CHAPTER 220

IMPROVED 3-D BEACH EVOLUTION MODEL COUPLED WITH THE SHORELINE MODEL (3D-SHORE)

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ABSTRACT

An improved 3-D beach evolution model coupled with the shoreline model, named "3D-SHORE", was newly developed to estimate both the spatial bottom topography change and the shoreline change. In calculation of the shoreline change, the total longshore sediment transport rate is estimated by integrating the local sediment transport rate in the direction parallel to the shoreline from the breaking point to the run-up point. The applicabilities of the model were verified through comparisons with both the results of the movable bed laboratory experiment and the actual beach evolution.

INTRODUCTION

In recent years, the 3-D beach evolution model which treats only the sediment transport due to nearshore currents have been applied to many practical problems in Japan. This model, based on the depth-averaged nearshore current model, is called "Medium-term 2DH Coastal Area Model" according to de Vriend et al.(1993). The authors have presented a few attempts to quantitatively verify its field applicabilities through comparisons with the actual medium-term topographical changes around a harbor entrance during 1 to 5 years(e.g. Shimizu et al., 1990, 1994). This conventional 3-D beach evolution model have reached the stage of being applicable for engineering use to estimating the volume of maintenance dredging around a harbor entrance and to investigating an effective countermeasure against harbor shoaling. It is, however, difficult to estimate the shoreline change, especially shoreline retreat, because the shoreline is used to be

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treated as a fixed boundary in the model. Therefore, we cannot assess the impacts due to construction of a harbor on neighbouring beaches with good accuracy. In order to make the 3-D beach evolution model more practically useful, the model should be improved to treat the shoreline as a moving boundary and to properly estimate the shoreline change.

In this study, we developed an improved 3-D beach evolution model, named "3D-SHORE", which is coupled with the conventional shoreline model. The applicability of the model is verified through comparison with the result of movable bed laboratory experiment for the beach evolution around a detached breakwater. And we also tried to simulate the actual bottom topography changes around an offshore man-made island type fishing port during approximately a year.

IMPROVED BEACH EVOLUTION MODEL

Basic Model Concepts

Our interests are focussed on the impact assessment of neighbouring beaches due to construction of a maritime structure. It is demanded to evaluate long-term beach evolution during more than 10 years after the construction. For the beach evolution around a maritime structure, the sediment transport due to nearshore currents plays a predominant role and the contribution from cross-shore sediment transports due to waves and undertow is usually cancelled for a long period beyond approximately a year.

The shoreline model which describes only the longshore sediment transport is widely used in practise for such a case. We have recognized that the shoreline model is applicable to estimating beach evolution caused by the unbalance of sediment budget in the alongshore direction over long time scales and for broad spatial scales. However, in the vicinity of the harbor, where the nearshore circulations occur and the offshoreward sediment transport due to nearshore currents exist, the shoreline model approach has a limited applicability.

The 3-D beach evolution model which treats only the sediment transport due to depth-averaged nearshore currents, "Medium-term 2DH Coastal Area Model", is based on the same concept as that of the shoreline model. This medium-term predictive model can be, therefore, regarded as an improved version of the shoreline model, which has an advantage of estimating the spatial beach topography changes.

Another 3-D beach evolution model is a short-term predictive model which treat both longshore and cross-shore sediment transports. This model is based on the quasi-3D or fully 3D current model which can describe the vertical structure of nearshore current and undertow. In order to properly estimate the beach profile changes, the short interval iterations, probably every one or two hour repetitions are needed. The computations of the wave and current fields are, however, much time-consuming. At present, it is unrealistic to improve the short-term predictive model to properly estimate the shoreline change. We, therefore, tried to develop the 3D-SHORE for practical use by coupling the medium-term predictive model

