# CHAPTER 155

# NUMERICAL MODELLING OF FLOW OVER RIPPLES USING SOLA METHOD

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# ABSTRACT

In order to simulate flow over ripples more accurately than existing approaches, a modified MAC scheme (called SOLA) proposed by Hirt et al.(1975) was adopted in the prescnt study. Primitive equations composed of velocities and pressure were directly solved instead of the usual vorticity and velocity potential function. The governing equations were the Reynolds momentum equations in the x and z directions and the water continuity equation. The driving force was assumed to be the acceleration of the wave orbital movement just above the wave boundary layer. A mixing length hypothesis was adopted to describe the time-and-space varying turbulent eddy viscosity and the shear stress. An explicit difference method was used to solve the equations on a regular grid. The model showed good result when applied to Sato's(1987) laboratory data. The model was applied to a series of ripple tests, using similar hydraulic conditions to Sato, to study the effect of bed ripple steepness and asymmetry. Only a small effect was found on vortex movement and flow characteristics, although a clear offshore vortex movement was found.

# INTRODUCTION

An example of the seabed shows that it is mostly covcred by ripples or dunes. Waves or currents affect the generation of ripples directly or indirectly. It is widely known that the flow or scdiment transport mechanism in shallow waters is closely related to the ripple parameters. It is an important step to understand the flow over ripples in order to accurately predict the sediment transport and the resulting seabed level change.

Bed material movement over ripples in the wave direction is so complicated that the wave-induced sediment transport rate or direction cannot be simply predicted by empirical formulae. Micro-scalc research within the ripple length should help the understanding of sediment transport over ripples. Interesting features related to ripples have been

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<sup>3</sup>Civil Engineering Department, Sung Kyun Kwan University, Chunchun-dong, Changan-ku, Suwon, Korea reported by previous researchers. For example, vortex generation and its contribution to the suspended sediment transport has been well described by previous laboratory or numerical works.

After Bagnold's(1946) pioneering investigation on flow over ripples, laboratory experiments on the flow or sediment movement over ripples have been carried out by Du Toit and Sleath(1981), Sato(1987), Horikawa Ikeda(1990). Ranasoma and Sleath(1992), and Horikawa and and Mizutani (1992). Numerical modelling works have also been undertaken to examine flow or sediment movement over ripples. One ripple length has usually been used as the computational domain of the models. Existing numerical models have adopted the procedure of solving a vorticity equation and a velocity potential function. The existing models can be classified into two groups, an Eulerian grid group, and a Lagrangian discrete vortex method group. Typical models of the former type include Sato S.(1987), Blondeaux and Vittori(1991), Huynh-Thanh and Temperville (1990), and Sato Y. and Hamanaka(1992), while typical models of the latter type include Hansen et al.(1992). The method of solving the vorticity equation is known to have some merits. For example, the continuity equation is automatically satisfied and the pressure need not be solved. However, it has a problem in assigning adequate boundary values at rigid boundaries which is not easy because of the rapidly varying vorticity near them. Once the vorticity field is obtained, the velocity potential function should be solved from the Poisson equation. This procedure involves an iteration step, and produces numerical error, which is a negative aspect of this approach. Model results of the vorticity type proposed by previous investigaters have shown rather poor agreement with measured experimental data sets up to the present. Therefore, it is proposed to adopt a method to solve the primitive velocities and pressures instead of the vorticity and velocity potential functions, and compare the two methods.

In the present study, the primitive variables are solved by an existing SOLA method to simulate flow over ripples. A mixing length hypothesis in the zero-equation turbulence closure was adopted to express time-and-space varying turbulent eddy viscosity. The SOLA approach is composed of explicit finite difference schemes. The present model uses a regular grid so that an arbitrary rigid bed boundary geometry can be easily expressed and modified by the rectangular grid points.

The present model is applied to synthetic situations to examine the effect of ripple steepness and non-uniform ripple shape.

