CHAPTER 259

Wave on pebble beach and deformation of pebble beach

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Abstract

Hydraulic function of pebble are investigated by carrying out 2-D experiments in laboratory. Numerical model for predicting wave height and wave run-up are developed by applying a Boussinesq type equation and a non-linear unsteady Darcy's law for the fluid motion on the pebble beach and in the pebble layer. The applicability of the model are examined using experimental results. Deformation of pebble beach are also measured in the field and laboratory to investigate the applicability of Dean's profile and to examine the shoreline change by a single-line theory.

Introduction

Urban coastal region in Japan have been developed in various ways for various purposes. Especially, after the World War II, through the post-war industrial reconstruction, Japan experienced a rapid and high economic growth. During that period, a large part of natural shoreline around big cities in Japan disappeared by the reclamation for heavy industries. As a result, public access to the shoreline decreased and natural coastal environment was lost. Recently, there are strong demands for restraining lost natural coastal environment and creating new pro-water front structures to increase public access to the coast and coastal amenity.

Target structure of this study is the pebble beach constructed as a permeable gentle slope seawall to increase public access and improve coastal view. It is usually permitted for such kind of pebble beaches to deform their profiles until they lose their originally expected function. The aims of this study are to examine hydraulic function of pebble beach and to establish numerical model for predicting wave transformation and run-up on pebble beach through carrying out two dimensional experiments. Characteristics of deformation of pebble beach is also investigated by using experimental results and field data.

2-D experiments on the hydraulic function of pebble beach

Experimental set-up and conditions:

Hydraulic function of pebble beach was examined by carrying out two-dimensional experiments in a laboratory. Figure 1 shows a rough sketch of the experimental set-up.

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We examined two slopes 1/10 and 1/5 constructed by pebbles of different sizes in a wave tank of 27m long, 1,9m high and 1,5m wide. To investigate the effect of permeability of the slope on incident wave, wave run-up, reflection, we also conducted the same measurements on the impermeable slope. The mean diameter D of the larger one was about 4.1cm and that of smaller one was 1.8cm. Table 1 shows the permeability k_p, turbulent drag coefficient C_f, added mass coefficient C_m and void ratio λ of these two pebbles obtained from the unsteady permeability tests. Depth at the horizontal bottom was varied from 25cm to 55cm and incident wave height was in the region of 6cm to 14cm with the period of 1.2s to 2.0s.

Surface displacement was measured between 0.5m landward from the shoreline and horizontal bottom. When deformation of pebble beach took place, we recorded the profile.

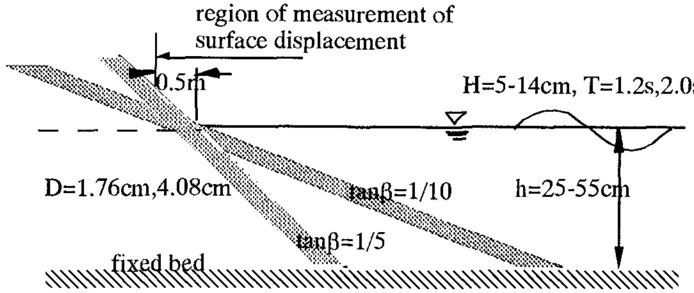

Figure 1 Experimental set-up

Table 1 Characteristics of pebbles

D (cm)	k_p (cm^2)	C_f	C_m	λ
4.08	0.0038	0.151	1.0	0.47
1.76	0.0015	0.255	1.0	0.46

Wave height distribution on pebble beach:

Figures 2 and 3 show measured cross-shore distribution of wave height on pebble beach and on impermeable slope of the slope 1/5 and 1/10. Incident wave period and height on horizontal bottom in both figure are 1.6s and 14cm and water depth at horizontal bottom was 50cm. Closed and open circles are the wave height and set-up measured on the impermeable slope and another symbols are the results obtained on the pebble beaches.

Wave height on pebble beach decreases significantly when compared with that on the impermeable slope. Especially the decay of wave height on the slope of 1/10 is large because incident waves have to travel for long distance on the permeable layer when compared with the case of the slope 1/5. On the other hand, there is little difference between the wave height measured on the pebble beaches of different sizes.