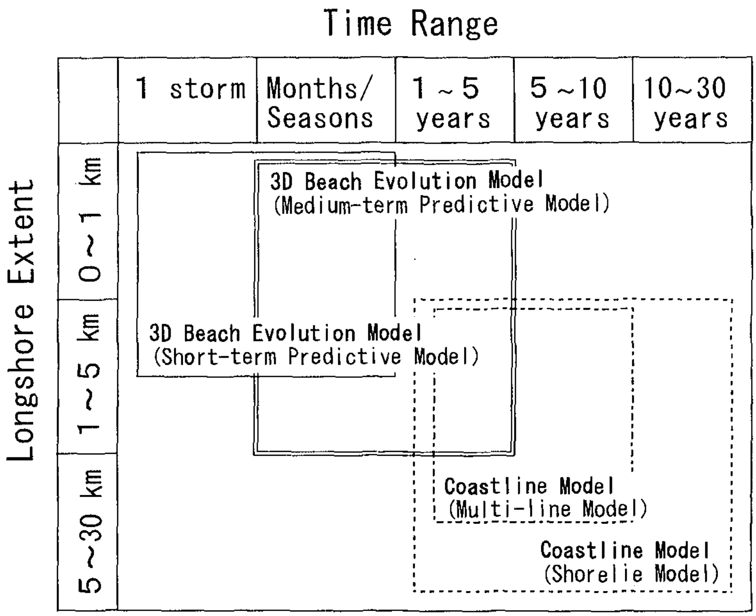


Fig. 1 Classification of numerical models of beach evolution.

Table 1 Comparisons of numerical models of beach evolution.

	Coastline Model	3D Beach Evolution Model (Coastal Area Model)	
	Shoreline Model/ Multi-line Model	Medium-term Predictive Model	Short-term Predictive Model
■Spatial Scale Temporal Scale	5~10 km 1~30 years	1~5 km 1~5 years	1~3 km 1 storm~1 year
■Current Calculation	×	2DH (Depth-averaged Nearshore Current)	• Quasi-3D : (Nearshore Current (2DH) +Undertow (1DVor2DV)) • Fully-3D
■Sediment Transport • Longshore Transport (due to nearshore currents) • On-offshore Transport (net transport due to waves + offshore transport due to undertow)	 ○ ×	 ○ ×	 ○ ○

with the shoreline model.

Fig.1 shows the classification of numerical models of beach evolution by spatial and temporal scales. The comparisons of the models are briefly summarized in Table 1.

Structure of 3D-SHORE

The flow chart of the improved 3-D beach evolution model (3D-SHORE) is shown in Fig.2. The model consists of four submodels for calculating 1)nearshore waves, 2)nearshore currents, 3)local sediment transport rate and spatial beach change, and 4)total longshore sediment transport rate by integrating local sediment transport rate and shoreline change.

The new bottom topography can be calculated by coupling the calculation results of shoreline change and spatial beach evolution. The new bottom topography is, then, fed back into the wave-current computations with appropriate intervals.

Wave Model

The waves in the swash zone play important roles on the shoreline change. In the nearshore wave model, the run-up height is estimated by the Hunt's formula, assuming the beach-face slope determined by the empirical relationship incorporating wave height, period and sediment grain size proposed by Sunamura(1984). The wave set-up and set-down are estimated by the approximate expressions for a plane beach according to Longuet-Higgins and Stewart(1962). The water depth in the swash zone is given virtually by decreasing linearly from the wave set-up height at the still water level to zero at the run-up point as shown in Fig.3. This virtual water depth is also used for calculation of the nearshore current field. Although this treatment of swash zone is not correct in a strict sense, it is a simple and effective method for engineering use in order to save computational time and take an important factor into consideration.

The parabolic-type equation model proposed by Isobe(1987) is employed in this study to properly estimate the wave field behind the offshore breakwater and man-made island and so on where combined diffraction and refraction occur. This basic equation is derived from the mild slope equation by using the wave ray-front coordinates. The energy dissipation term due to wave breaking is included. Random waves are described as a superposition of component regular waves with different frequencies and directions. The applicabilities of the model to the actual wave field were verified through comparisons with field measurement data (e.g. Shimizu et al.,1992).

