Iranian Journal of Science & Technology, Transaction B, Engineering, Vol. 33, No. B1, pp 49-60
Printed in The Islamic Republic of Iran, 2009

THE EFFECT OF BEACH REFLECTION ON UNDERTOW[*]

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Abstract– Based on experiments, a model is introduced to calculate the vertical and horizontal distribution of undertow in the surf zone due to monochromatic and random wave attack for reflective beaches. The present model is a modification of the original model presented by Okayasu et al., [2] for natural, non-refiective beaches in which the wave set up, radiation stress and mass flux due to breaking waves are modified as described by Mehrdad and Neshaei [6] to include the effect of partially reflected waves. The results of experimental investigation and model development show that the existence of reflective conditions on beaches results in a reduction in the magnitude of undertow and modifies its distribution across the beach profile.

Keywords– Beach reflection, mass flow, sediment, surf zone, undertow

1. INTRODUCTION

There are a number of numerical and experimental studies on wave interaction with coastline [1]. The time mean flow, or undertow, is considered one of the dominant mechanisms in the erosion of beaches [2, 3]. In order to predict the sediment transport in the surf zone, it is necessary to estimate the cross-shore distribution of the undertow. Although advanced models which predict the undertow for natural beaches do exist, surprisingly there have only been a limited number of works on estimating the undertow in the case of reflective beaches where partially standing waves are presented [4]. Such beaches can be observed in front of reflective seawalls and natural steep slopes, particularly during storm conditions.

The vertical and horizontal distributions of undertow in front of a partially reflective seawall in a series of random wave experiments were measured by researchers [5, 6]. Their investigation revealed that the magnitude of the undertow is reduced in the presence of partially standing waves, which is in agreement with the work of Rakha and Kamphuis [7], indicating a reduction in undertow by reflected waves [7]. The present study is a contribution to compensate for the lack of information concerning the effect of reflective beaches on the distribution of undertow in the surf zone due to regular and random wave attack. The results of the present work can be used for the cross-shore sediment transport and beach evolution models where reflective conditions exist.

2. EXPERIMENTAL INVESTIGATION OF UNDERTOW IN THE SURF ZONE

a) Experimental apparatus and procedure

In order to consider the effect of reflective beaches on the distribution of the mean flow, a series of experiments were performed in the Coastal Engineering Laboratory of Kagoshima University, Japan. The magnitude and distribution of undertow were obtained from different cases of reflective beaches [8].

[*]Received by the editors February 25, 2007; Accepted November 4, 2008.
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Figure 1 shows the experimental set up. Monochromatic waves were generated and water particle velocities were measured in the surf zone using an Electromagnetic current meter.

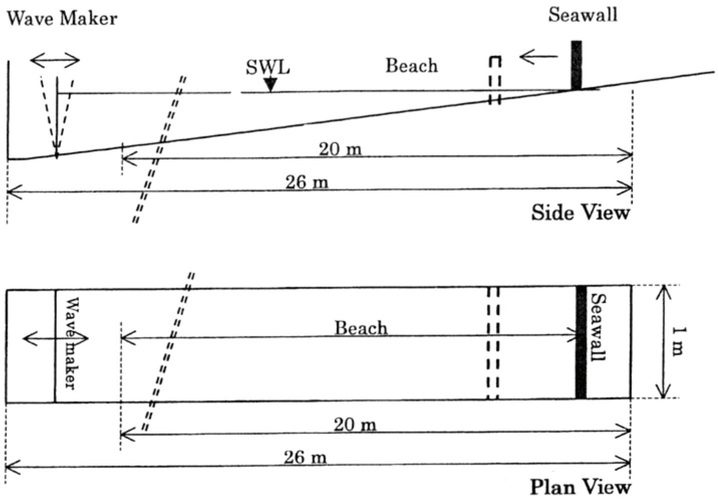

Fig. 1. Illustration of the experimental set up for regular wave experiments

The overall dimensions of the tank were 1.00 m wide, 1.2 m deep and 26 m long. A plane beach profile with a constant slope of 1:20 was built at the end of the tank. Waves were generated at one end of the tank by a wave generator controlled by an electro-hydraulic system and the water particle velocities were measured in the surf zone using a two-component Electro-magnetic current meter. Different horizontal locations were chosen in the surf zone, where measurements were made at several points between the bottom and still water level. The locations for all measured points are given in Table 1.