### **MODEL DESCRIPTION**

### **Governing** Equations

We have four basic equations for incompressible fluid dynamics, i.e. water continuity and the Reynolds momentum equations in three directions. To simplify the problem, a two dimensional vertical situation was assumed so that the gradient terms in the y direction disappear in the equations. Then, the governing equations are the water continuity and two Reynolds momentum equations in the x and z directions:

- Continuity Equation

$$\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{w}}{\partial z} = 0 \tag{1}$$

- Momentum Equations

$$\frac{\partial \overline{u}}{\partial t} + \overline{u} \frac{\partial \overline{u}}{\partial x} + \overline{w} \frac{\partial \overline{u}}{\partial z}$$

$$= -\frac{1}{\rho} \frac{\partial \overline{p}}{\partial x} + \left( \frac{\partial (\overline{u})^2}{\partial x} + \frac{\partial (\overline{u})^2}{\partial z} \right) + \nu \left( \frac{\partial^2 \overline{u}}{\partial x^2} + \frac{\partial^2 \overline{u}}{\partial z^2} \right)$$
(2a)

$$\frac{\partial t}{\partial t} + \frac{u}{\partial x} + \frac{u}{\partial z} \frac{\partial z}{\partial z} = -\frac{1}{\rho} \frac{\partial \overline{p}}{\partial z} + \left(\frac{\partial u}{\partial x} + \frac{\partial (w)^2}{\partial z}\right) - g + \nu \left(\frac{\partial^2 \overline{w}}{\partial x^2} + \frac{\partial^2 \overline{w}}{\partial z^2}\right) \quad (2b)$$

where, x, z are horizontal and vertical cartesian coordinates, respectively; u, w are the instantaneous velocity components in the x, z directions, respectively;  $\overline{u}$ ,  $\overline{w}$  are the time-mean velocity components in the x, zdirections, respectively; u, w are the turbulent fluctuation velocity components in the x, z directions, respectively;  $\overline{p}$  is the pressure; g is the acceleration due to gravity; and  $\nu$  is the kinematic viscosity.

The momentum equations are further simplified, firstly, by ignoring the molecular viscosity. Secondly, the turbulent normal stresses are included in the pressure terms. The Reynolds stress term u w requires a turbulent closure to complete the system.

#### Turbulent closure

Boussinesq's eddy viscosity concept was adopted in the present study. The turbulent stress was assumed to be proportional to the mean-velocity gradients, that is:

$$-\overline{u}\,\overline{w} = \nu_t \left(\frac{\partial \overline{u}}{\partial z} + \frac{\partial \overline{w}}{\partial x}\right) \tag{3}$$

Prandtl's mixing-length hypothesis was also applied to express the time and space varying turbulent eddy viscosity. Prandtl's mixing length hypothesis relates the eddy viscosity to the local mean velocity gradient and involves a single unknown parameter, the mixing length  $l_m$  as follows:

$$\nu_{t} = l_{m}^{2} \cdot \left| \frac{\partial \overline{u}}{\partial z} + \frac{\partial \overline{w}}{\partial x} \right|$$

$$(4)$$

where  $\nu_t$  is the turbulent eddy viscosity,  $l_m$  is the mixing length (=  $x l_{sb}$ ), x is the von Kalman constant, and  $l_{sb}$  is a length scale. In the present model,  $l_{sb}$  is assumed to be the shortest distance from the calculation point to the solid boundaries.

Three kind of boundary conditions were applied in the present model. A zero velocity condition was used at the rigid bottom boundary, and a periodic condition in a ripple length was used at the two side boundaries. At the top boundary a zero shear stress condition was applied where no influences are assumed to be reached at the height of two ripple lengths.

The solution of the Reynolds equations yields velocity and pressure distribution in the flow field. When a submerged structure is exposed to fluid motion, non-uniform pressure distribution occurs adjacent to the structure. In solving the Reynolds equation, this pressure distribution gets into trouble. The MAC(Marker-And-Cell) method was proposed by Welch et al.(1965) at Los Alamos Scientific Laboratory(LASL) of the University of California to treat the problem. After then, the SMAC was proposed by Amsden et al.(1970) and the SOLA by Hirt et al.(1975) at LASL. The SOLA scheme uses a simple method to calculate the pressure by adjusting the tentative velocities iteratively until changes are within a given tolerance in the whole computational domain.