Nearshore Current Model

In most of the previous computation of nearshore currents, the friction term is expressed as the general nonlinear form and a constant value has been used for the frictional coefficient C_f in the calculation domain. Its value, however, affects the magnitude of the nearshore current velocity and the resultant sediment transport rate. We, therefore, tried to directly estimate the local values of bottom frictional

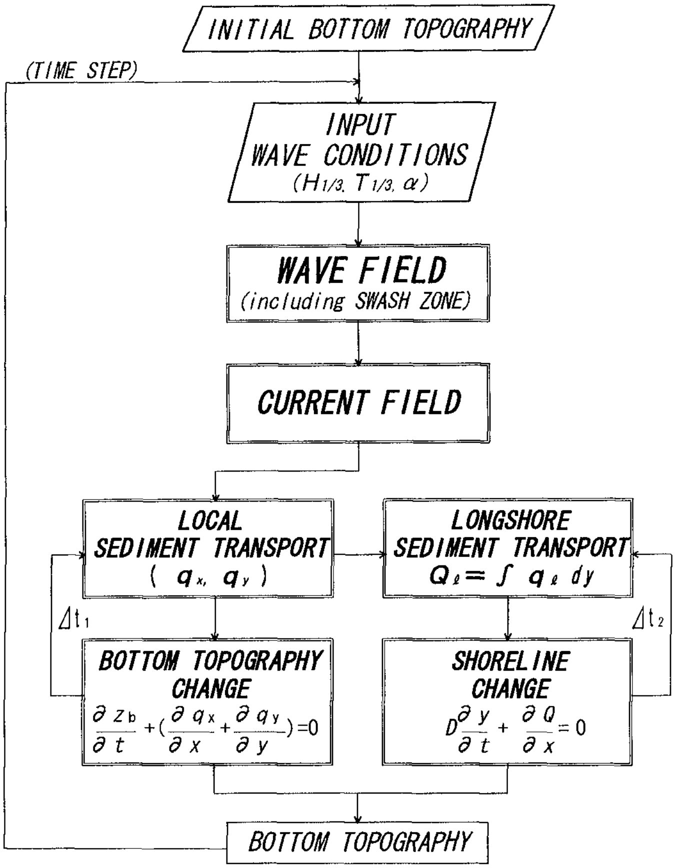


Fig. 2 Flow chart of the 3D-SHORE.

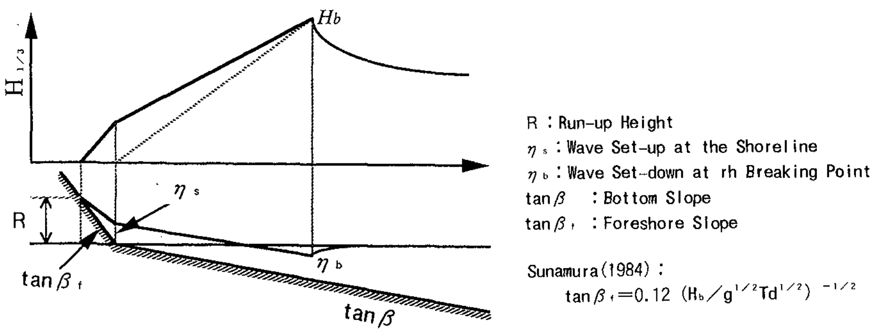


Fig. 3 Schematic illustration of the estimation method of the wave height and water level in the swash zone.

Table 2 Outline of the nearshore wave and current models.

【WAVE MODEL】

Parabolic Equation Model

using the curvillinear coordinates (Isobe, 1987)

- Combined Refraction, Diffraction, Shoaling and Wave Breaking
- Field verification: Shimizu et al. (1992, 1994)

【NEARSHORE CURRENT MODEL】

Depth-averaged Current Model

- Friction Term:

①Conventional Expression

$$\left.\begin{aligned}\tau_x &= \rho C_f (U+u_b)\sqrt{(U+u_b)^2+(V+v_b)^2}\\ \tau_y &= \rho C_f (V+v_b)\sqrt{(U+u_b)^2+(V+v_b)^2}\end{aligned}\right\} \quad (1)$$

where U, V: the mean currents, u_b, v_b: the orbital velocities, C_f: the friction coefficient.