The measured points were in the middle of the flume (0.50 m from the inside face of the side-wall). Additionally, a resistance type wave gauge measured the water surface elevation (synoptic with the velocity measurements) at each location. Also, a deepwater wave gauge was mounted further offshore to measure the deep water incident wave spectrum. Data was acquired and analyzed using a personal computer with a sampling rate of 20 Hz for each channel. The recording length was 3.5 minutes taking approximately 200 waves into account. A solid-reflective wall was placed at different locations across the surf zone and the velocity measurements were repeated in front of the structure.

Table 1. Specifications of measured points

Position	Distance from Shoreline (m)	Water Depth (m)	Elevations above the Bed (mm)
1	1.00	0.0500	5 to 45
2	1.25	0.0625	5 to 55
3	1.50	0.0750	5 to 65
4	1.75	0.0875	5 to 75
5	2.00	0.1000	5 to 85
6	2.25	0.1125	5 to 95
7	2.50	0.1250	5 to 115
8	2.75	0.1375	5 to 125
9	3.00	0.1500	5 to 135
10	3.25	0.1625	5 to 155
11	3.50	0.1750	5 to 165
12	3.75	0.1875	5 to 175
13	4.00	0.2000	5 to 185
14	4.25	0.2125	5 to 195
15	4.50	0.2250	5 to 205
16	4.75	0.2375	5 to 225
17	5.00	0.2500	5 to 235

b) Monochromatic wave experiments

Table 2 summarized the different wave conditions (wave heights and wave periods) used in the experiments. The reflection coefficient of the beach was measured using the moving probe method to detect the envelope of partially standing waves formed in front of the seawall.

Table 2. Characteristics of monochromatic waves used in the experiments

Deep Water Wave Height (m)	Wave Period (s)	Deep Water Wave Length (m)	Deep Water Wave Steepness
0.100	2.0	6.24	0.016
0.125	1.5	3.51	0.036
0.150	1.0	1.56	0.096

Figure 2 shows the variation of the wave height across the beach for one of the wave conditions used in the experiments. As can be seen, the wave attenuation model based on the linear wave theory can predict the measured data with a reasonable level of accuracy. However, at the breaking point, a discontinuity can be observed in the prediction, due to the different criteria used in the wave transformation phase of the model to predict the attenuated wave heights before and after the breaking point, respectively.

In the present model, the wave height in the offshore region of the breaking point, i.e. outside the surf zone, was computed based on the linear shoaling coefficient [9]; whereas inside the surf zone a wave decay model based on a linear relationship between the broken wave height (H_b) and water depth (h) was used ($H_b = \gamma h$ in which γ is the breaker index normally taken as 0.78). Therefore, just at the breaking point, a discontinuity in the model prediction can be observed.

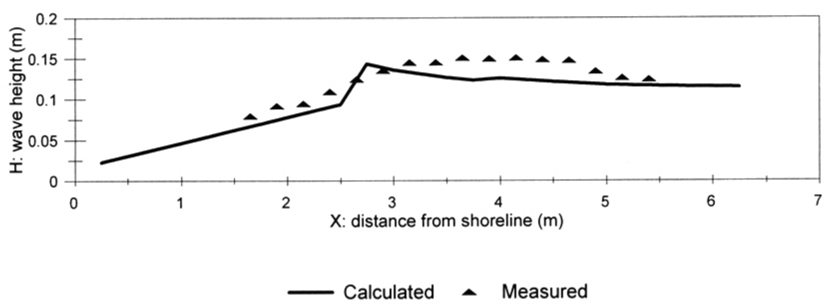

Fig. 2. Comparison between calculated and measured wave heights across the profile for one of the wave conditions (H=12.5 cm and T=1.5 sec)

The velocity was measured for three cases of seawall location; i.e., without seawall, and seawall located in the surf zone with 50 and 100 mm water depths in front of the wall, respectively. The results were compared with those obtained from natural beaches (with no reflection) and existing theoretical models. The main objective was to undertake a quantitative comparison of the undertow in two cases (i.e. with and without reflective conditions).

Figure 3 shows a comparison of the measured wave heights for one of the wave conditions and different locations of the seawall. The effect of partially standing waves and the resulting rise in the wave heights can be seen in Fig. 3. Using the measured envelopes of the partially standing waves for different wave conditions in front of the seawall, the reflection coefficients of the beach were obtained within the range of 10% to 30%.