# **MODEL VERIFICATION**

The present model with the SOLA method was tested against Sato's(1987) laboratory results for non-uniform waves, and asymmetric ripple geometry (Case 7), in order to examine its validity. The ripple had asymmetric geometry with a round crest. The ripple length was 12 cm; the ripple height was 2 cm. The generated waves were close to the Stokes third order wave; first, second, and third harmonics of the near bed orbital velocity amplitude were -29.5, -7.611, and -1.416 cm/s, respectively. Sato's(1987) asymmetric ripple profile was tested, which had a round crest shape.

The spatial increments in the x, z directions were both 0.25 cm. The time increment was 1/800 of the wave period of 2 seconds. The parameter which controls the accuracy of the continuity equation in the SOLA method was chosen to be sufficiently small. The CPU required for the execution of five real wave periods was typically 7200 seconds on a CRAY-2S/YMP machine.

#### Flow Field

The vorticity or the shear stress are directly related to the flow information. The model should be able to reproduce the flow fields first. The calculated and measured velocity fields were found to match reasonably well for the whole wave period. Fig. 1 shows the calculated velocities at the wave phase of  $19\pi/10$ (see Fig.10), and Fig. 2 shows the measured velocities at the wave phase of  $3\pi/10$  of Sato's experiment as same phase with this study. The present model results reproduces the correct position and size of the vortex. The above phase is for the flow reversing time, and clearly shows the newly-generated vortex over the ripple trough. It should be mentioned that the present model results show

better agreements with the laboratory experimental data sets than the previous vorticity model results, although the previous models are not systematically assessed in the present work.

# Vertical Distribution of horizontal velocities

Fig. 3 shows that the calculated horizontal velocity profile over the ripple trough at the wave phase of  $19\pi/10$  agrees well with the measured values for Sato's experimental conditions. The present model also reproduced the correct position and size of the wave-induced vortex throughout the wave period. The horizontal velocity profile agrees well with the measured one above the level of about half a ripple height from the ripple trough, while the agreement becomes less good near the ripple surface. This would partially be due to the unsatisfactory presentation of the smooth seabed shape with the regular grid.

# **Residual Currents**

Since the residual flow is the secondary flow, it is expected that the agreement between calculated and measured residual flow may not be so good as that of the primary flow. The calculated and measured residual currents (wave period average velocities) are shown in Figs. 4 and 5 respectively. Sato's laboratory wave condition was close to the Stokes third order wave theory, and the order of magnitude of the measured residual current over ripples was about 0.1 cm/s in the offshore direction. The calculated residual current shows similar magnitude and direction, although the separated small circulation cell just next to the ripple crest shows a slightly different pattern from the measured one. The reason for the deviation may eventually be the boundary treatment techniques, which require further investigation.

# Vorticity Contours

The vortex (circulation cell) was well reproduced by the present model at the lee of the ripple crest at the wave phase of  $19\pi/10$  in Fig. 6. The calculated vorticity field gives reasonable agreement on the vorticity magnitude with the Sato's laboratory experiment shown in Fig. 7. The secondary vortex proposed by Blondeaux et al.(1991) was also well reproduced by the present model just over the ripple surface.

# Effect of Sharp Crest Shape

In order to examine the effect of ripple crest shape (round and sharp), the present model was applied to a sharp crested ripple profile. The ripple crest shape of Sato's Case 7 experiment was modified from a round to a sharp shape for the present numerical test, while all the other parameters for the experiment were retained. The calculated flow field for the sharp crested ripple at the wave phase of  $19 \pi/10$  is shown in Fig. 8. The position of the vortex centre is higher, and the area occupied by the vortex is larger than that for the round crested ripple case, as expected. The inter-wave-period (IWP) variation of the maximum absolute vorticities over the round and sharp crested ripples are shown in Fig. 9, which

reveals that the maximum absolute vorticities for the sharp-crested ripple were larger than those for the round-crested ripple.

