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An Experimental Investigation of Broken Wave over Mud Bed

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ABSTRACT

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The physical nature of the beach profile, wave condition and sediment property of muddy coast are different from those of sandy coast. At muddy coast, which is characterized by almost flat or horizontal bed close to the shore line, wave can break with significantly low value of the incipient breaker height to water depth ratio. The effect of reduced incipient breaker height on surf zone dynamics are not known when wave break with spilling action. For the purpose of correct estimation of the coastal process at muddy coast, it is important to know the dynamics of surf zone in comparison to that of sand coast. In the present study, the hydrodynamics under breaking wave over mud bed has been examined by carrying out a number of laboratory experiments. The dissipation of wave, velocity and turbulence field was observed for varying wave conditions over flat and very mildly sloped beds. The incipient wave breaking condition was found to be the most important parameter to characterize the surf zone dynamics over mud bed. The contribution of mud bed to dissipation of broken wave was determined by observing the nature of wave decay over rigid bed. The size of the surface roller, which is typically considered as constant, was found reduced with the decrease of incipient breaker height over flat bed. The mean velocity and turbulent energy was significantly dependent on the beaker height to water depth ratio. The vertical transfer of turbulence was higher when the bed was sloped in comparison to the case of horizontal bed.

ADDITIONAL INDEX WORDS: *Surf zone, roller size, dissipation, undertow, turbulence.*

INTRODUCTION

Description of the processes such as shoaling and breaking are absent in most of the studies on field wave condition at mud coasts as those activities are not prominent in many areas. However, at the coast where the mud is relatively dense, the action of wave breaking is often found. LEE and MEHTA (1997) described a phenomenon of 'reduced wave breaking' over fluidized mud bed. The process of wave breaking over mud flat critically affects the region's hydrodynamics and sediment transport. The wave can break at the seaward end of the flat, over the flat or near the shoreline depending on the wave and tide condition. However, the dynamics of surf zone at muddy coast may not be same as that of the sand coasts because of the two main reasons. Firstly, the mud flat is often characterized by horizontal or very mildly sloped bed, and secondly, excessive amount of sediment in suspension that influences the microscopic fluid motions.

Most of the studies reported the surf zone dynamics in generalized form that is spatially invariant and independent of bed slope as well as breaking condition. A very simple and earliest method to show breaking position over a mild slope, which shows the breaking height is a fraction of water depth, is

$$(H/D)_b = \gamma_b \quad (1)$$

where H = wave height and D = mean water depth. The subscript 'b' stands for the breaking point. The value of empirical constant, γ_b, may vary over a range of 0.6~0.9 depending on the bed topography and wave condition (DALLY *et al.*, 1985). GALVIN (1996) showed a value as low as 0.55 that can cause wave breaking when the bed is flat. However, for typical sand beaches, the most widely used value is 0.78 as was suggested by THORNTON and GUZA (1985). Even though, wave can break with widely varying $(H/D)_b$ values, no information is available on the effect of such on the surf zone hydrodynamics.

BATTEJES and JANSSEN (1978) proposed (H/D) to be a constant parameter across the surf zone. However, such assumption was shown as unacceptable by DALLY *et al.* (1985) for the cases of flat beds. They mentioned that a process of stabilization, that transformed the breaking wave into non-breaking form, was present as the wave broke over flat bed. Even though a number of researcher (NADAOKA and KONDOH, 1982; HATTORI and AONO, 1985; NADAOKA *et al.*, 1989) has investigated the flow and turbulence field under breaking wave over flat bed, none of their results was compared either

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qualitatively or quantitatively with the cases of breaking over sloped bed.

The present study investigates the dynamics of surf zone over flat bed and very mildly sloped beds on the basis of experimental results. The wave, which broke over the rigid part of a bed backed by the slope, was allowed to propagate over mud layer. The mud bottom and breaker induced wave dissipation, that significantly influences the turbulence and velocity field under breaker, was observed. The influence of mud density on broken wave was analyzed by carrying out several tests on rigid bed. The effect of varying incipient breaking condition on mean flow and turbulence was observed. The study also focused on the spatial variation of the mean flow and turbulent energy.

Another distinct feature of the dynamics of mud coast is the breaking of mud-water interfacial wave and it occurs when the mud layer is sufficiently soft. The interfacial wave has noticeable impact on the dynamics of the water layer as well as sediment transport (MAA and MEHTA, 1987). It is obvious that such impacts are modified when the interfacial waves are broken. However, as the present study observes a time averaged phenomena, it can be considered that the effect is incorporated into the mean results. Effort was not given to study this matter separately under current scope of work.

SURF ZONE HYDRODYNAMICS

With the progression of the broken wave a mass of water is carried by the wave front in the form of surface roller and this net flow is balanced by a mean flow, commonly known as undertow, developed in the opposite direction below the crest level. This flow balances the mismatch between the shoreward radiation stress gradient and longitudinal variation of the pressure induced by the mean water surface. For the convenience of the momentum estimation under breaking wave, SVENDSEN (1984a,b) considered the roller as a detached body of fluid separated from the waveform and perched on the wave face. The surface roller is believed to play an important role in surf zone dynamics including the generation of setup and wave driven currents (DEIGAARD and FREDSOE, 1989). The breaker generated turbulence characterizes the dynamics of this region critically. The breaking process transforms the ordered wave energy to turbulent energy, which spreads towards the bottom. The mechanics of dissipation and process of spreading has been focused by numerous studies theoretically and experimentally. It is well recognized that the fluctuating part of the velocity plays a significant role to characterize the vertical distribution of mean flow and suspended sediment concentration within the surf zone. The turbulent energy is the most appropriate parameter to measure the fluctuating flow quantities as given by

$$k = \frac{1}{2}(u'^2 + v'^2 + w'^2) \qquad (1)$$

Here, $u' = u - u_w - U$, $v' = v - v_w - V$, $w' = w - w_w - W$, (u, v, w are the velocity components in the direction x, y and z respectively; u_w, v_w, w_w are the wave orbital velocities and U, V, W are the time averaged velocities). For two dimensional breaking condition, SVENDSEN (1987) proposed the expression, $k = 0.667(u'^2 + w'^2)$, for turbulence estimation.