Figure 4 shows the effect of beach reflection on the measured set up across the profile for one of the wave conditions used in the experiment. As can be seen, partially reflected waves have caused the breaking point to be shifted slightly offshore, resulting in the reduction of both wave set down and set up. This, in turn, will cause a reduction in the undertow inside the surf zone, which is in agreement with the velocity measurements. It should be noted that there is a small rise in the mean water level due to the formation of partially standing waves close to the seawall, which can affect the set up measurements in that region.

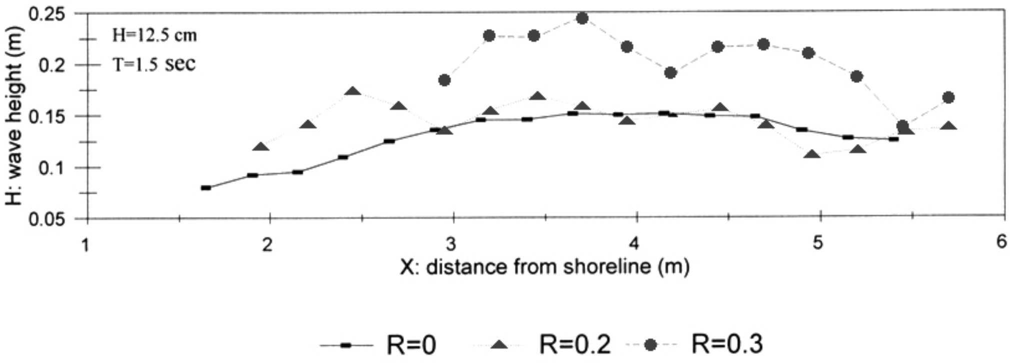

Fig. 3. Comparison between measured wave heights across the profile for different coefficients of the beach (R) using one of the wave conditions (H=12.5 cm and T=1.5 sec)

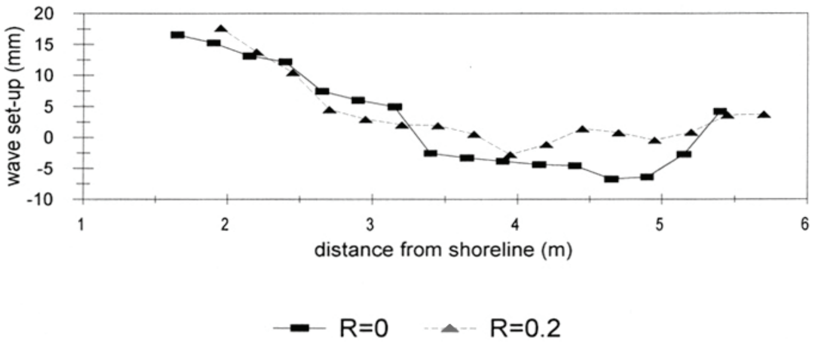

Fig. 4. Comparison between measured wave set up (and set down) across the profile for different coefficients of the beach (R) using one of the wave conditions, (H=12.5 cm and T=1.5 sec)

Figure 5 shows examples of comparison between the measured vertical distributions of undertow for non-reflective and reflective beaches for different wave conditions used in the experiments. The locations of the measured points were selected in such a way that a wide range inside and outside the surf zone were covered. As can be seen, it is clear that the undertow was reduced in front of the reflective wall and this reduction was more significant for the higher reflection coefficient of the beach.

Figure 6 contrasts the horizontal distributions of undertow for the non-reflective beach with those obtained in front of the seawall for a particular point above the bed and for different wave conditions. As indicated in this figure, the reduction of undertow for reflective beaches is more significant for the points inside the surf zone. As for further offshore points, because of the small magnitude for undertow, the reduction due to the reflective conditions of the beach is not pronounced.