# MODEL APPLICATION

#### **Application Conditions**

In order to examine the effect of ripple steepness and ripple asymmetry on the flow over ripples, the present numerical model was applied to various artificial conditions. The model run conditions were the water depth of 40 cm; the wave height of 15 cm; the wave period of 2 seconds. The waves were assumed to be the Stokes third order waves, i.e. the near-bed wave orbital velocity was obtained from the following equation(refer to Fig. 10)

$$u_{\infty} = c \ (F_1 . \cos \omega t + F_2 . \cos 2\omega t + F_3 . \cos 3\omega t \ ) \tag{5}$$

where  $u_{\infty}$  is the near-bed wave orbital velocity outside the wave boundary layer. *c* is the wave celerity.  $F_1, F_2$ , and  $F_3$  are the constants in the Stokes third order wave. *g* is the acceleration due to gravity. *k* is the wave number  $(k = 2\pi/L)$ .  $\omega$  is the angular frequency ( $\omega = 2\pi/T$ ). *h* is the water depth. *a* is the wave amplitude. *L* is the wave length. *T* is the wave period. The coefficients of equation (5) can be obtained from following relationships:

$$c^{2} = \frac{g}{k} \cdot \tanh(kh) \cdot \left(1 + a^{2}k^{2} \frac{8\cosh^{4}(kh) - 8\cosh^{2}(kh) + 9}{8\sinh^{4}(kh)}\right) \quad (6)$$

$$F_1 = \frac{a R}{\sinh(k\hbar)} \tag{7a}$$

$$F_2 = \frac{3}{4} \frac{a^2 k^2}{\sinh^4(kh)}$$
(7b)

$$F_3 = \frac{3}{64} \frac{a^3 k^3 \{13 - 4\cosh^2(kh)\}}{\sinh^7(kh)}$$
(7c)

$$a = \left(\frac{H}{2}\right) / \left[1 + a^2 k^2 \frac{3\{8\cosh^6(kh) + 1\}}{64\sinh^6(kh)}\right]$$
(8)

where H is the wave height.

The ripple dimensions (length and height) were calculated from Nielsen's(1981) empirical formulae. The ripple profile for the given ripple dimensions was obtained from the following equations proposed by Sleath(1974):

$$x = X_c - (\eta/2) \sin(2\pi X_c/\lambda)$$
(9a)

$$z = (\eta/2) \cos(2\pi X_c / \lambda) \tag{9b}$$

where  $X_c$  is the parameter for a curvilinear coordinate; x, z are the horizontal and vertical cartesian coordinates, respectively; and  $\eta$ ,  $\lambda$  are the

ripple height and the ripple length, respectively.

In order to examine the effect of ripple steepness and asymmetry, a fixed ripple length was chosen. The wave height of the ripple  $(\eta)$  varied between 1.0 and 2.0 cm, and the longer half of ripple length ( $\lambda$ 1) varied between 4.5 to 6.3 cm. Ripple geometries for the tests are given in the following table:

Run Case	Ripple Length (cm)				Height(cm)		Demontor
	λ1	λ2	λ	$\lambda 1/\lambda$	η	η/λ	Kemarks
RS-1		4.5	9.0	0.5	1.00	0.11	Variation of Ripple Steepness
RS-2					1.25	0.14	
RS-3	4.5				1.50	0.17	
RS-4					1.75	0.19 0.22	
RS-5					2.00		
RA-1	4.50	4.50	9.0	0.50	1.50	0.17	Variation of Ripple Asymmetry
RA-2	4.95	4.05		0.55			
RA- <b>3</b>	5.40	3.60		0.60			
RA-4	5.85	3.15		0.65			
RA-5	6.30	2.70		0.70			

# Table 1 Ripple geometries for numerical tests



#### Application Results

Fig. 11 shows the typical flow pattern at a wave phase for case RS-5. Fig. 11 confirms the fact that the near-bed flow turns it's direction before the ambient flow (outside the wave boundary layer) turns it's direction. Existing one-dimensional vertical wave boundary layer models have also produced the phase shift between the ripple-length-averag boundary layer flow and the outside boundary layer flow. However, the two-dimensional vertical model can track the detailed movement of vortices which directly affect the sediment transport in suspension or as bed load.