In most turbulence modeling, the surf zone parameters are assumed as constant with time and in space. COX *et al.* (1994) made an attempt to verify such claims through a number of experiments with breaking waves over rigid sloped bed and found that those coefficients were noticeably dependent on time and location. Under spilling breaker, the vertical variation of k is insignificant as was evident in experimental results (STIVE and WIND, 1980; HATTORI and AONO, 1985; NADAOKA and KONDOH, 1982). SVENDSEN (1987) conjectured that the large scale vortices created a strong vertical mixing which included a convective dispersion of moderate and small scale turbulence over the full depth. NADAOKA and KONDOH (1982) investigated the velocity field under spilling breaker over horizontal bed and found that the phase averaged velocity below the trough level was increasing downward which was similar to the case of breaking over sloped bed. HATTORI and AONO (1985) reported that the turbulence generated by the breaker was confined to the upper water layer and the intensity of turbulence was constant vertically at the lower layer. An existence of obliquely descending eddy behind the wave crest was reported by NADAOKA *et al.* (1989) on the basis of experimental evidences.

EXPERIMENTAL SETUP

The study was made in a 18 m long flume with cross section of 95 cm× 55 cm as shown in Figure 1. A false bed with a slope in front was made by plywood. The 400 cm long and 15 cm deep test section was at the middle of the flume. The flume was equipped with a piston type wave generator. The flume also had a PC controlled traverse system. Wave probes were installed along the flume length with suitable spacing in such a way that they did not disturb the movement of the traverse system.

Bed sediments were collected from the Coast of Kuala Perlis, West Coast Malaysia. Effort was given to keep the bed properties as close as those of the field. Required amount of water was added and sediments were stirred in the container by a mechanical stirrer for sufficiently long time. For experiment 2a, no extra water was added before stirring. The stirred mud was poured into the test section using a crane. For Run 1a, Run 2a and Run 3a, required bed slopes were prepared. After bed preparation, the flume was filled with water and beds were left under stagnant water for several days (Table 1) to achieve a homogeneous bed density. It was most likely that some density gradient was developed near the bed surface while mud was left under water. For experiment 4d, a settled bed was prepared. Mud water slurry was prepared with 1:2 mud water ratio and pumped into the partitioned section. The slurry was allowed to settle for 28 days. Before the initiation of the experiment, the partitions were removed. A thin plastic sheet was used to cover the bed. This was done to prevent the erosion of very soft mud bed by the wave action. The velocity of water was measured using an Acoustic Doppler Velocimeter (ADV). The wave period for all

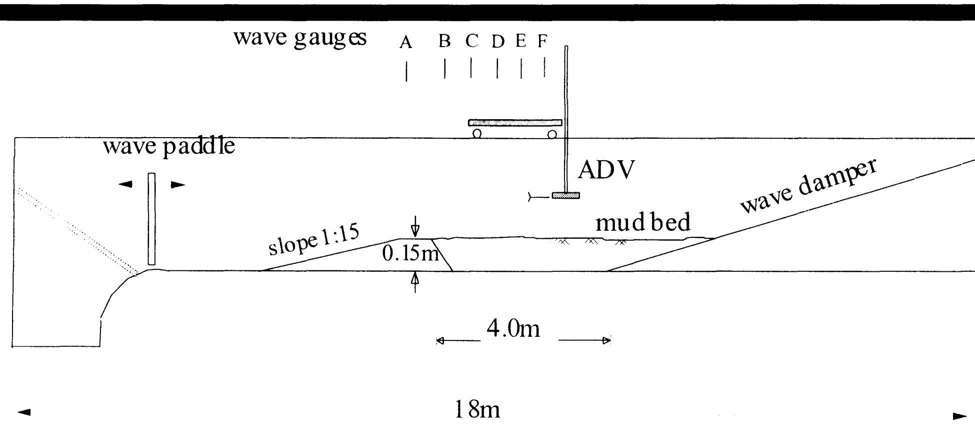

Figure 1. Wave flume and experimental setup.

the experiments was 1.68 sec and the wave and current data sampling rate was set to 25 Hz. The number of data acquired in each wave cycle was 42.

EXPERIMENTAL PROCEDURE

The waves were generated with different parameters to conduct the tests under the hydrodynamic actions of different intensities. The water depth and wave height were set in a way that the wave broke at the edge of the slope before the bed. All the wave parameters are shown in Table 1. For the mud bed experiments, it was obvious that the bed experienced erosion under wave action. The objective of the laboratory measurements were to observe the time averaged consequences arisen due to breaking wave. It was assumed that a steady condition existed during a complete set of measurements, which covered all the vertical and longitudinal points. Several steps were taken to ensure the consistency of the assumption while a single equipment was used for a set of measurements. Those were:

(i) Minimization of the instrument shifting time;
(ii) Efficient operation of the data acquisition system;
(iii) Optimization of data acquisition period;
(iv) Precisely regular wave generation;
(v) Maximum coverage with minimum number of measuring points in the vertical and longitudinal.

Table 1. *The wave parameters for all the runs. (The wave period was 1.68 sec for all the cases.)*

Run	Bed Settings	Bed Density (kg/m^3)	Depth D (cm)	Wave Height H (cm)
1a	1:60 slope	1254	16.3	13.3
2a	1:80 slope	1288	18.8	13.7
3a	1:100 slope	1212	17.3	14.4
4a	Flat	1224	15.8	12.5
4b	Flat	1273	16.6	13.8
4c	Flat	1209	18.8	14.8
4d	Flat	1187	21.9	16.4
4x	Rigid flat	—	21.3	14.7
4y	Rigid flat		21.4	15.0
4z	Rigid flat		20.8	16.3

Immediately after initiation of the wave generation, vertical and horizontal velocities were measured with the ADV. The wave and current was acquired within the zone where the wave rolling action was prominent. Measurement of velocity close to the bed and near the water surface was not possible due to instrumental limitations.

RESULT AND DISCUSSION

Wave Dissipation

Figure 2 shows the change of the height of waves (H) after they were broken and propagated over mud beds of different densities. The deformation of wave height was mainly due to the breaking induced energy dissipation and transfer of energy into the mud layer. The dissipation of wave with distance can be shown using a coefficient, k_i, through an exponential profile given by

$$H = H_b \exp(-k_i x) \quad (2)$$

H_b is the wave height at the breaking point and x is the distance. The dissipation constants (k_i) varied between 0.10 and 0.23. and obtained values for all the tests are presented in Table 2. The variation of dissipation coefficient happened due to two main reasons. One, when the wave had stronger breaking action due to higher breaking height, the rate of rate of energy dissipation was increased. Second, when the mud density decreased, the bed was subjected to increased deformation causing higher rate of wave dissipation. The soft mud bed behaved as a visco-elastic material under oscillatory loading and absorbed energy from the water layer (SHUHAYDA, 1986; MAA and MEHTA, 1990). The rate of energy absorption increased with the decrease of mud density as was found by MAA and MEHTA (1986) in the case of regular non-breaking waves.