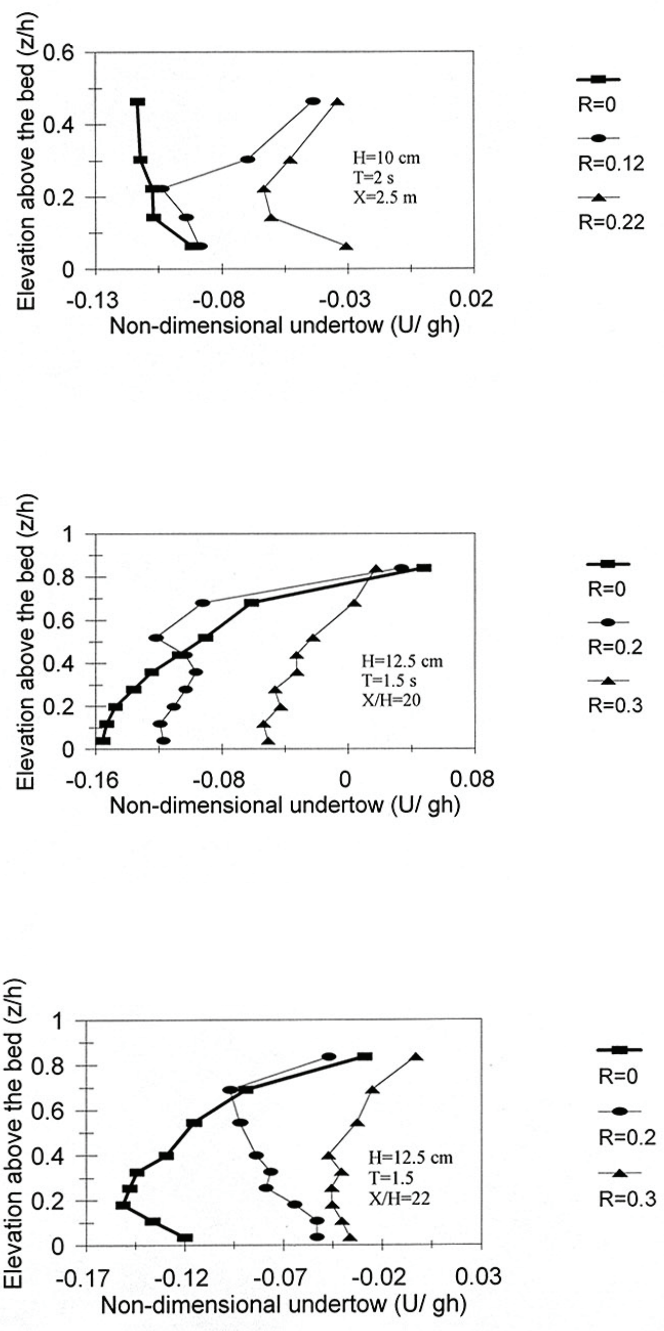

Fig. 5. Comparison between measured undertows for different reflection coefficients of the beach (R) and different locations across the profile (X/H) using different wave conditions

3. THEORETICAL DEVELOPMENT

A model was presented to estimate the distribution of undertow in the surf zone for arbitrary beach topography [2]. Here, a modification of that theory is presented which takes the effects of reflected waves into account. Radiation stress, wave set up and mass flux due to the wave motion are modified to take the effects of reflected waves into consideration.