### 1) Vertical distribution of horizontal velocities

Fig. 12 (a) shows the vertical distribution of horizontal velocities over the ripple trough at the wave phase of  $18\pi/10$  for various ripple steepnesses, and Fig. 12 (b) for various ripple asymmetry. The centre of the strong vortex generally positions at the ripple crest level. Another weak vortex at the two ripple height is also seen in Fig. 12. The vertical distribution of horizontal velocities for various cases is nearly the same at the upper part above two ripple heights  $(2.0 \eta)$  from the ripple trough.

If the ripple is steep, the level of the vortex centre is generally high at

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the wave phase of  $18\pi/10$ . However, if the wave period is not long enough, the vortex cannot grow sufficiently to fill the ripple space between the two crests.

Fig. 12 (b) shows that the position of the vortex centre and the vertical distribution of horizontal velocities are almost the same for various ripple asymmetry. The ripple asymmetry seems not to affect the vortex movement very much.

#### 2) Time variation of horizontal velocities

The time variation of horizontal velocities at ripple crest is shown in Figs. 13 (a) and (b). At the ripple crest the horizontal velocities show little difference for various ripple steepness or asymmetry. In contrast to the ripple crest, the velocities at the ripple trough surface for various ripple steepness, see Figs. 13 (c), produces the double peak time variation of horizontal velocity. This pattern is closely related to the vortex motion over the ripple trough.

#### 3) Track of vortex

Bagnold(1946) briefly described the track of a vortex over the ripples. Longuet-Higgins(1981) presented the vortex motion by time series using his discrete vortex model. He proposed that the vortex would reach upto the level of  $2.5 \lambda$  when the water particle excurtion length ( $d_0$ ) is  $1.5 \lambda$ from his discrete vortex model results.

In the present study, the track of the separated vortex from the ripple crest was calculated for the case RS-3, see Fig. 14. The calculated movement of the two vortices generated in the onshore and offshore directions is not symmetric due to the asymmetry of the wave orbital velocity in both directions. The vortex generated at the lee side of the ripple crest moves about  $2.5\lambda$  in the onshore direction and disapears, i.e. the vorticity approaches zero after about a wave period time. On the other hand, the vortex generated at the front side of the ripple crest moves about  $3.0\lambda$  in the offshore direction and turns its direction. It disapears after about one and half wave periods.

The movement of the vortex generated at the lee side of the ripple crest for case RS-3 can be devided into 3 phases. The first phase is the generation phase. This starts at the wave phase of about  $3\pi/10$ . The vortex centre moves slightly upwards by the strong offshore ambient wave orbital velocity and slightly sinks down at the wave phase of  $7\pi/10$  due to the weak wave orbital velocity until the wave phase of  $11\pi/10$ . The second phase is the rising phase by the change of the wave orbital velocity direction. During the second phase, the vortex departs from the ripple trough by the onshore return flow. The third phase is the free vortex phase. The rising phase between the wave phase of  $3\pi/10$  and  $11\pi/10$  produces the two peak time variation of horizontal velocity at the ripple trough surface, see Fig. 13 (c).

The behaviour of the vortex generated at the front side of the ripple

crest shows quite different behviour, i.e. asymmetric movement to the former pair vortex, see Fig. 14. The movement of the vortex generated at the front side of the ripple crest can also be devided into 3 phases. The vortex rises from the wave phase of  $15 \pi / 10$  to  $19 \pi / 10$ . The vortex starts to turns it's direction at the wave phase of  $19 \pi / 10$  by the outside return flow. The distance moved is about  $3.0\lambda$ .

#### 4) Vorticity

The vorticity contours for the wave phase of  $19 \pi/10$  are shown in Fig. 15. It is interesting to note that the smaller the ripple steepness ( $\eta/\lambda$ ), the larger the vorticity of the separated vortex as shown in Fig. 16 (a) and the maximum vorticity of the separated vortex for all cases was between  $33 - 38 \sec^{-1}$ . If the ripple became steeper, the area occupied by the vortex was expanded. The ripple surface provides higher energy dissipation rate due to the strong bed shear stress which may reduce the vorticity at the vortex centre. On the other hand, ripple asymmetry(cases RA-1 to 5) shows little effect on the vorticity of the separated vortices, see Fig. 16 (b).