②Improved Expression

directly estimate the local friction term in the mean current direction by using the friction law under combined wave and current action proposed by Tanaka and Thu (1994).

$$\tau_c = \rho u_{c*}^2 = \rho \kappa \alpha \sqrt{\frac{f_{cw}}{2}}\, U_w^2 \quad (2)$$

$$\alpha = \begin{cases} \dfrac{1}{\ln(z_h/z_0)-1}\,\dfrac{u_c}{U_w} & \text{: rough turbulent} \\[2ex] \dfrac{1}{\left[\ln\left(9.0\,\dfrac{R_c}{u_c/U_w}\sqrt{\dfrac{f_{cw}}{2}}\right)-1\right]}\,\dfrac{u_c}{U_w} & \text{: smooth turbulent} \\[2ex] \dfrac{1}{\kappa}\sqrt{\dfrac{f_{c(L)}}{2}} & \text{: laminar} \end{cases} \quad (3)$$

where u_c: the mean current, U_w: the amlitude of near-bottom orbital velocity, z_h: thewater depth, z_0: the roughness height, κ: the Karmanconstant, f_{cw}: the wave-current friction coefficient, $R_c = u_c z_h/\nu$, ν: the kinematic viscosity.

$$\tau_c = f_2\{f_1 \tau_{c(L)} + (1-f_1)\tau_{c(S)}\} + (1-f_2)\tau_{c(R)} \quad (4)$$

- f_1, f_2: weight function [see Tanaka and Thu (1994)]
- Subscripts L, S, R describe Laminar, Smooth turbulent and Rough turbulent flows respectively.

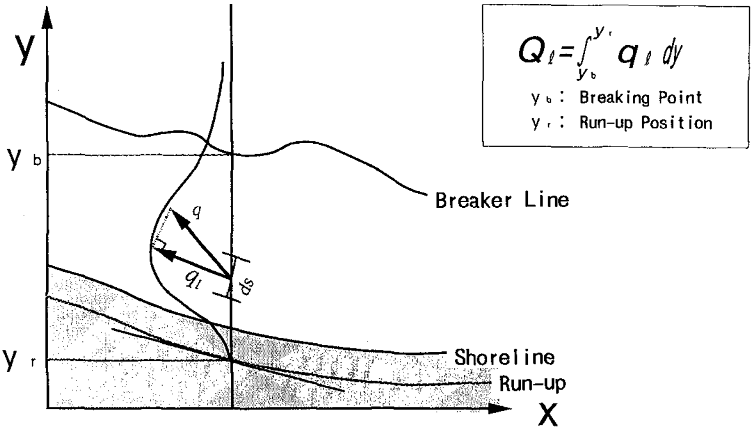


Fig. 4 Schematic illustration of the estimation method of the total longshore sediment transport rate by the cross-shore integration of the local sediment transport rate.

term by using the full-range explicit approximate expressions of frictional law for a wave-current coexistent system proposed by Tanaka and Thu(1994). The outline of the nearshore wave and current models is summarized in Table 2.

Sediment Transport and Beach Evolution Model

Fig.4 shows schematically the cross-shore integration of the local sediment transport rate in the direction parallel to the shoreline from the breaking point to the run-up point. The shoreline change is calculated using the mass conservation equation of the shoreline model based on the alongshore balance of the total longshore sediment transport rate.

In coupling the spatial bottom topography changes with the shoreline changes, both results are interpolated near the shoreline. In the area of shoreline retreat, the profile is determined by the smaller depth comparing between the profile extended offshoreward from the new shoreline position with the foreshore slope estimated by empirical formula by Sunamura(1984) and the profile extended onshoreward from the grid point adjacent to the old shoreline position with the local bottom slope. In the area of shoreline advance, in order to prevent the new shoreline calculated based on the mass conervation of total longshore sediment transport rate from advancing the new shoreline calculated by that of local sediment transport, the appropriate local sediment transport rate coefficient and duration of time-stepping are to be selected.

The local sediment transport rate is evaluated by the formula proposed by Watanabe et al.(1986). The outline of the model is shown in Table 3. The formula for local sediment transport rate under combined wave-current action was formulated so as to be consistent with previous studies on both longshore drift and cross-shore sediment transport. The total transport rate vector is divided

Table 3 Outline of the local sediment transport rate formula.