Figure 3 show the longitudinal variation of wave height over rigid flat bed after the wave was broken. The ratio of the incipient breaker height to water depths, $(H/D)_b$, were 0.69, 0.71 and 0.79 in experiment 4x, 4y and 4z respectively. The wave heights were reduced only as a result of wave energy loss due to wave breaking.

The wave breaking criterion suggested by THORNTON and

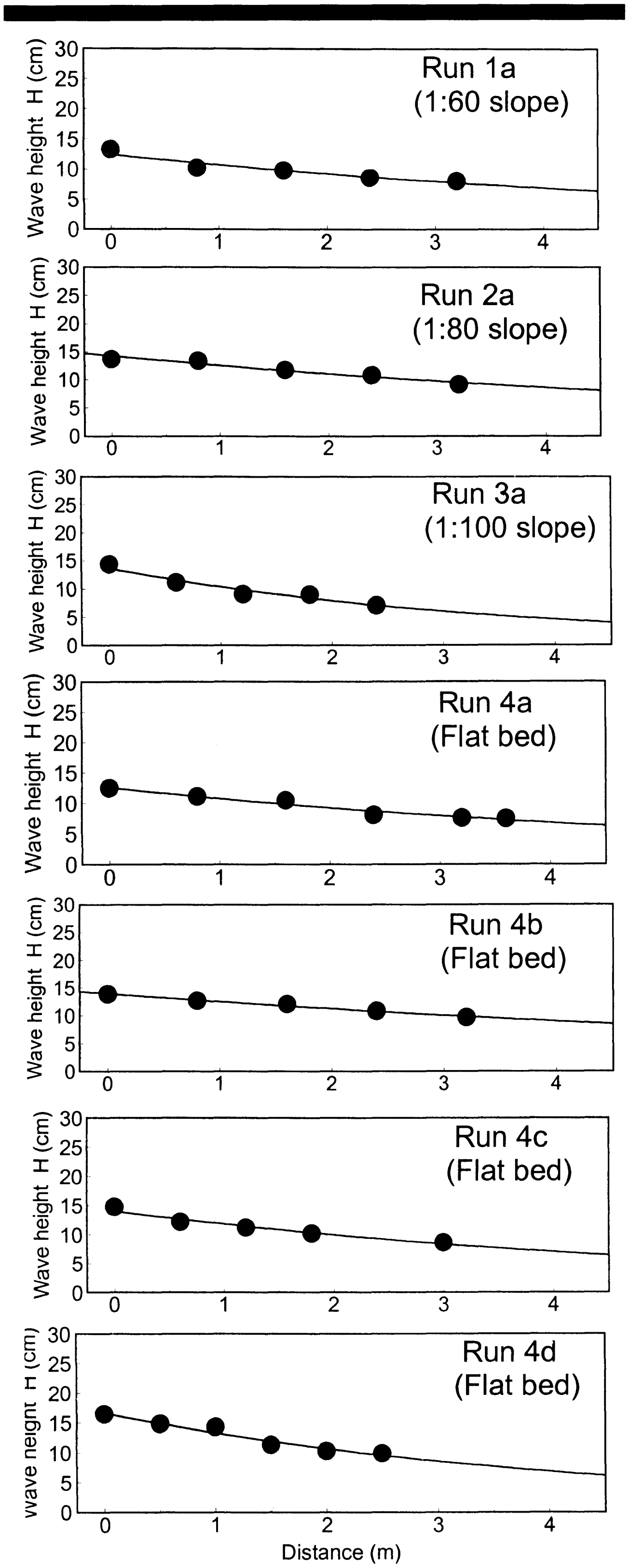

Figure 2. Wave height variation with distance over mud bed.

Table 2. *Incipient H/D ratio and dissipation coefficients in exponential wave profiles for all the Runs.*

Run	$(H/D)_b$	Dissipation Coefficient k_i
1a	0.81	0.150
2a	0.73	0.104
3a	0.82	0.203
4a	0.79	0.154
4b	0.83	0.156
4c	0.78	0.172
4d	0.75	0.220
4x	0.69	0.100
4y	0.71	0.110
4z	0.79	0.150

GUZA (1985), $(H/D)_b = 0.78$, can be considered a critical point by observing the present experimental results. It was found that the rate of reduction of wave height immediately after breaking was less, when $(H/D)_b < 0.78$ in Run 4x and 4y (Table 1). After about the distance of $2L/3$ (L is the wave length) from the point of breaking, the wave height decreased with higher rate as the wave propagated further. It was also visually observed that the roller size was increasing after breaking until a saturated breaker was developed in those cases. The decrease of wave height, which is the consequence of turbulence generation by the breaker, was maximum after the point of saturation and after this point the intensity of the breaker was decreasing until the roller disappeared. In Run 4z, where $(D/H)_b = 0.79$, a saturated breaker was formed at the point of breaking and a higher rate of wave dissipation

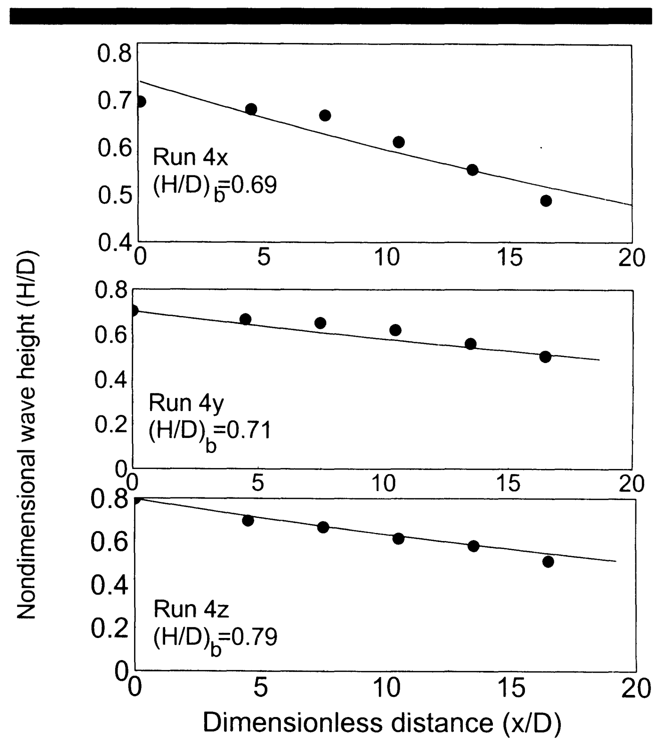

Figure 3. Wave height distribution with distance of propagation over flat rigid bed.