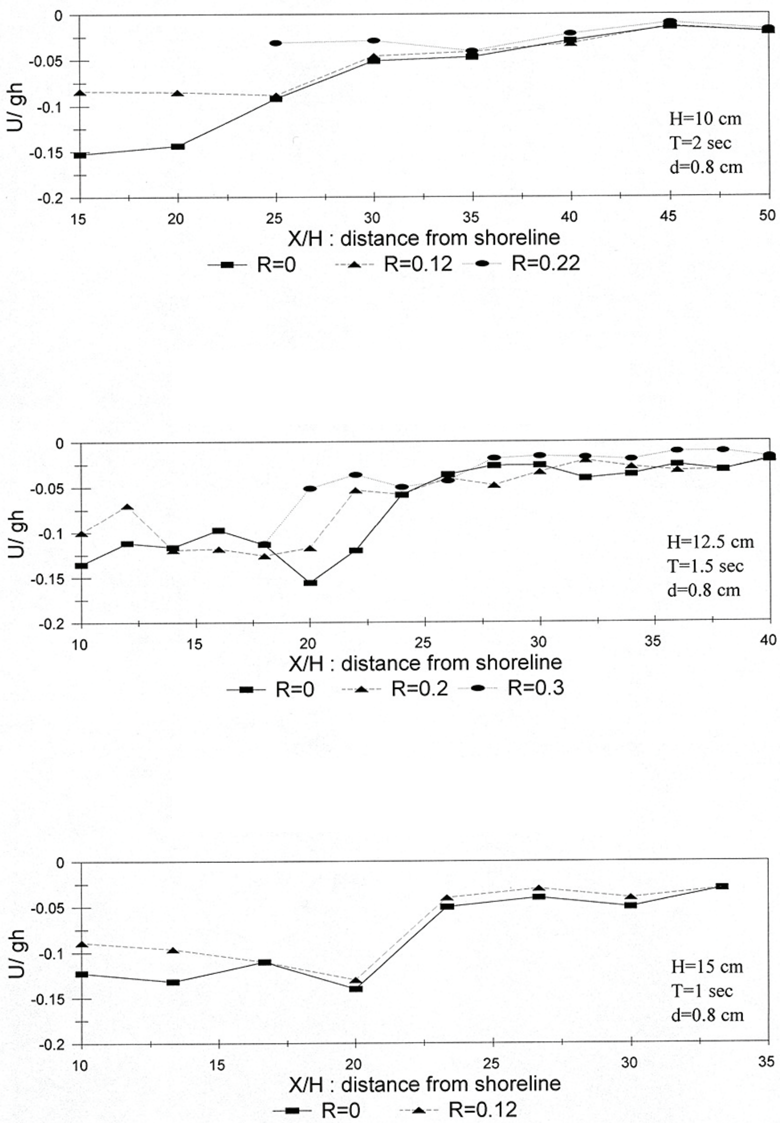

Fig. 6. Comparison between measured undertows across the profile at 0.8 cm above the bed for different reflection coefficients of the beach (R) using different wave conditions

The basic equation to calculate the vertical distribution of undertow in the surf zone is given by [2]:

$$U = \frac{a'_\tau}{a_v}(z' - \frac{d_t}{2}) + \frac{a_v b'_\tau v}{a}(1 + \log\frac{a_v z' + v}{a_v d_t + v} - \frac{v}{a_v d_t}\log\frac{a_v d_t + v}{v}) + U_m \tag{1}$$

where:

U = undertow at elevation z' from the bed

U_m = mean undertow below trough level (calculated from Eq. (7))

v = kinematic viscosity of water

d_t = water depth at wave trough

and a_v, a'_τ and b'_τ are calculated based on the following equations [2, 3]:

$$a_v = 0.06h\rho^{-\frac{1}{3}} D_B^{\frac{1}{3}} d_t^{-1} \tag{2}$$

$$a'_\tau = \frac{1}{15}\rho^{\frac{1}{3}} D_B^{\frac{2}{3}} d_t^{-1} + \frac{va^2\sigma k}{2h^2 \sinh^2 kh}(3kh\sinh 2kh + \frac{3\sinh 2kh}{2kh} + \frac{9}{2}) \tag{3}$$

$$b'_\tau = -\frac{1}{75}\rho^{\frac{1}{3}} D_B^{\frac{2}{3}} - \frac{va^2\sigma k}{4h\sinh^2 kh}(2kh\sinh 2kh + \frac{6\sinh 2kh}{2kh} + 9) \tag{4}$$

in which:
ρ = density of water
a = wave amplitude
σ = wave angular frequency
κ = wave number
h = mean water depth
D_B = rate of energy dissipation by wave breaking (calculated from Eq. (5))
The energy dissipation rate is calculated based on the linear wave theory on a constant slope and can be expressed as [10]:

$$D_B = \frac{5}{16}\rho g^{\frac{3}{2}}(\tan\beta)\gamma H^2 h^{\frac{3}{2}} \tag{5}$$

where:
g = acceleration of gravity
$\tan\beta$ = bottom slope
γ_H = ratio of wave height to water depth
It has to be noted that in the present model the concept of variable eddy viscosity through depth is used to derive the vertical distribution of undertow. The eddy viscosity can be expressed as:

$$v_e = 0.06\rho^{-\frac{1}{3}} D_B^{\frac{1}{3}} \frac{h}{d_t} z' \tag{6}$$

The vertically averaged value of the undertow is calculated based on the following equation:

$$U_m = -\frac{1}{d_t} M_t \tag{7}$$

In which the total mass flux by the breaking wave, M_t, is calculated as:

$$M_t = M_w + M_v \tag{8}$$

It can be seen that inside the surf zone, the total mass flux by the breaking wave is caused by the mass flux due to the wave motion, M_w, and organized large vortexes, M_v. Outside the surf zone, however, the mass flux is caused only by the wave motion. The following equations are used to calculate the mass fluxes:

$$M_w = \frac{1.6c}{\rho g h} E_p \tag{9}$$

$$M_v = 0.09\rho H c \tag{10}$$

where:

c = wave celerity
H = wave height (in case of random waves, sum of the broken wave heights [11])
E_ρ = potential energy of wave motion $(\frac{\rho g H^2}{16})$

For the conditions in which the reflected waves exist, the mass flux by the reflected wave, M_w, is subtracted from the total mass flux to modify the mass balance in the surf zone. It is assumed that the reflected waves reduce the total mass flux in the surf zone with the consequence of reduction in the mean undertow according to Eq. (7). Therefore, for reflective beaches, the total mass flux by breaking and reflected waves can be written as:

$$M_t = (M_w + M_v)_i - (M_w)_r \tag{11}$$

in which subscripts i and r represents the incident and reflected waves, respectively. The reflected wave height can be calculated as RH where R is the reflection coefficient of the beach. Although in the case of random waves the reflection coefficient is a function of frequency and varies for different wave components, at this stage of calculations an average reflection coefficient is used to modify the wave height.