【LOCAL SEDIMENT TRANSPORT RATE FORMULA】

Watanabe Model (Watanabe et al., 1986)

・Seiment transport due to nearshore currentn q_c:

$$\vec{q}_c = A_c\ (\tau_m - \tau_c)\ \vec{u}_c / \rho g \tag{5}$$

・Seiment transport due to nearshore current q_w:

$$\vec{q}_w = A_w F_D\ (\tau_m - \tau_c)\ \vec{u}_b / \rho g \tag{6}$$

where τ_m : the maximum bottom shear stress under waves and currents,
τ_c : the critical shear stress,
u_c : the mean current, u_b : bottom orbital velocity
F_D : the direction function(+1 for onshore, −1 for offshore)

・Relationships among the coefficients

(Watanabe et al., 1991; Shimizu et al., 1994)

$$A_c = 10 A_w \tag{7}$$

$$A_w = w_0 \sqrt{0.5 f_w} / \{(1-\lambda) s' \sqrt{s' g D}\}\ B_w \tag{8}$$

where B_w : the nondimensional coefficient of the wave-induced sediment transport rate formula by Watanabe(1982),
f_w : the wave-current friction coefficient proposed by Tanaka and Shuto(1981),
w_0 : the fall velocity, D : teh grain diameter,
λ : the porosity, g : the gravity acceleration,
$s'(=\rho_s/\rho - 1)$ (ρ_s, ρ : the densities of sand and fluid) .

・Determination of local coefficients

① Previous studies → $B_w \begin{cases} = 3\sim5 & \text{for field} \\ = 7 & \text{for laboratory experiment} \end{cases}$

② H, T, θ, h, D, s' → f_w
→ A_w at each loacal point (eq. (8))

③ $A_w \rightarrow A_c$ (eq. (7))

into that due to mean currents including both nearshore current and undertow and that due to waves. This formula is based on the power model concept and assume that the sediments set in motion by the excess shear stress under combined wave-current action are transported with both mean currents and wave motion into the respective directions. In this study, only the sediment transport due to nearshore currents is taken into account. The value of the sediment transport rate coefficient is determined by using the empirical relations, according to the previous studies (Watanabe et al.,1991; Shimizu et al.,1994). The local transport rate coefficients depend on local wave conditions and properties of sea-bed material.

MODEL VERIFICATION

Outlines of Laboratory Experiment and Numerical Calculation

The applicability of the newly developed model is investigated on the basis of the movable bed laboratory experiment conducted by Mimura et al.(1983). The experiment was carried out using a wave basin 14m long and 7.5m wide. The sediment grain diameter was 0.2mm and the initial bottom slope was 1/20. After the initial beach was subjected to wave attack for approximately 12 hours, a 1.5m long detached breakwater was placed approximately at the breaker line. The incident wave height was 5.7cm and the period was 0.9s. The verification data used in this study are the beach topography change for about 6 hours after placement of the detached breakwater.

In the calculation of beach evolution, the new bottom topography is fed back into the hydrodynamic and sediment transport computations and the dynamic time-evolution of the seabed is calculated. The calculations of waves, currents and beach topography changes were repeated every 20 minutes and 18 time iterations in total were conducted. The change in the bottom shear stress caused by bottom elevation change is taken into account every 4 minutes in the calculation of beach evolution. The grid spacing is 15cm. The local sediment tarnsport rate coefficient B_w is 7 and the depth of closure D is set to 10cm.

Calculation of Nearshore Wave and Current Fields

Fig.5 shows the alongshore distribution of breaking wave height. The calculations show good agreement with the measurements.

Fig.6(a) and (b) show the examples of the calculated depth-averaged nearshore currents. Fig.6(a) is for initial bottom topography and Fig.6(b) is for that after 5 hours and 40 minutes. The shoreline advance behind the detached breakwater and the strong and sharp nearshore circulations are simulated.