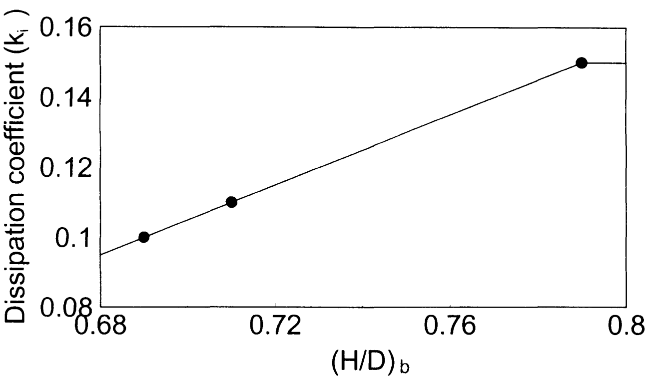

Figure 4. Dissipation coefficient variation with changing breaking condition over rigid bed.

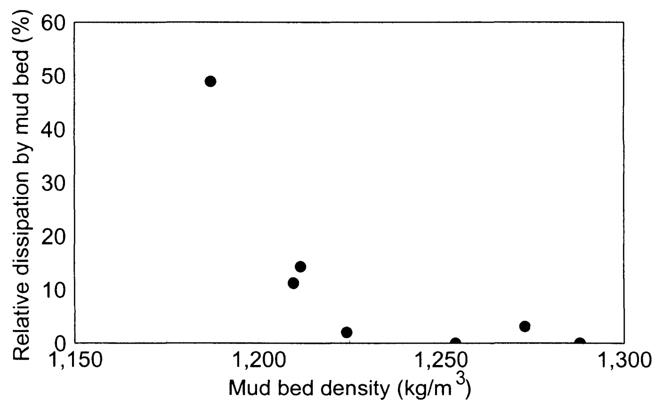

Figure 5. The mud bed induced dissipation coefficient relative to the breaker induced dissipation coefficient (in percent) is shown against the mud bulk density variation.

is found after initiation of breaking. Even though, in mud bed experiments, the bed rigidity influenced the wave dissipation rate, the effect of saturation is observed in Run 2a. In brief, a point of saturation existed after some distance from the breaking point when $(H/D)_b < 0.78$. In other cases, the saturation point coincided with the breaking point.

In the same figure, best-fit exponential plots (firm line) of wave dissipation are shown without stabilization effect. The dissipation coefficients, in this case, were 0.10 m^{-1}, 0.11 m^{-1} and 0.15 m^{-1} for Rum 4x, Run 4y and Run 4z respectively. Such variation was mainly due to occurrence of non-saturated type breaker, when $(H/D)_b < 0.78$. The relation between the wave dissipation coefficient and incipient breaker height can be used to find the effect of mud bottom on breaker height dissipation in the cases of other experiments. As a limited number of data are available on wave dissipation over rigid bed, a linear variation of k_i with $(H/D)_b$ can be assumed on the basis of observation made in Run 4x, Run 4y and Run 4z. It was also assumed that the maximum value for the coefficient of dissipation due to wave breaking was 0.15 m^{-1} when the $(H/D)_b$ was 0.79 over rigid bed (Figure 4). Such assumption was justified by observing the results of rigid bed experiments and also the results of Run 1a and Run 4b (Table 2), where the beds were significantly consolidated (Table 1). When the variation of wave dissipation coefficient (k_i) with incipient breaking condition is known, it becomes easy to find the effect of mud bed deformation on wave decay. It was found previously that the height of breaking wave decreased exponentially over mud bed (Equation 2). The variation of non-breaking wave over mud bed was also exponential with distance as was found by MAA and MEHTA (1987). With these information and using the result from Figure 4, the average dissipation of broken wave caused by the mud bottom was determined for all mud bed experiments. Figure 5 shows the plot of relative dissipation rate, which is the percent ratio of the mud bed induced dissipation coefficient to breaker induced dissipation coefficient, against mud bed density. The wave dissipation due to mud bottom was 48% of breaker generated dissipation when the bed was settled type (Run 4d) and very soft in nature. However, the amount varied within a lower range (up to 15%) in the cases of semi-consolidated type beds.

Surface Roller

An indirect method was accepted to estimate the roller size from the setup gradient, which is the longitudinal increase of the mean water level. LONGUET-HIGGINS and COKELET (1976) explained theoretically the formation of setup within the surf zone as a consequence of shoreward gradient development of radiation stress. In the light of this idea, the simple stress balance equation for sand bed was presented (SVENDSEN, 1984a) as

$$\frac{\partial S_{xx}}{\partial x} = \frac{\partial}{\partial x}(b\rho g + p) \tag{3}$$

with, S_{xx} = the radiation stress, b = setup, ρ = density of water, p = pressure. SVENDSEN (1984) transformed the expression into simpler form by representing the radiation stress gradient in terms of surf zone parameters. That relation can be rewritten for the case of flat bed as

$$A = -\frac{L}{2D}\left[\frac{D}{H}\left(\frac{\partial b}{\partial x}\bigg/\frac{\partial H}{\partial x}\right) + 0.25\right] \tag{4}$$

A is the cross sectional area of the surface roller. As the Equation 3 does not include the mud bed induced energy dissipation, direct estimation of which is rather difficult, the relation is not applicable for mud bed experiments. This relation was applied in all the three cases (Run 4x, 4y and 4z), where the wave broke over flat false bed with $(H/D)_b$ value of 0.69, 71 and 0.79. The mean water level variation was plotted as shown in Figure 6. The wave height and setup gradients were estimated from the longitudinal profiles at different points to determine the roller sizes (A) in all those cases. On the basis of experimental results, DUNCAN (1981) showed that the cross sectional area of the roller was proportional to the square of the wave height. *i.e.*,

$$A = C_A H^2 \tag{5}$$

where the value of the coefficient, C_A, was found to be 0.9 for spilling type of breaker over sloped bed. Using the estimated value of A and Equation 5, the coefficients of the roller area