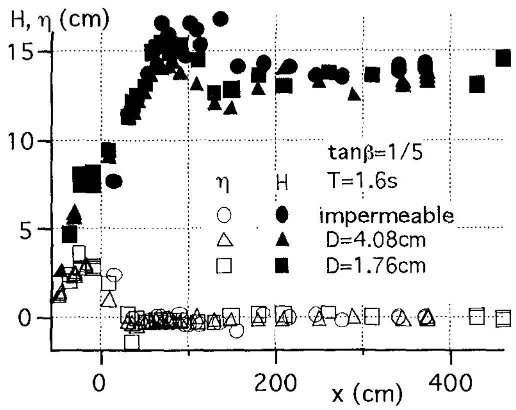

Figure 2 Wave height distribution on 1/5 slope

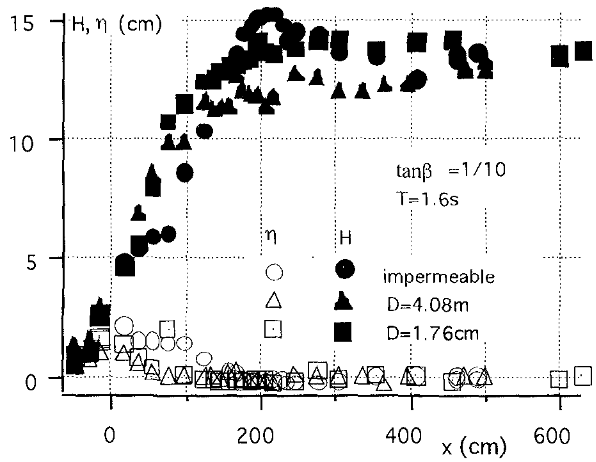

Figure 3 Wave height distribution of 1/10 slope

Wave run-up and reflection coefficient:

Figure 4 shows the non-dimensional run-up height normalized by the incident wave height R/H. The horizontal axis is the surf similarity parameter. Measured run-up height on pebble beaches shown by closed triangle and reetangle are 40 to 50% smaller than that measured on impermeable slope shown by the closed circles. Solid line in the figure show the relation R/H=ξ that is usually applied to the run-up height on impermeable slope. Broken line in the figure is the empirical result for the non-dimensional run-up height on rubble mound breakwater obtained by Losada and Kurto(1981).

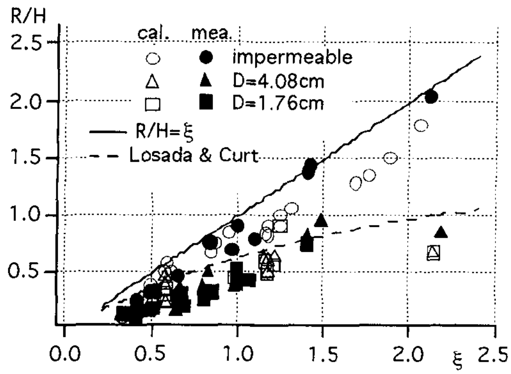

Figure 4 Wave run-up height

Figure 5 illustrates measured reflection coefficient K_r by Goda's method using two time series of measured surface displacements on the horizontal bottom. Horizontal axis is the incident wave steepness. The value of K_r in all cases are less than 30% and significant difference between the value of K_r measured on impermeable slope and pebble beaches can not be seen. K_r plotted in the region of wave steepness smaller than 0.005 is the result of long wave generated by a bichromatic waves.

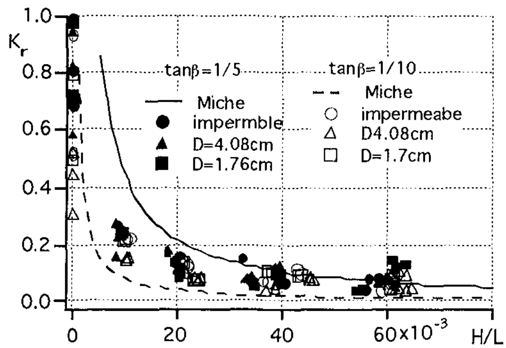

Figure 5 Reflection coefficient

Solid and broken line in the figure are the reflection coefficient on the impermeable slope of 1/5 and 1/10 evaluated by the Mich's formulae.