Calculation of Beach Evolution

Fig.7 shows comparisons between the calculated and the measured positions of the shoreline and the depth contours of 2cm and 4cm. The shoreline position calculated by the shoreline model is also plotted. The shoreline change is reproduced better by the shoreline model than by the 3D-SHORE, because the

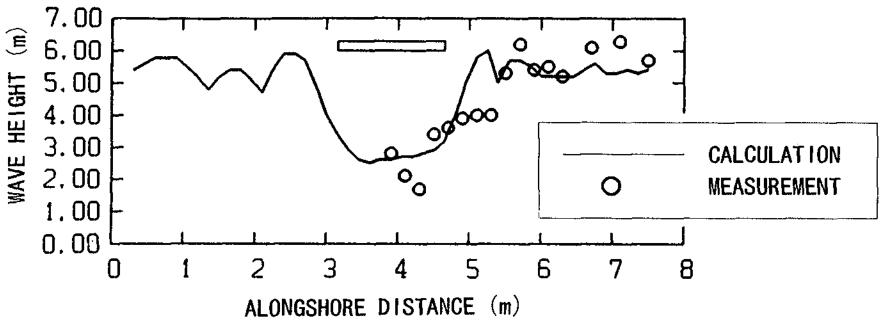


Fig. 5 Alongshore distribution of breaking wave height.

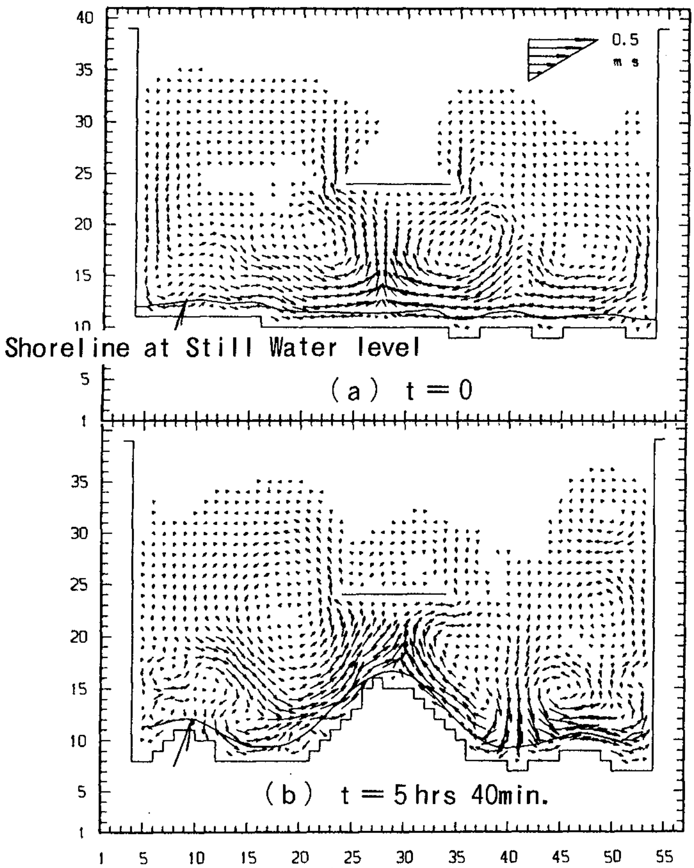


Fig. 6 Calculted nearshore current fields.