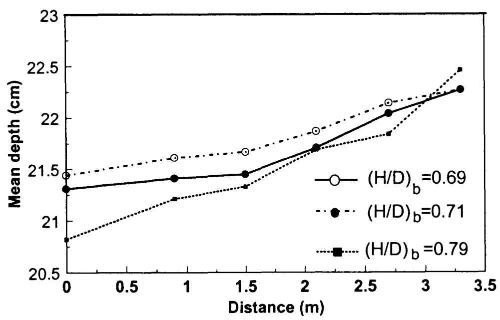

Figure 6. Variation of mean water level with distance while wave broke over rigid flat bed.

were determined for the present case. The longitudinally averaged coefficient values for Run 4x, Run 4y and Run 4z were 0.47, 0.51 and 0.71 respectively. Results show that when the wave broke over flat bed, the roller size was smaller compared to that over the sloped bed. It is also interesting to notice that roller size decreased significantly as the incipient breaker height decreased. That means, when the $(H/D)_b$ value decreased, the rolling action was reduced which is usually considered as constant in conventional coastal engineering practices.

Velocity

Time Varying Velocity

It is very difficult to comment on a turbulent flow field by observing the results of instantaneous measurement unless suitable arrangements of the data are made. For the present case, fluctuating part of the velocity was separated using phase averaging method, which is more accurate than the numerical filtering method (SVENDSEN, 1987). Ensembled averages of horizontal and vertical velocities along with square of the turbulent parts are shown in Figure 7. Results are shown for three different elevations over the bed in experiment 1a and 4a. In Run 1a, wave broke over a bed of slope 1:60 with wave height (H) = 13.3 cm and mean depth (D) = 16.3 cm. Bed was flat in Run 4a with H = 12.5 cm and D = 15.8 cm (Table 1). The phase averaged horizontal flows showed a clear dominance in negative direction. In other words, a mean flow existed in the opposite direction of wave propagation and this flow is commonly termed as 'undertow'.

The turbulent fluctuations in the vertical direction were strong and comparable to vertical wave orbital velocity, especially in the case of Run 1a. Some of the fluctuations occurred periodically and appeared as regularized movement of water. Therefore, complete removal of the fluctuations from the averaged vertical velocity diagram was not possible. This showed that, under the breaker, the vertical motions of the water particles were more random in nature, whereas, the horizontal motions remained more organized. The energy curves show that the turbulence was stronger at upper elevation and decreased downward. This supported the fact that, unlike the cases of non-breaking wave, the source of turbulence was near the water surface. The large eddies generated by the breaking process interacted with the wave motion. Through the process of 'energy cascade' (RODI, 1980), the kinetic energy was passed to smaller and smaller eddies until the viscous forces became active.

Even though the magnitude of velocity was stronger in the horizontal direction, the turbulence contribution by the vertical velocities was significantly high. In most of the cases, the turbulent energy reached peak values when the vertical oscillatory flow was negative or downward.

Mean Velocity

Figure 8 shows the vertical distribution of longitudinal average of the undertow, which is the mean horizontal current below the trough level. For the purpose of comparison of the results from different tests with different water depth, velocities were made dimensionless with the assumption that the velocity was proportional to the wave celerity. The measurements made at individual positions and times are placed somewhere else (AZAM, 1998). The common feature in most of the cases is that the mean velocity increased downward from the trough level and had a peak at elevation between 10% to 30% of the mean depth from the bed. The shear stress induced by the roller above the mean water surface level to the wave flow direction caused the decrease of the velocity near the trough level. The magnitude of velocity reduced with decrease of (H/D) value at the point of initiation of breaking. As found earlier, increase of $(H/D)_b$ value caused enlargement of the roller volume and increased the net transport of water at the wave front. Therefore, the mean flow was also increased in the opposite direction. Scattering of data was probably due to discretizetion error and also because of the noises imposed to the Doppler signal by the breaker generated tiny bubbles.

Depth integrated mean velocities, which were measured at different positions immediately after initiation of the experiments, are plotted in Figure 9. For all the cases, except experiments 4d and 2a (Table 1), longitudinal decrease of mean current was evident. From previous discussion, it was understood that the magnitude of the mean flow was dependent on the roller size. The size of the roller (A) was proportional to the square of the wave height, *i.e.*, $A = C_A H^2$, which DUNCAN (1981) showed on the basis of experimental investigation. As the wave height decreased with propagation, the amount of water carried was also reduced which resulted in lowering of mean velocity. Therefore, when the wave decreased also by other reasons except breaking, the longitudinal gradient of the mean current increased. In the case of Run 2a and Run 4d, wave broke with a low $(H/D)_b$ value resulting an unsaturated breaker where the roller kept growing for some distance and then started decreasing. As a result, the magnitude of the depth averaged undertow also showed an initial increase. By observing the mean horizontal flow under breaking wave, it can be concluded that the idea of invariant roller size for all breaking condition is not correct. The intensity of mean flow was dependent on the roller area coefficient C_A that was also varying across the surf zone.

Turbulence

Turbulence in the field of hydraulic engineering is usually represented in terms of the velocity fluctuations separated