Numerical model for predicting wave height distribution on pebble beach

We have already proposed a simple model for estimating wave height on the permeable slope (Deguchi et al., 1995). Definition of variables and coordinate system used in the model is illustrated in Fig.6. h is the depth on pebble beach and d is the thickness of the pebble layer. For evaluating wave height on the sloping beach, we apply nonlinear shoaling model proposed by Shuto(1974) with the energy dissipation after wave breaking E_b, energy loss in the permeable layer E_p and surface drag on the pebble beach E_{fb}. These expression are shown below:

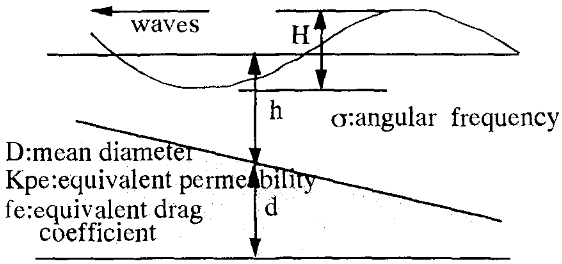

Figure 6 Definition of variables

In the calculation, wave height on the sloping beach was firstly calculated from Eq.(1) by giving incident wave height at offshore. When the wave height became grater than wave breaking height, wave height was reduced according to the energy loss by wave breaking that is given by Eq.(2) (Sawaragi, et al., 1984).

$$
\begin{aligned}
&gHT^2/h^2 \leq 30: \textit{small amplitide wave theory}\\
&30 \leq gHT^2/h^2 \leq 50: Hh^{2/7} = const.\\
&50 \leq gHT^2/h^2: Hh^{5/2}\left(\sqrt{gHT^2/h^2} - 2\sqrt{3}\right) = const.
\end{aligned}
\tag{1}
$$

$$
E_b = \alpha_1\left(5.3 - 3.3I_r - \frac{0.07}{\tan\beta}\right)\left(\frac{\left(\rho g H^2/8\right)^3}{\rho h^3}\right)^{1/2} \tag{2}
$$

where ρ is the density of water, g is the gravitational acceleration, β is the slope, ξ is the surf similarity parameter and α_1 is the empirical constant of the order of one.

When waves propagate on pebble beach, wave height is also reduced by energy dissipation on the permeability and the surface drag that are expressed by Eqs.(3) and (4) (Sawaragi et al., 1992).

$$
E_p = \frac{\rho g H^2}{4} C_g k_i \tag{3}
$$

$$
E_{fb} = \frac{2}{3}\pi^2 \frac{\rho f_w H^3}{T^3 \sinh^3 kh}(1-\lambda) \tag{4}
$$

where C_g is the group velocity, f is Jonsson's friction factor, and k_i is the imaginary wave number determined by the following dispersion relation on the permeable layer:

$$
\sigma^2 = g\mathbf{k}\frac{\left(S/f_e + i\right)\sinh \mathbf{k}h \cosh \mathbf{k}d + \left(1/f_e\right)\cosh \mathbf{k}h \sinh \mathbf{k}d}{\left(S/f_e + i\right)\cosh \mathbf{k}h \cosh \mathbf{k}d + \left(1/f_e\right)\sinh \mathbf{k}h \sinh \mathbf{k}d} \tag{5}
$$

in which $\mathbf{k}$ is the complex wavenumber and f_e is the equivalent drag coefficient defined by using equivalent permeability k_{pe} as follow:

$$
1/f_e = K_{pe}\sigma/\nu \;, f_e = 0.1 + 1.8\left(u/\sigma D_m\right) \tag{6}
$$

Figure 7 is the comparisons of measured and calculated wave height and set-up on permeable and impermeable slope of 1/10. The mean diameter of the pebble on the permeable slope was D=1.76cm. Shift of the location of breaking point and decrease in wave height are reproduced well by the model.

