roughness.

3. With different arrangement of roughness elements, we will have different roughness coefficient factor, and the distance between rigid bodies is one of the main important factors. The conclusion that the roughness elements become smaller, is not accurate. The maximum resistance occurs in some medium spacing arrangement, (In our case $\frac{c}{a} \geq 0.66$).

4. The most noticeable effect as regards to our wave height decay measurements is the reduction of the wave height due to current influence to waves parameters. In other words in a waves + currents + roughness element system, the presence of the current plays a dominant role in the change of wave parameters than the roughness elements.

5. Shear stress due to waves and currents ($\tau_{cw}$) is much larger than in the case of pure current ($\tau_c$), and pure waves ($\tau_w$) for the calculation of longshore sediment transport, $\tau_{cw}$ should be considered instead of $\tau_c$ or $\tau_w$.

6. The current Eddy viscosity ($\varepsilon_{c}$) is different from the wave eddy viscosity ($\varepsilon_w$), and Waves + Current eddy viscosity $\varepsilon_{cw}$ is much larger than $\varepsilon_c$ and $\varepsilon_w$, and plays a dominant role in the damping of waves parameters.

ACKNOWLEDGEMENTS
The writer would like to thank Dr. a. Bidokhty of the university of Tehran (Geophysics Branches) and Dr. V. Cheginy of the Islamic Azad University, (college of ocean & marine science), for providing very helpful comments through the review of the research works.
References:

4. Kamphuis and Soulsby, “Friction Factor Under Oscillatory Waves”.