Finally, calculation of the wave set up in the surf zone is based on the mean balance of the onshore momentum equation [10]:

$$\frac{ds_{xx}}{dx} + \rho g h \frac{d\overline{\eta}}{dx} = 0 \tag{12}$$

where:
x = horizontal coordinate in cross-shore direction
S_{xx} = radiation stress
$\overline{\eta}$ = wave set up
The component of radiation stress tensor normal to the shore can be calculated based on linear wave theory as:

$$S_{xx} = (\frac{1}{2} + \frac{2kh}{\sinh 2kh})E \tag{13}$$

where:
E = total energy of the wave $(\frac{\rho g H^2}{8})$
$h = d + \overline{\eta}$, d being still water depth

It is to be noted that for the case of reflected waves the radiation stress component should be modified by adding an extra term representing the radiation stress due to the reflected wave. This will result in a modified wave set up in the surf zone. Therefore, the total radiation stress can be written as:

$$S_{xx} = (S_{xx})_i + (S_{xx})_r \tag{14}$$

in which $(S_{xx})_r$ represents the radiation stress for the reflected wave and can be calculated from the reflected wave height.

In summary, it can be concluded that reflected waves modify the radiation stress; wave set up and mass flux in the surf zone, which will, accordingly, change the undertow. It should be mentioned that in the case of random waves, wave transformation across the profile is calculated based on the Goda [12] method which includes the shoaling of irregular waves outside the surf zone and wave height decay model for inside the surf zone. The fraction of broken wave heights, Q_b, is calculated based on Battjes and Janssen [10]:

$$\frac{1 - Q_b}{-\ln Q_b} = (\frac{H_{rms}}{H_b})^2 \tag{15}$$

where H_b, is the wave height at the breaker point and according to Goda [12]:

$$\frac{H_b}{L_0} = A\{1 - \exp[-1.5\frac{\pi h}{L_0}(1 + 15\tan^{\frac{4}{3}}\beta)]\} \tag{16}$$

where:

$\tan\beta$ = slope of the bottom

L_0 = deep water wave length

h = water depth

And parameter A varies between 0.12 for the lower and 0.18 for the upper breaking limit.

4. RESULTS AND DISCUSSIONS

Figures 7 and 8 show examples of comparison between the predicted and measured undertows for different locations across the surf zone using different regular wave conditions. Calculated undertows are based on the proposed model introduced in the present work.