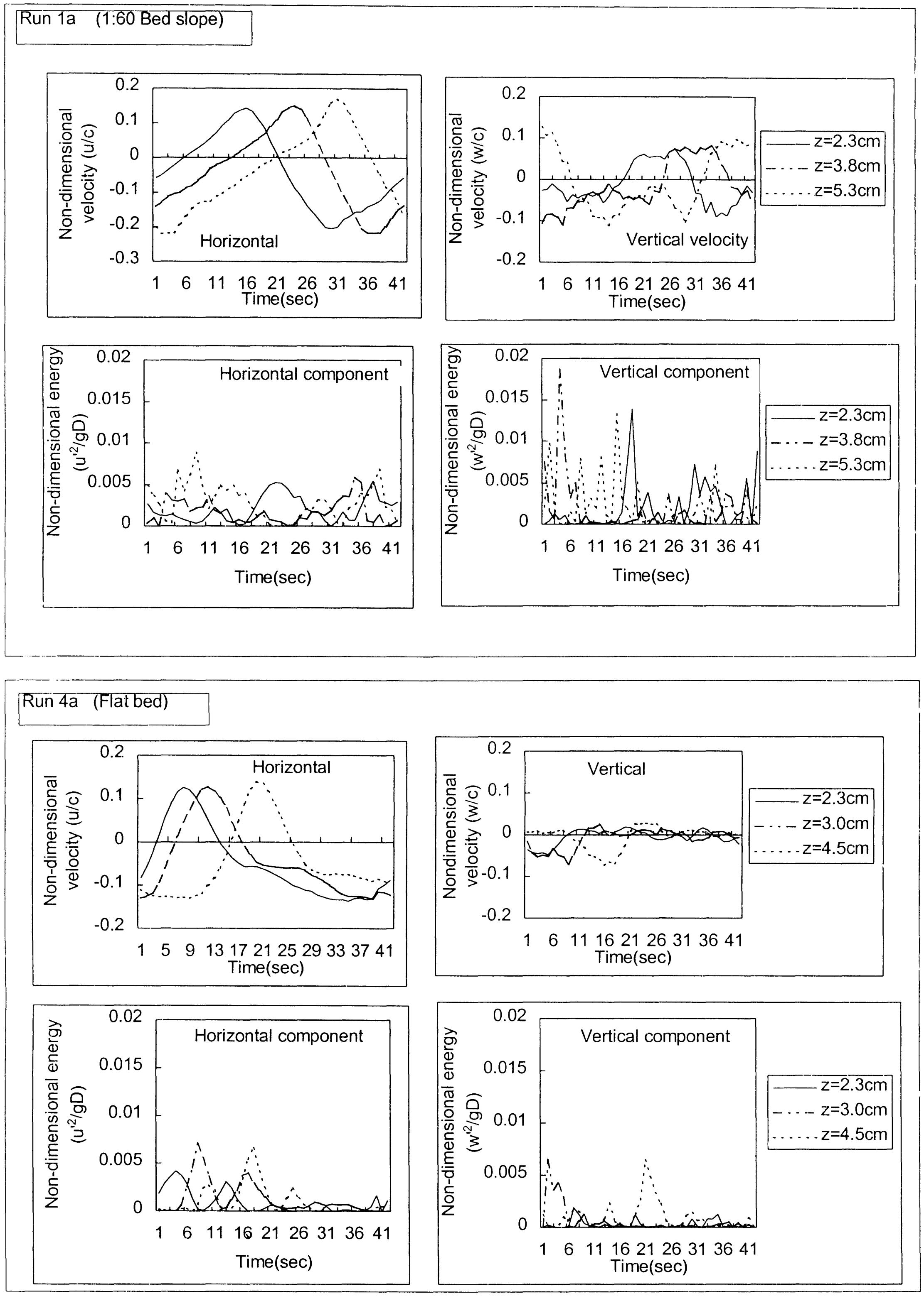

Figure 7. Variation of phase averaged velocity and turbulent energy in (a) Run 1a and (b) Run 4a.

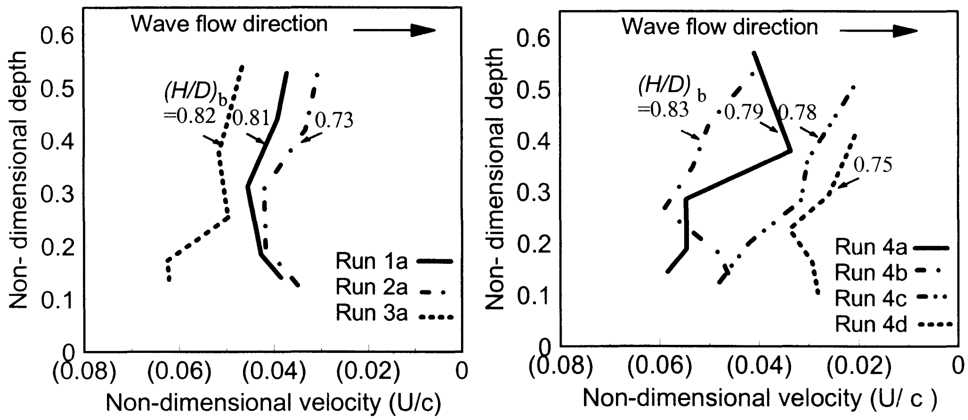

Figure 8. Longitudinally averaged mean horizontal velocities over mud bed.

from the ensemble averaged velocity. Since the turbulence is initiated at the toe of the breaking front, which propagates with the wave speed c, k can be expected to vary proportionally to c^2 or gh. Based on this assumption, results were converted to non-dimensional form to facilitate the comparison of the results from all the tests with different water depths. Figure 10 shows the vertical distribution of turbulent energy for flat and mildly sloped beds. The results covered only 40%–50% of total water depth and showed a part of the generated turbulence. Previous studies showed that, intensity of turbulence was maximum inside the roller and most of its dissipation occurred within this region. The turbulence generated by the roller was transported by convective dispersion rather than diffusion and reached close to the bed (PEREGRINE and SVENDSEN, 1978). However, rate of decrease of turbulence towards down was higher in the case of flat beds and bed of 1:100 slopes and similar results were observed by HATTORI and AONO (1984) and NADAOKA and KONDOH (1982). Vertical variation was less