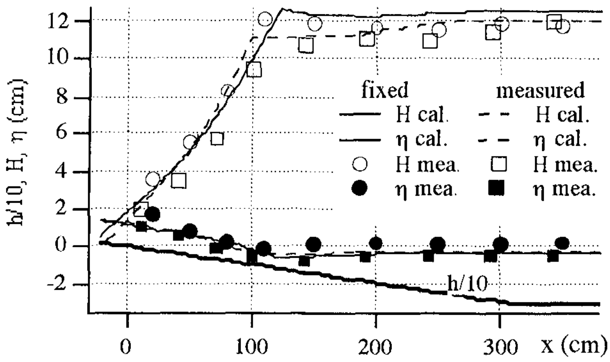

Figure 7 Comparison of measured and calculated wave height

Numerical model for predicting wave run-up on pebble beach

Some numerical model have already developed to predict wave run-up on the permeable slope (fro example, Kobayashi and Wurjanto, 1990). However, it is not sufficient to explain various non-linear phenomena including wave breaking, wave propagation into the permeable layer , wave run-up on the slope and so on. Here, we developed a numerical procedure for predicting surface displacement on the slope in a coordinate system shown in Fig.8. To construct numerical model, we neglected a vertical water particle velocity and applied Boussinesq type equation and a non-linear unsteady Darcy's law for the fluid motion on and in the pebble beach. Driving force of the fluid motion on and in the pebble beach is the pressure gradient. Although pressure on the pebble beach calculated from the Boussinesq equation is not hydrostatic, driving force on fluid motion in the pebble layer is assumed to be determined by the gradient of surface displacement. Definition of variables are shown in Fig.8.

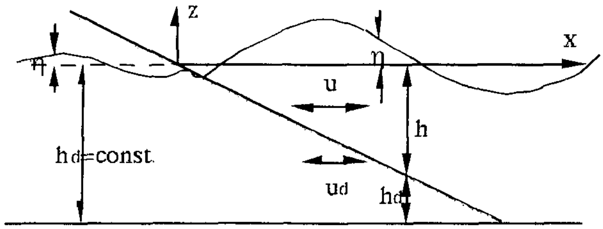

Figure 8 Coordinate system and definition of variables

Equation of motion of water particles on and in the pebble beach are expressed as follows:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+g\frac{\partial \eta}{\partial x}=\frac{h}{2}\frac{\partial}{\partial x}\left[\frac{\partial}{\partial x}\left(h\frac{\partial u}{\partial t}\right)\right]-\frac{h^2}{6}\frac{\partial}{\partial x}\left[\frac{\partial}{\partial x}\frac{\partial u}{\partial t}\right]-D_l \tag{7}$$

$$D_l=\alpha_2\frac{\partial}{\partial x}\left[\kappa g(h+\eta)\left(\frac{u}{h}\right)^2\right]+\frac{\alpha_3}{h+\eta}fu|u| \tag{8}$$

$$S\frac{\partial u_d}{\partial t}+u_d\frac{\partial u_d}{\partial x}+g\frac{\partial \eta}{\partial x}=-\frac{\nu}{K_p}u_d-\frac{C_f}{\sqrt{K_p}}u_d|u_d| \tag{9}$$

$$S=\{1+(1-\lambda)C_m\}/\lambda$$

where u and u_d are the water particle velocity on the pebble beach and in the pebble layer, ρD_l is the momentum dissipation, κ is Karman's constant, α_2 and α_3 are the empirical constants.

Equation of continuity of the fluid motion on the horizontal bottom and on the pebble beach are expressed by the following two equations.

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}[(\eta+h)u]=0 \tag{10}$$

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}[(\eta+h)u+h_d u_d]=0 \tag{11}$$

In the region shoreward of the wave front on pebble beach, h in Eq(11) becomes zero.

These equations are transformed into finite difference equations and are solved by giving time variations of surface displacement and water particle velocity at the offshore boundary. Continuity condition of surface displacement inside and on the pebble beach is imposed. A so-called moving boundary condition is used to determine the location of wave front on the pebble beach.

Figure 9 illustrates a comparison of calculated and measured surface displacements in the breaker zone on the pebble beach of the slope 1/5 of large grain size.