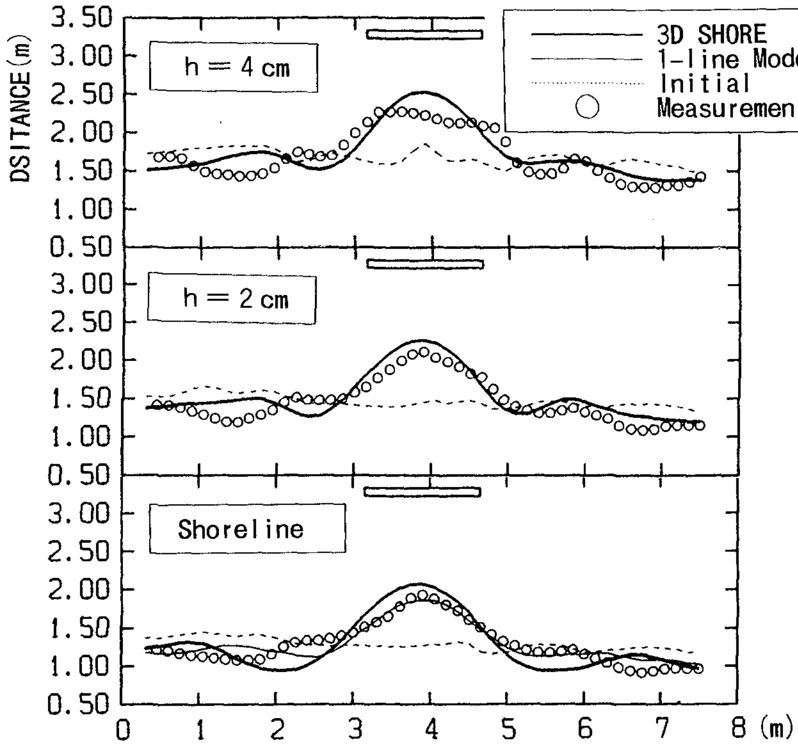
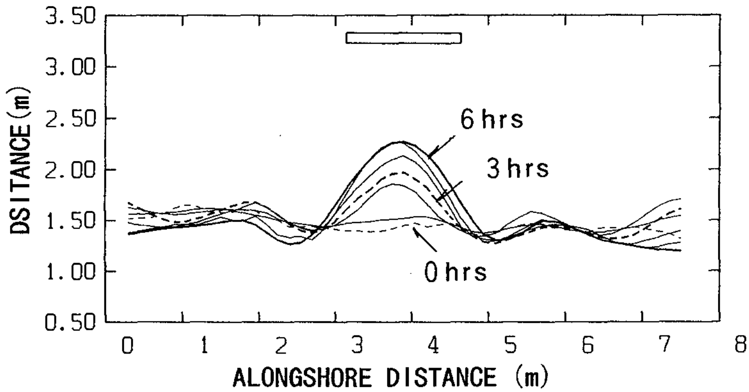


Fig. 7 Comparisons between the calculated and the measured positions of the shoreline and the depth contours of 2cm and 4cm.

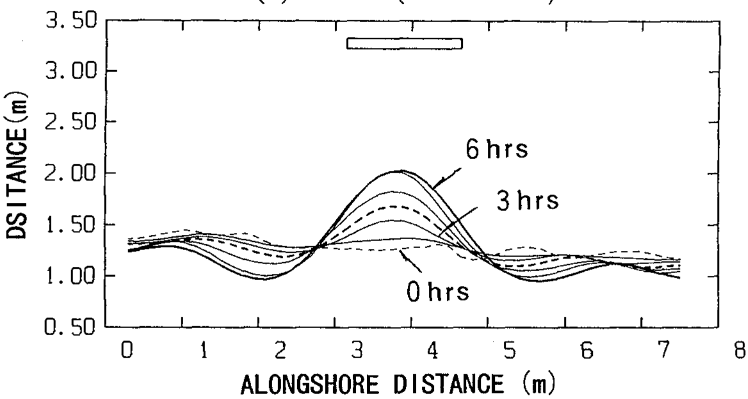
computational time of the shoreline model is considerably shorter than that of the 3D-SHORE and it is, then, easy to adjust the parameters to agree with the measurement. The shoreline model, however, can calculate only the shoreline and cannot estimate the spatial bottom topography change. The present improved model, on the contrary, has good accuracy for estimating the changes in both the shoreline and the depth contours for approximately 6 hours.

Fig.8(a) and (b) show the time-evolutions of the shoreline and the 2cm depth contour calculated by the 3D-SHORE and (c) shows the time-evolution of the shoreline calculated by the shoreline model. The shoreline behind the detached breakwater advances gradually and reaches an equilibrium state after 5 hours according to the calculation result of the 3D-SHORE. The contour of 2cm advances faster than the shoreline.

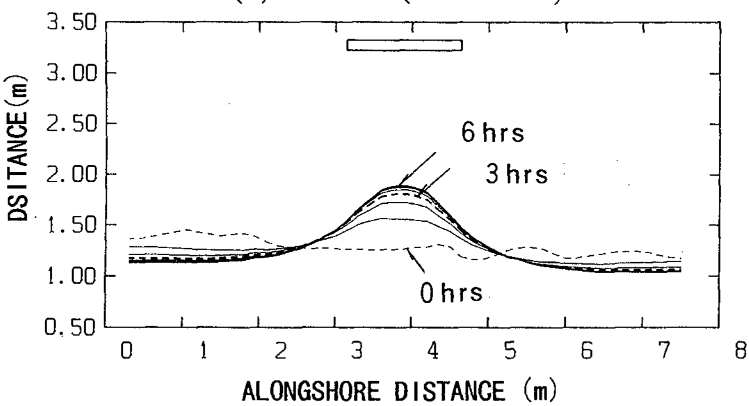
According to the result calculated by the shoreline model, on the contrary, the shoreline advances rapidly and reaches an equilibrium state after only 3 hours. In the shoreline model, the longshore sediment transport rate becomes zero at the equilibrium state, because the breaking wave crest angle to the shoreline becomes zero. This shows that the shoreline model can describe only the static equilibrium. The improved 3-D beach evolution model, on the other hand, can describe