The maximum vorticity is shown in Fig. 17 for various ripple stcepness and asymmetry at a wave phase of  $15 \pi / 10$ .

The time variation of maximum vorticity on the ripple surface is presented in Fig. 18 for the cases of ripple steepness and asymmetry variation. In this figure, (+) value indicates the clockwise vorticity.

#### 5) Bottom shear stress

Longuet-Higgins(1981) derived a horizontal velocity distribution for oscillatory laminar boundary layer from the Navier-Stokes equation. Bottom shear stress for oscillatory laminar boundary layer can be derived from that formula, and the phase different between the bottom shear stress and the water particle velocity outside the oscillatory laminar boundary layer is known to be 45°.

In the present study, the bottom shear stress can be calculated from the mixing length assumption, i.e. the multiplication of the mixing length squared and the gradient of vertical velocity as follows:

$$\frac{\tau_b}{\rho} = l_m^2 \left| \frac{\partial \overline{u_b}}{\partial n} \right| \left( \frac{\partial \overline{u_b}}{\partial n} \right)$$
(10)

where  $l_m$  is the mixing length  $(l_m = x \cdot l_{sb})$ ,  $l_{sb}$  is the shortest distance from the calculation point to the solid boundaries, x is the von Karman's constant(0.4),  $u_p$  is the velocity parallel to the solid boundary surface, and n is the normal direction to the solid boundary.

The time variation of bottom shear stress divided by the density  $(\tau_b/\rho)$ and water particle velocity(non-scale) at the ripple crest is shown in Fig. 19. Jonsson and Carlsen(1976) proposed that that the phase shifts between the wave orbital velocity and the bed shear stress are  $18^{\circ}$  and  $31^{\circ}$  in the onshore and offshore directions, respectively, for a rough turbulent flow over a flat bed with relatively small roughness. The phase differences for the turbulent flows are smaller than that (45°) for the laminar flow.

The present model results show that the phase shift between the bottom shear stress and the water particle velocity for the test cases are between 16° and 40°. The value varied depending on the vortex strength. The steeper the ripple, the bigger the phase difference. For the less steep ripple of case RS-1, the phase shift was 16° and 30° in the onshore and offshore directions, respectively. For the steep ripple of case RS-5, the phase shift was 25° and 40° in the onshore and offshore directions, respectively. The ripple asymmetry gives little influence on the phase shift between the bottom shear stress and the water particle velocity.

#### CONCLUSIONS

A numerical model is proposed here to obtain the wave-induced turbulent flow information over ripples. The present model directly solves primitive velocities and pressure from the continuity and Reynolds momentum equations. The calculation of pressure term followed the existing technique, SOLA. The turbulence was modelled by a mixing length zero-equation closure. A regular model grid was chosen for the present model.

The numerical model was firstly verified using Sato's laboratory experimental conditions. The model results generally agree well with the measured values in the velocity field, vorticity, and the residual flow field.

The model was then applied to various situations to assess the importance of ripple steepness and asymmetry. In order to examine the effect of ripple steepness and asymmetry, the waves were assumed to be Stokes third order waves. The two vortices generated in the onshore and offshore directions move in a different manner due to the asymmetry of the wave orbital velocity. It moves  $2.5\lambda$  in the onshore direction, and  $3.0\lambda$  in the offshore direction. The vorticity becomes very small after about 1.5 wave periods.

The smaller the ripple steepness, the larger the vorticity for the separated vortex. If the ripple became steeper, the area occupied by the vortex was expanded. The ripple surface provides higher energy dissipation rate due to the strong bed shear stress which may reduce the vorticity at the vortex centre.

The time variation of horizontal velocity at the ripple trough surface shows two peaks, which become clearer for steeper ripples because of the strong vorticity. The two peaks can only be explained by the vortex movement.

The phase differences between the wave orbital velocities outside the

wave boundary layer and the bottom shear stresses at the ripple crest are shown to be about  $30^{\circ}$  on average. The phase difference slightly varies depending on the vortex strength at the ripple crest.

Judging from the model results, ripple asymmetry gives only a small influence on the vortex movement or the flow characteristics over the ripples.