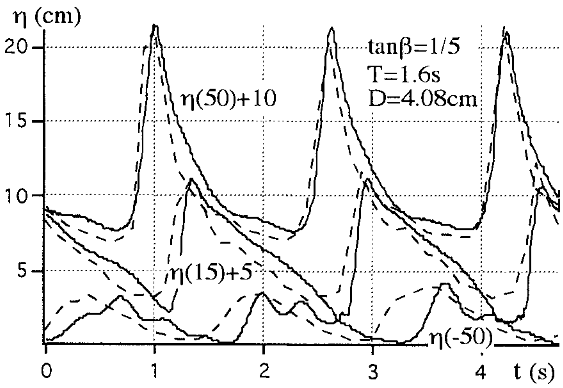

Figure 9 Comparison of calculated and measured time variation of surface displacement

In the figure, η(-50), η(15) and η(50) are the surface displaeements at -50em , 15em and 50em from the initial shoreline, solid and broken lines are the ealeulated and measured surfaee displaeement. Caleulated and measured surfaee displaeements in front of the pebble beaeh, η(15) and η(50), coineide well with eaeh other. Caleulated amplitude of the surfaee displacement in pebble beach, η(-50), also reproduces the measured one. However, the time variation of measured surfaee displaeement is smooth when eompared with the caleulated result and there is a small phase lag between them. Until now, we ean not explain the reason of these diserepancy.

Figure 10 is an example of caleulated surfaee profiles drawn at time interval of 0.2s on impermeable slope of 1/5. Ineident wave period is 2.0s.

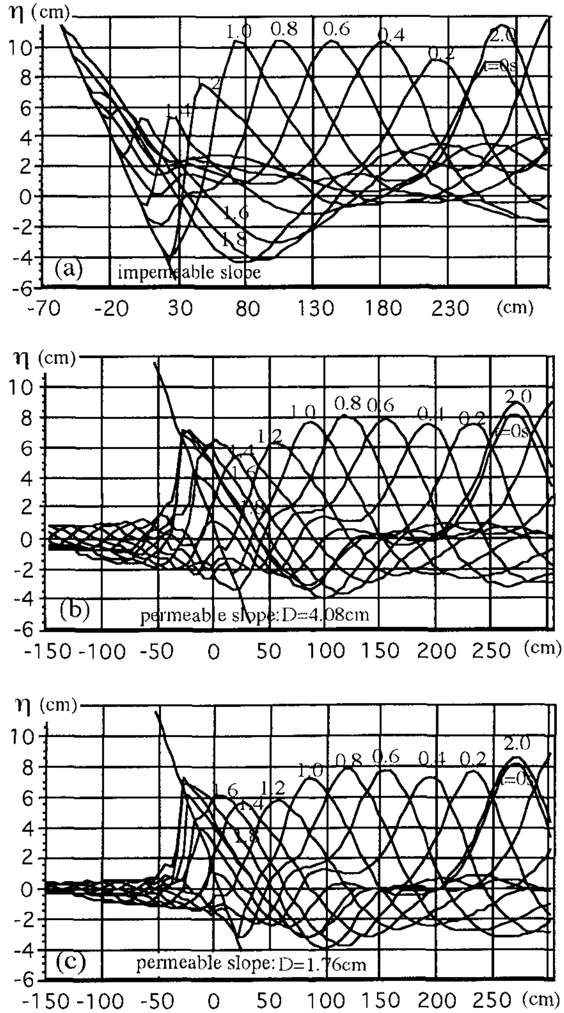

Figure 10 Surfaee profile in front of impermeable slope and pebble beaeh

Figure(a) is the result on the impermeable slope and Figures(b) and (c) are the results on the pebble beach of different materials. The maximum run-up height on the impermeable slope is almost the same as the incident wavc height. Run-up height on thc pebble bcach of large materials under thc same wave conditions shown in Fig,(b) is smaller than the incident wave height and even in the permeable layer, surface displacement of the amplitude of more than 1cm exists. Run-up height on the pebble beach of small materials shown in Fig.(c) is almost the same as that in the former case but the amplitude of the surface displacement in the permeable layer is smaller then the former case.

Open symbols in Fig.4 are the run-up height determined from the calculated surface profiles examples of which are shown in Fig.10. Although the predicted run-up height on both pebble beach and impermcable slope are a little bit smaller than those of the measured results, the decrease in the run-up height on a pebble beach is expressed by the numerical model.