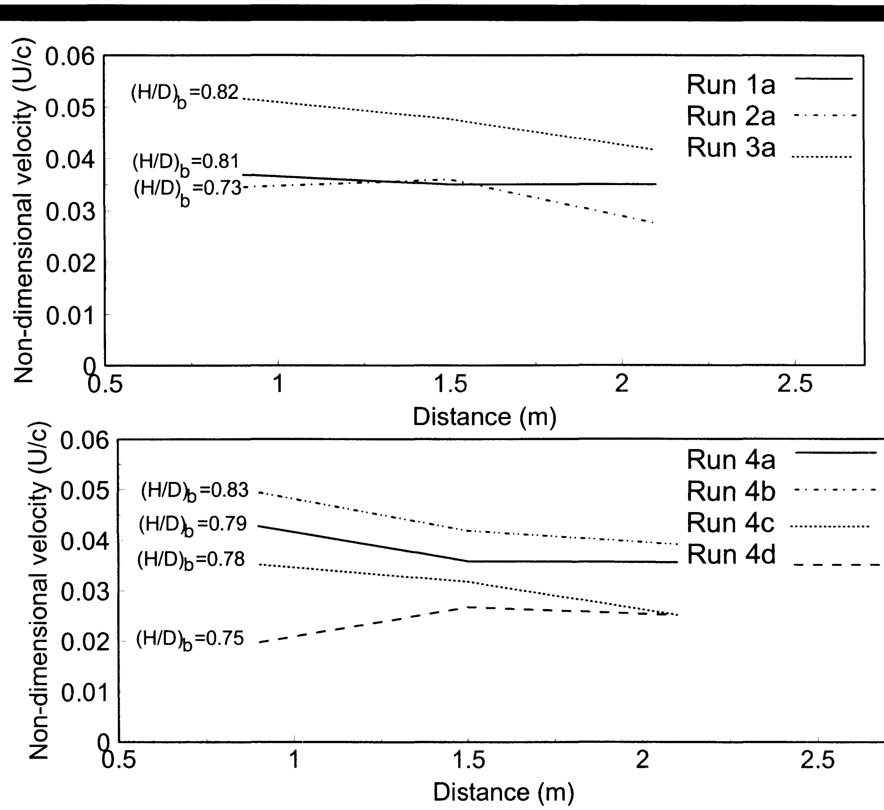

Figure 9. Variation of depth averaged undertow currents along the bed length.

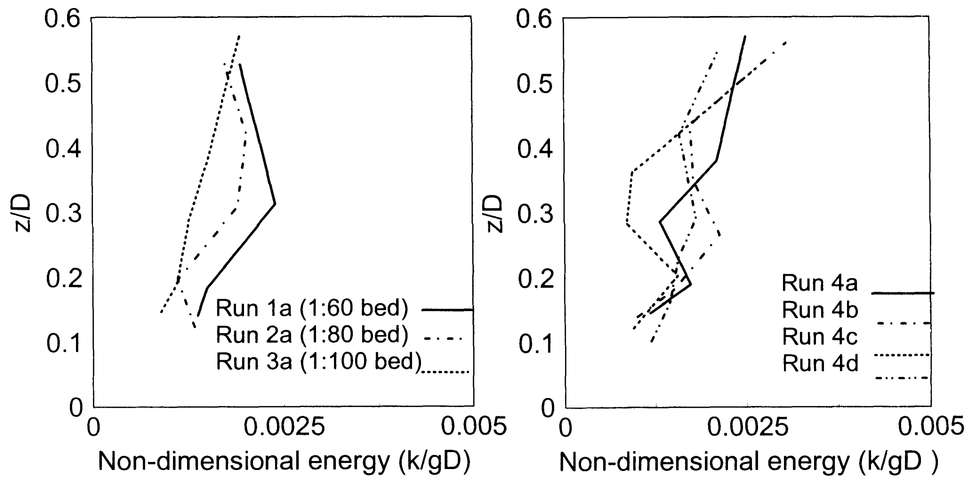

Figure 10. Vertical distributions of dimensionless turbulent energy over (a) mildly sloped and (b) flat mud beds.

in experiment 1a and 2a where slopes were steeper. Such results showed larger convective dispersion of turbulence for steeper beds with stronger breaking action which was in accordance with visual observation. Vortices of larger scale created stronger vertical mixing and transported the smaller eddies downward. In the case of flatter beds, less eddies were dispersed and more turbulent energy was dissipated near the water surface. As was mentioned by SVENDSEN (1978) the bottom generated turbulence was negligible in comparison to the wave generated turbulence in the surf zone. Almost no evidence was found on bed induced turbulence in all the measurements for present observations.

Variation with Breaking Intensity

The dimensionless time averaged turbulent energies are plotted against z/D in Figure 11 for $(H/D)_b$ value of 0.69, 0.70 and 0.78. Measurements, which were made at three locations over 1.2 m section of the rigid bed, are plotted in each graph. By following SVENDSEN's (1987) suggestion, the vertical distribution of mean turbulent energy is shown with the best-fit exponential curve. The profiles shown in a non-dimensional vertical axis are represented as

$$\frac{k}{gD} = C_k \exp(z/D) \tag{6}$$

where C_k is a constant varying with the intensity of turbulence. It is evident that magnitude of the turbulence increased with higher $(H/D)_b$ value. As those results show turbulence only over a rigid bed, the dissipation of ordered wave energy happened mainly due to the wave breaking. Due to the flat nature of the bed, wave deformation by depth variation was absent here. Therefore, from the results, an evaluation of the amount of transformed wave energy into turbulence would be easier. As was shown by LE MEHAUTE (1962) that

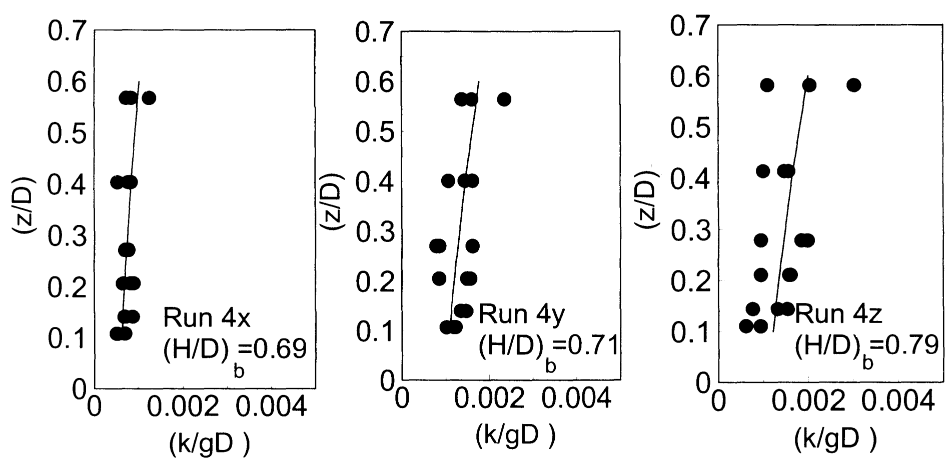

Figure 11. Vertical distribution of non-dimensional turbulent energy over rigid false bed. The firm line represents the best exponential curve.