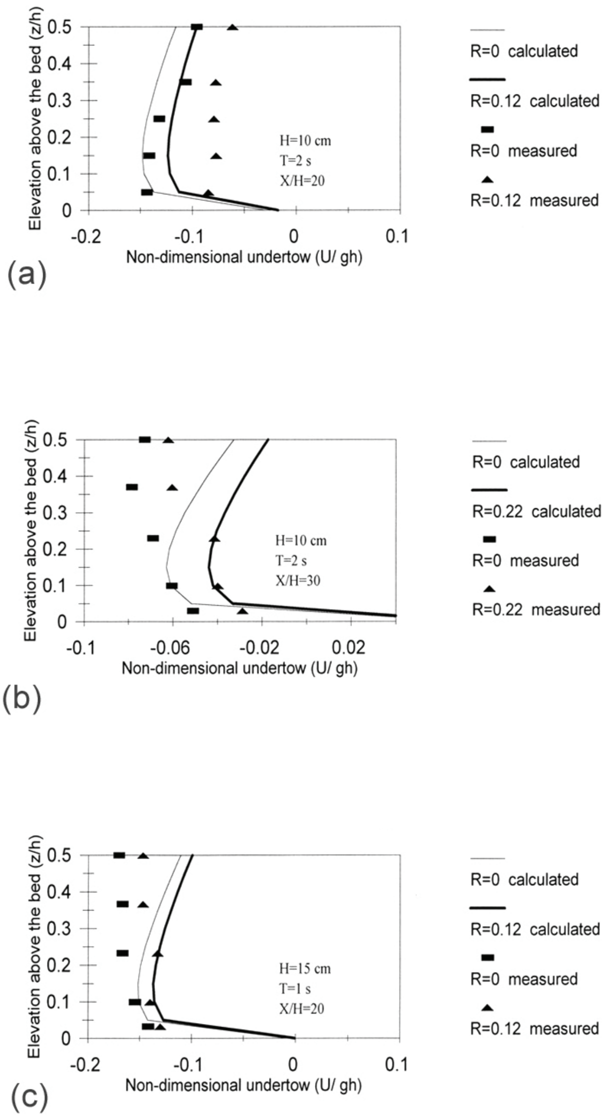

Fig. 7. Comparison between calculated and measured undertows for different reflection coefficients of the beach (R) and different locations across the profile (X/H) using different wave conditions

Comparison between calculated and measured undertows, as indicated in these figures, shows good agreement, particularly for the locations inside the surf zone. The discrepancy for further offshore points could be attributed to the small magnitudes of undertow at those points.

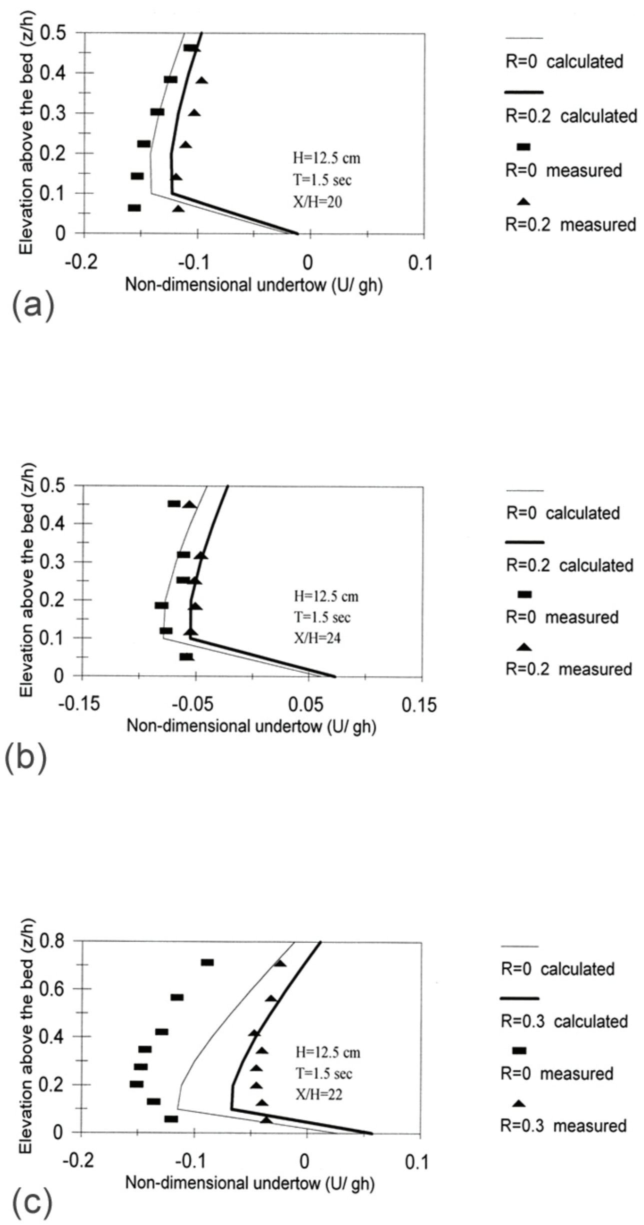

Fig. 8. Comparison between calculated and measured undertows for different reflection coefficients of the beach (R) and different locations across the profile (X/H) using one of the wave conditions

Comparison of the predicted and measured horizontal distribution of undertow in the surf zone for different cases of reflective beaches, as shown in Fig. 9, clearly indicates the applicability of the proposed model to predict the effect of beach reflection on the mean flow velocity for different cases of regular waves. It should also be noted that the effect of turbulence has not been included in the present model. Clearly, there is a need to improve the model by including the effect of turbulence and interaction between incident and reflected waves in the surf zone.