Characteristics of topography change of pebble beach

Field and laboratory experiments:

We examined the characteristics of the deformation of the pebble beach based on the bottom topographies measured in two dimensional experiments and field measurements. In the experiments, significant deformation took place only in the case of pebblc beach of small materials of the slope of 1/5. Field measurement were carried out on the artificial pebble beach constructed as a gentle slope seawall of the reclamation just landward of the Kansai International Airport in Osaka Bay as shown in Fig.11. The total length of the beach is about 3km and we measured bottom topography in one section of the beach surrounded by two groins. The length of the section is 300m. Construction of the beach finished in March 1992. In this paper, characteristics of the deformation arc discussed based on the measured results on October 1995 about 3.5ycars after the construction of the beach.

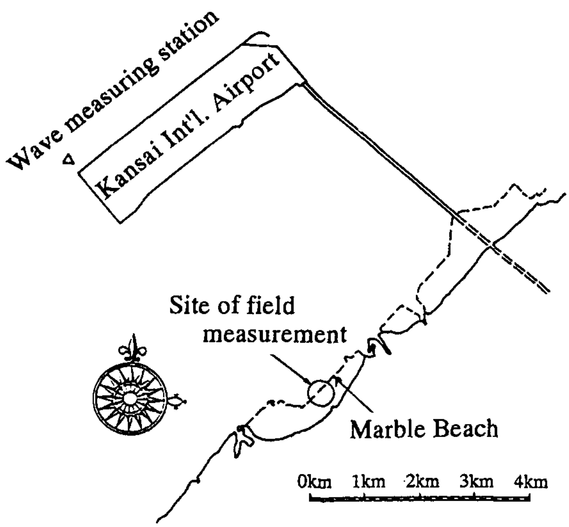

Figure 11 Location of field measurement

The representative planned cross-section of the beach is shown in Fig.12. Average depth at the toe is about 5m and the slope of the beach is 1/15. The surface of the beach is covered by pebbles of marble of the diameter 4-10cm. The thickness of the cover layer is 1m. We call this beach as Marble Beach.

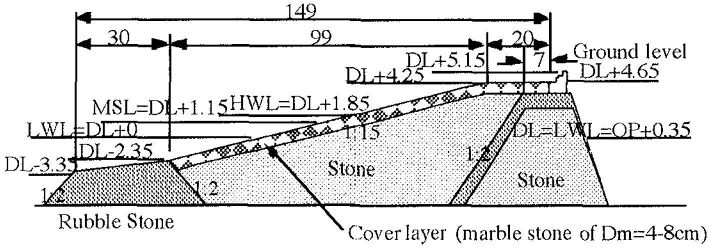

Figure 12 Representative cross-section of the Marble beach

Bottom topography was measured along 15 measuring lines set at an interval of 20m. Figure 13 illustrates the bottom topography when we see the beach from the land. There are groins at both side of this section.

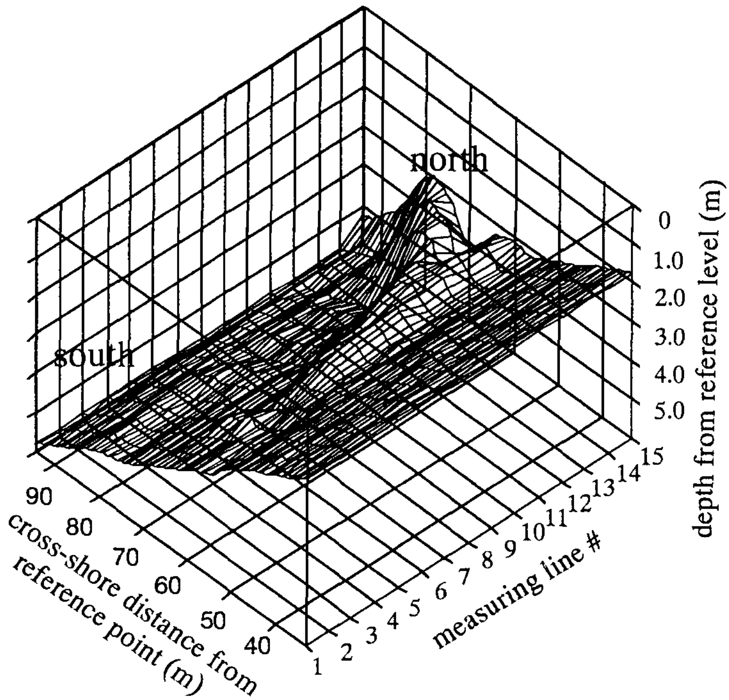

Figure 13 Measured topography of Marble Beach

Characteristics of topography change took place on Marble Beach:

In Fig.13, two berm crests can be seen at the north side of the beach and it is easy to imagine that pebbles were transported landward to form landward berm at first stage of the deformation and then they were transported from south to north to form the second berm. According to the empirical eigenfunction analysis, it is found that about 60% of the total deformation was caused by the longshore pebble transport and about 30% was caused by the net onshore pebble transport. Measuring line #15 is the north end of the beach and #8 is almost the neutral section for the topography change due to longshore transport.

Applicability of 2/3-power law:

Figures 14 and 15 are the representative cross-sections measured on the Marble Beach and in the laboratory.

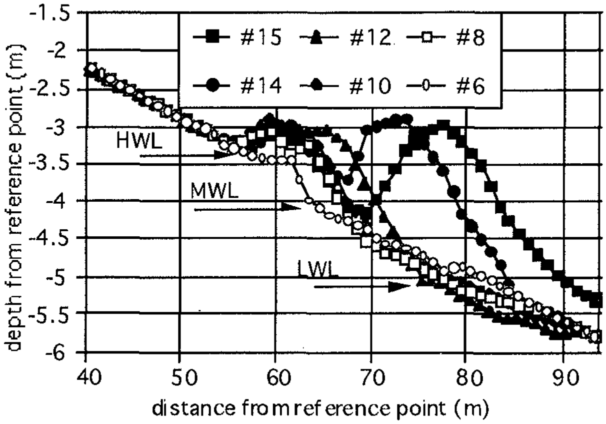

Figure 14 Representative measured cross-sections of Marble Beach

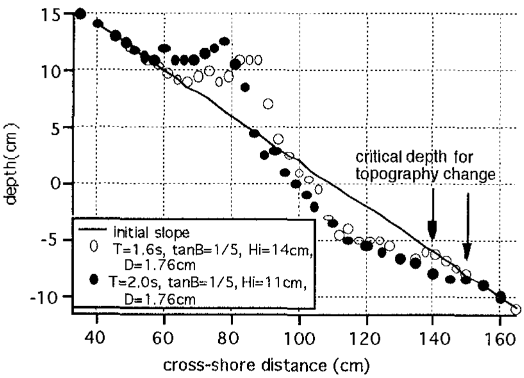

Figure 15 Measured cross-sections in experiments

Both sections shown in the figure, as well as those shown in Fig.14, are the typical accretion-type profile. We examined the applicability of the 2/3-power-law to these sections. Bruun(1962) and Dean(1991) proposed the equilibrium beach profile that is expressed by Eq.(12).

$$h = Ax^{2/3} \tag{12}$$

where h is the depth of the equilibrium beach profile, x is the cross-shore distance and A is the empirical constant.

Dean (1991) gave physical meaning to Eq.(12) from the view point of energy dissipation in the surf zone and proposed the following empirical expression for the value of A as a function of settling velocity of the bed material W_f.

$$A = 0.067W_f^{0.44} \tag{13}$$

We examined the applicability of the expression of Eq.(12) to the measured profile of pebble beach in the laboratory and in the Marble Beach. Figures 16 and 17 are the results. Profiles of both laboratory and field roughly coincide with the predicted profiles with the value of A 0.34 and 0.4, respectively.