Table 3. *The spatially averaged eddy viscosity and dimensionless coefficients for all the experiments.*

Run	Averaged Eddy Viscosity (m^2/sec)	$v_b/(D\sqrt{gD})$
1a	1.58×10^{-3}	7.66×10^{-3}
2a	1.73×10^{-3}	6.78×10^{-3}
3a	1.73×10^{-3}	7.77×10^{-3}
4a	1.39×10^{-3}	7.07×10^{-3}
4b	1.87×10^{-3}	8.83×10^{-3}
4c	1.64×10^{-3}	6.42×10^{-3}
4d	1.68×10^{-3}	5.23×10^{-3}

$$D = -\frac{dE_f}{dx} \tag{7}$$

where D is the dissipation per unit area, averaged over wave period, and E_f is the energy flux of the breaker. From the relation it can be shown that

$$\beta = \epsilon \Big/ \left(\rho g \frac{d}{dx}[cH^2B]\right) \tag{8}$$

where, β is the ratio between the dissipated turbulence energy below the trough level (ϵ) to the produced turbulent energy at the wave front. B is the non-dimensional energy flux. The numerical integration of the best fit curves (Figure 11) in the vertical gave the transported turbulent energy and the measurement of the total production was done following DEIGAARD *et al.*'s (1986) approach. The present result showed that $\beta \approx 0.01$. Which means, about one percent of the lost wave energy was transported below the trough level being converted to turbulence. In other words, almost all the turbulent energy produced by the wave breaking is dissipated between the crest and trough level. SVENDSEN (1987) reported after analyzing STIVE and WIND's (1982) experimental data that 2% to 5% of total produced turbulent energy transported down to the water layer below the trough level over a rigid bed of 1:40 slope. From these assessments and comparisons it can be concluded that the amount of downward transported turbulence over flat bed is much less than that over sloped bed.

For the mud bed experiments, the turbulent energy at different vertical longitudinal locations were averaged and those values were used to calculate eddy viscosity with the relation $v_t = l\sqrt{k}$, where, $l = 0.2D$ as suggested by SVENDSEN (1987). The values of $v_t/(D\sqrt{gD})$ or the dimensionless eddy viscosity for different tests are shown in Table 3. The value of the same parameter was calculated as 1.0×10^{-2} by STIVE and WIND (1982) from experimental measurements and SVENDSEN (1987) determined the value to be 3.0×10^{-2}. These values obtained for the tests with sloped rigid bed were one order of magnitude higher than the present findings. The reduction of the eddy viscosity was caused by two main reasons. One is the reduced vertical transport of turbulent energy due to decreased bed slope. The other reason was the presence of high concentration of the suspended sediment in the water that affected the small scale fluctuations of the water particle.

Longitudinal Variation

Figure 12 shows the depth averaged non-dimensional kinetic energy variation with distance over sloped and flat beds

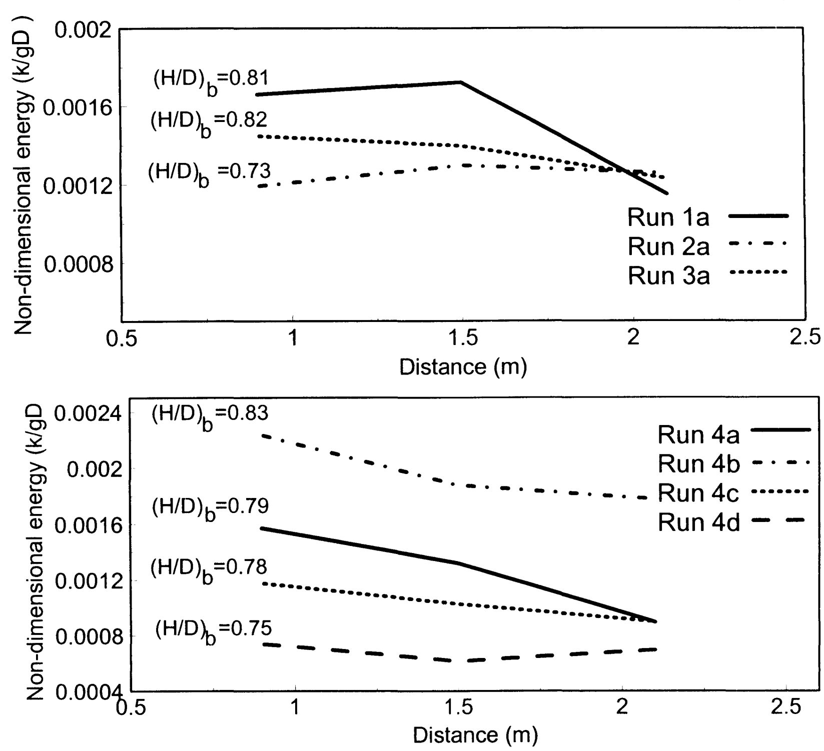

Figure 12. Longitudinal variation of depth averaged mean turbulent energy over mud beds.

respectively. Even though, accurate estimation of the vertical average with measurements with only at 5 or 6 points was not possible, an approximate idea of the nature of variation is possible to obtain. In all the cases, averaged turbulence measured at x = 0.6 m was higher than that at x = 1.2 m, which implies a longitudinal reduction of turbulence intensity when the breaking occurs over very mild slope or flat bed. Results may not be the same in the case where the slope is steeper and the bottom is rigid. The breaking continues over sloped bed with almost unchanged H/D ratio as well as the intensity of breaking. Whereas the breaker height tended to stabilize while propagate over the flat or mildly slopping bed resulting lengthwise reduction in turbulence.

CONCLUSION

In a series of laboratory experiments, broken waves were generated over flat or very mildly sloped bed with varying incipient breaker height. The results showed that the broken wave dissipated exponentially with distance and the coefficient of dissipation ranged between 0.10–0.22. An unsaturated type breaker was developed when $(H/D)_b$, the wave height to water depth ratio at the breaking point, was less than 0.78. The dissipation coefficient over rigid bed increased up to 0.15 when $(H/D)_b$ was more than 0.78. For semi-consolidated type mud bed, the wave dissipation due bottom was very low. The size of the surface roller and the magnitude of the mean flow below the trough level was significantly dependent on the incipient breaker height and these were increasing with $(H/D)_b$. The turbulent energy transported below the trough level was considerably less than the case of typical wave breaking over sloped bed. Both the mean flow and turbulent energy was decreasing with the distance of wave propagation in most of the cases. Results showed the vertical mixing was increased with the increase of the bed slope. The dimensionless eddy viscosity, $v_t/(D\sqrt{gD})$, was found an order of magnitude lower than that over sloped rigid bed.

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