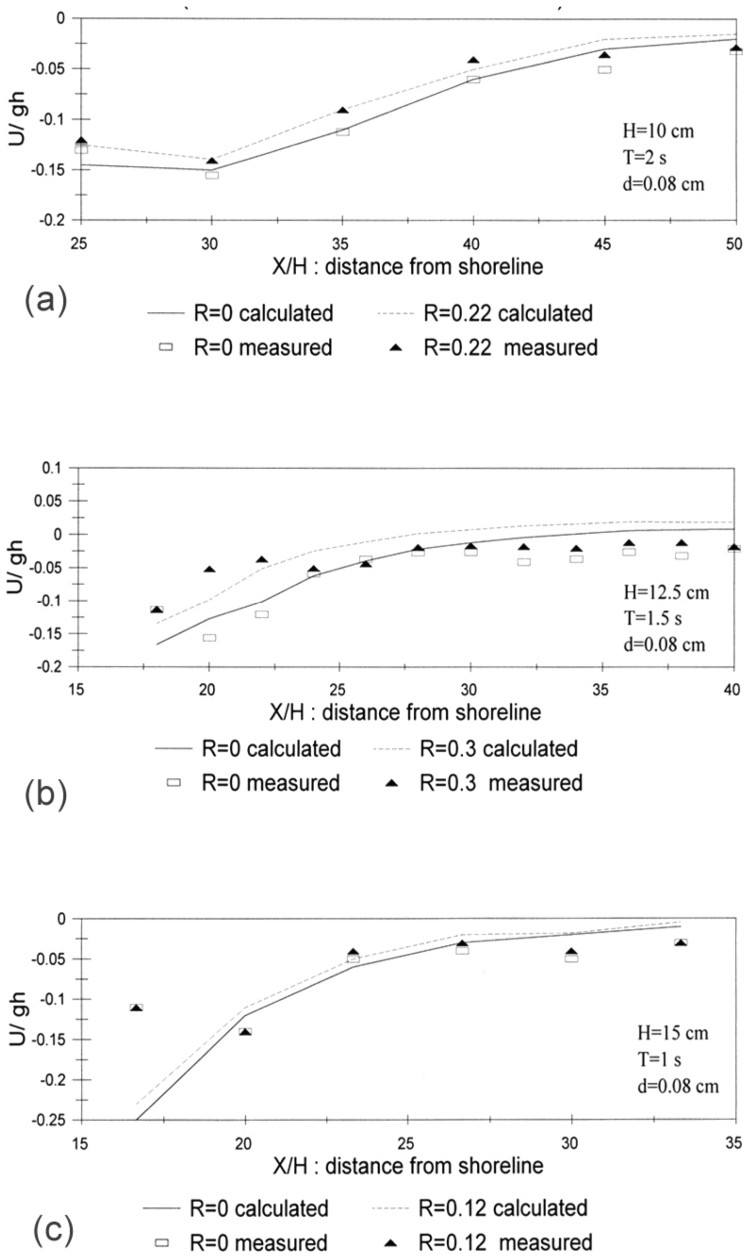

Fig. 9. Comparison between calculated and measured undertows across the profile at 0.8 cm above the bed for different reflection coefficients of the beach (R) using different wave conditions

5. CONCLUSION

The presence of partially standing waves due to reflective conditions in the surf zone results in a reduction in the magnitude of the mean flow (undertow) and changes its distribution across the surf zone. The level of reflectivity of the beach is an important parameter to control the magnitude and distribution of the undertow. The results obtained from experiments and theoretical investigations show that as the reflection coefficient of a beach increases, the magnitude of undertow reduces, which can affect the offshore sediment transport rate in the surf zone. This reduction is more pronounced for the inner surf zone points. The results obtained from regular and random wave experiments are consistent and clearly support the conceptual elements of the proposed model to predict the undertow for reflective beaches.

NOMENCLATURES

a	wave amplitude
c	wave celerity
d_t	water depth at wave trough
D_B	rate of energy dissipation by wave breaking
E	total energy of the wave
E_ρ	potential energy of wave motion
g	acceleration of gravity
h	water depth
H	wave height
H_b	wave height at the breaker point
κ	wave number
L_0	deep water wave length
U	undertow at elevation z' from the bed
U_m	mean undertow below trough level
S_{xx}	radiation stress
$(S_{xx})_r$	radiation stress for reflected wave
x	horizontal coordinate in cross-shore direction
$\tan\beta$	bottom slope
$\overline{\eta}$	wave set up
ρ	density of water
γ_H	ratio of wave height to water depth
σ	wave angular frequency
v	cinematic viscosity of water

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