(a) h=2cm (3D-SHORE)



(b) Shoreline (3D-SHORE)



(c) Shoreline (1-LINE MODEL)

Fig. 8 Time-evolution of the calculated depth contours.

the dynamic equilibrium and is, therefore, more effective for properly predicting the time-evolution of bottom topography.

FIELD APPLICATION

In order to verify the field applicability, we try to simulate the beach evolution due to construction of the Kunnui Fishing Port, an offshore man-made island type fishing port, in Hokkaido, Japan (Kawaguchi et al., 1994). The man-made island is located about 200m offshore from the initial shoreline. The maximum width of the man-made island is about 180m, which approximately equals to the detached distance. Although the bottom contours are straight and parallel to the shoreline in 1985 before construction of the fishing port, they extend offshoreward like a tongue behind the fishing port owing to extreme accretion caused by nearshore circulations. The rapid and extreme beach evolution took place during only a year from 1989 to 1990 after the start of the construction of man-made island. At present, the tombolo is formed behind the fishing port.

The calculation was conducted with the area of 1.0km long in the alongshore direction and 0.8km long in the cross-shore direction. The grid spacing is 10m. The bottom slope is approximately 1/75. The grain diameter is about 0.2mm and the transport rate coefficient B_w is 4. The numerical simulation was performed under simply modelled two series of the storms by repeating the calculations of waves, mean currents and beach changes. The modelled series of waves have the same occurrence frequency in total as that of the observed wave climate data. The depth of closure D was expressed as a function of the incident wave conditions.

Fig.9 shows the comparisons between the calculated and the measured depth contours after a year from 1989 to 1990. The calculations show fairly good agreements with the measurements. The field applicability of the proposed model is also verified.

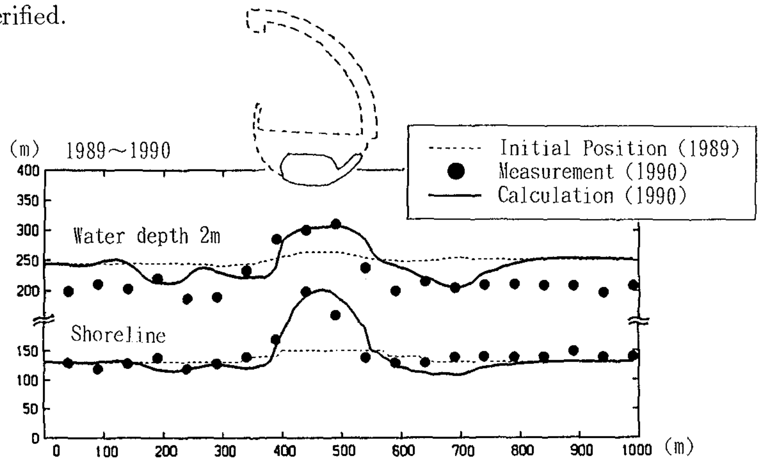


Fig. 9 Reproduction of the beach evolution around the Kunnui Fishing Port during a year.

CONCLUSIONS

In this study, an improved 3-D beach evolution model coupled with the shoreline model (3D-SHORE) is newly developed. And the applicabilities of the model were successfully verified through comparisons with both results of movable bed laboratory experiment and the actual beach evolution. The 3D-SHORE can describe the dynamic equilibrium of beach evolution and is, therefore, more effective for properly predicting the time-evolution of bottom topography than the conventional shoreline model which can only the static equilibrium. It is concluded that the 3D-SHORE has enough accuracy for practical use.

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