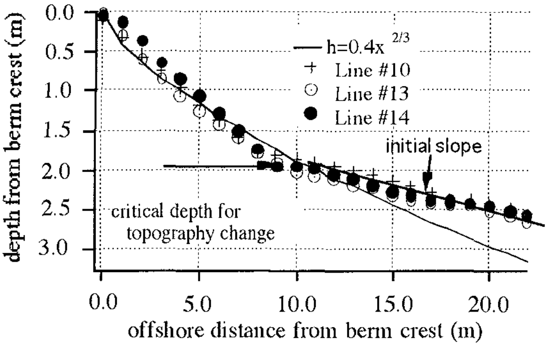

Figure 16 Comparison of Dean's profile and that measured on Marble Beaeh

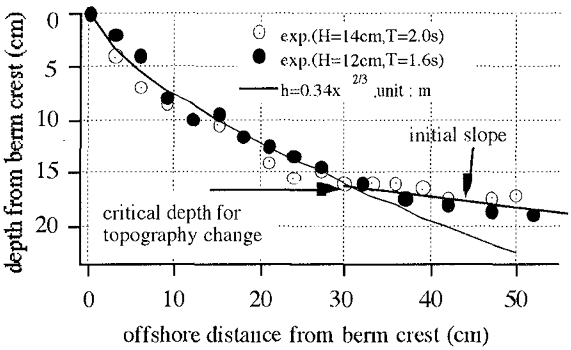

Figure 17 Comparison of Dean's profile and that measured in experiments

Shoreline change:

To evaluate total energy flux to the beach, we used wave records measured at observation station near the Kansai International Airport where various quantities eoncerning with the sea state are measured at one hour interval.

The total incident wave energy flux are evaluated from south to north and from north to south separately. The result is shown in Table 2. Energy flux from south to north is larger than that from north to south. Using this result together with the calculated volume of pebbles that were transported from south to north, we determined the longshore pebble transport rate and one representative wave to calculate location of contour line by a so-called one line theory.

Table 2 Incident wave energy flux in longshore direction (ton)

	1992	1993	1994	1995	total
from south to north	107280	178740	136656	68076	490752
from north to south	45720	61128	56988	32580	196416

It is found that the total longshore pebble transport rate Q_y is related to the longshore energy flux of incident waves in deep water by the following relation:

$$Q_y\left(m^3/day\right) = 0.036\left(EC_g\right)_o \sin\theta\cos\theta\left(t/m/day\right) \qquad (14)$$

where $(EC_g)_O$ is the incident wave energy flux in deep water and θ is the incident wave direction.

Figure 18 is the comparison of the calculated shift of the -4m contour line and measured location of the same contour line. As can be seen from the figure, -4m contour line almost becomes equilibrium 4 years after the construction and the measured location coincides calculated location fairly well. The measured contour line locates a little shoreward than the location of the calculated contour line. This is because the advancement of the contour line caused by the net onshore pebble transport is not taken into account in the calculated location of the -4m contour line.

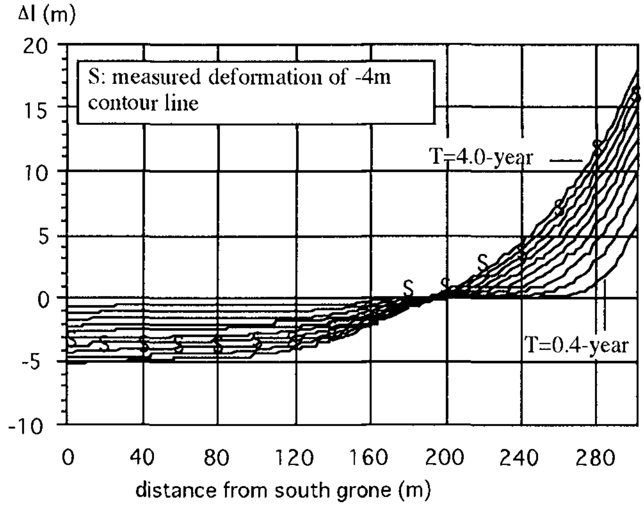

Figure 18 Comparison of measured and calculated deformation of -4m contour line

Conclusions

In this paper, numerical models for predicting wave height and run-up on pebble beach are proposed and the applicability of the model are examined through the laboratory experiments. Although the proposed model is too simple to reproduce the phenomena perfectly, we can predict rough figure of the wave tun -up on pebble beach.

Characteristics of the deformation of the pebble beach are also investigated using measured bottom topography in the field and laboratory. It is found that we can apply a so-called 2/3-power law and a single line theory for the cross-sectional profile and shoreline change of pebble beach.

Acknowledgment

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