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#### REFERENCES

- Amsden, A.A. and Harlow, F.H. 1970. The SMAC Method-A numerical Technique for calculating incompressible fluid flows. Los Alamos Scientific Laboratory of the Univ. of California
- Bagnold, R.A. 1946. Motion of Waves in Shallow Water Interaction Between Wave and Sand Bottoms. Proc., Royal Society of London, Series A, Vol. 187.
- Blondeux, P. and Vittori, G. 1991. Vorticity dynamics in an oscillatory flow over rippled bed. J. of Fluid Mech., Vol. 226, pp 257-289.
- DuToit, C.G. and Sleath, J.F.A. 1981. Velocity measurement close to rippled beds in oscillatory Flow, J. of Fluid Mech., Vol. 112, pp 71–96.
- Hansen, E.A., Fredsoe, J. and Deigaard, R. 1992. Distribution of suspended sediment over wave-generated ripples. J. of Waterway, Port, Coastal, and Ocean Engineering Vol. 120. No1. ASCE. pp 37-55
- Hirt, C.W., Nichols, B.D. and Romero, N.C. 1975. SOLA-A numerical solution algorithm for transient fluid flows. Los Alamos Scientific Laboratory of the Univ. of California
- Horikawa, K. and Ikeda, S. 1990. Characteristics of oscillatory flow over ripple models, 22nd Coastal Engineering Conference, ASCE, pp 661-694
- Horikawa, K. and Mizutani, S. 1992. Oscillatory flow behavior in the vicinity of ripple model, 23rd Coastal Engineering Conference, ASCE, pp 2122-2135
- Huynh-Thanh, S. and Temperville, A. 1990. A numerical model of the rough turbulent boundary layer in combined wave and current interaction, 22nd Coastal Engineering Conference, ASCE, pp 853-867
- Jonsson, I.G. and Carlsen, N.A. 1976. Experimental and theoretical investigations in an oscillatory turbulent boundary layer, J of

Hydraulic Research

- Longuet-Higgins, M.S. 1981. Oscillating flow over steep sand ripples, J. of Fluid Mech., Vol 107, pp 1-35
- Nielsen, P. 1981. Dynamics and geometry of wave-generated ripples, J. Geophys. Res., Vol 86, No C7., pp 6467-6472
- Ranasoma, K.I.M. and Sleath, J.F.A. 1992. Velocity measurements close to rippled beds, 23rd Coastal Engineering Conference, ASCE, pp 2383-2396
- Sato, S., 1987. Oscillatory boundary layer flow and sand movement over ripples. Ph.D. Thesis, The University of Tokyo, Tokyo, Japan.
- Sato, Y. and Hamanaka, K. 1992. Quasi-turbulent boundary layer of oscillatory flow over ripples, 23rd Coastal Engineering Conference, ASCE, pp 2424-2437
- Sleath, J.F.A. 1974. Mass Transport over a Rough Bed, J. of Marine Research, pp 13-24
- Welch, J.E., Harlow, F.H., Shannon, J.P. and Daly, B.J. 1965. The Mac Method A computing technique for solving viscous, incompressible, transient fluid-flow problems involving free surfaces. Los Alamos Scientific Laboratory of the Univ. of California

#### FIGURES



Fig. 1 Calculated flow field over a round crest



Fig. 3 Comparison of horizontal velocities over a ripple trough



Fig. 2 Measured flow field over a round crest(after Sato, 1987)



Fig. 4 Calculated residual flow field over a round crest



Fig. 5 Measured residual flow field over a round crest (after Sato, 1987)



Fig. 7 Measured vorticity over a round crest(after Sato, 1987)



Fig. 9 IWP variation of maximum vorticity over round and sharp crests



Fig. 6 Calculated vorticity over a round crest



Fig. 8 Calculated flow field over a sharp crest



Fig. 10 Wave orbital velocity profile



Fig. 11 The process of return flow









Fig. 15 Vorticity for each computational condition at the wave phase of  $19 \pi/10$ 







Fig. 17 Maximum vorticity at the wave phase of  $15 \pi/10$ 



Fig. 18 IWP variation of maximum vorticity



Fig. 19 IWP variations of bed shear stress for each computational condition