京 都 大 学 防 災 研 究 所 年 報　第46号B 平成15年4月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No.46 B, 2003

Coastal Current System and Its Simulation Model

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Synopsis

Field observations in the Jouetsu-Ogata Coast, Niigata, Japan facing the Japan Sea in winter 1999 showed clearly that wind has a great influence on the generation of coastal currents in the coastal sea. Based on the observational findings, three-dimensional model for wave and wind-induced coastal currents was developed. The model applicability was confirmed with the simulation of coastal current and observational results. Intensive investigation of the effects of wind and waves on coastal currents made clear that the wind affects coastal current generation and development in the offshore region and the wave effect is important in the nearshore region including surf zone. The influence of a large-scale structure on coastal topography changes as well as coastal current system was also investigated by the numerical experiment on the parallel contour coast.

Keywords: Coastal current, coastal waves, three-dimensional current model, sea surface wind, sediment transport

1. Introduction

One of the most important problems in coastal management is the prediction of changes in coastal morphology, which is achieved by predicting winds, waves, currents and sediment transport in the coastal zone. So many researches have been conducted to make clear the mechanism of beach erosion, to develop its control measures, and to create a desirable coastal environment. In these researches, very few mathematical models consider the effect of wind-induced currents on beach changes under the storm condition, such as hurricane and typhoon. Too much attention has been given to the wave action and wave-induced current in the surf zone, as a major external force for morphological and dynamical changes in coastal environment. We should give attention to the material movement and sediment transport, which are driven by both wind-induced and wave-induced currents in wide areas of the coastal sea as well as wave action itself. For the beach management in the Japan Sea, the wind and wave-induced coastal current systems (coastal current in the coastal zone under the strong wind condition) should be considered driving forces of sediment transport in the wide coastal zone (from the shore to 20-30m deep sea-area). Some observations were carried out to make clear the mechanism of coastal current generation in the coastal region in the several coasts of Japan (e.g. Yasuda et al., 1996; Yamashita et al., 1998; Baba et al., 1999; Tamura et al., 2001). The results of these observations show that the effect of wind (wind-induced currents) in the coastal region is important for current generation in the wide area, together with wave-induced currents in the surf zone. Therefore we conclude that the wind effect must be included in the numerical model of coastal current and beach changes.

In this paper, first, field observations (setup and results) for coastal currents and waves are briefly summarized, which was conducted on the Ogata coast facing the Japan Sea in 1999. Then three-dimensional model developed by Kato et al. (2000) for coastal currents is introduced, which considers the effect of wind on current generation. Model verification using the observed data are carried out together with the investigation of the effects of wind and waves on coastal currents in the wave shoaling region. The influence of a large-scale structure on coastal currents is also briefly discussed by numerical experiment in the model beach with parallel contour.

2. Summary of Field Observation

The Disaster Prevention Research Institute (DPRI), Kyoto University has conducted field observation of wind, wave and current under the winter monsoon condition every year since 1997 using the T-shaped Observation Pier (TOP). This pier and Ogata Wave Observatory (OWO) are located at the center of the Jouetsu-Ogata Coast. The sea surface elevation and wind direction and speed are measured with seven ultrasonic wave gauges and a propeller anemometer along TOP. In winter, ADCP (Acoustic Doppler Current Profiler) is installed at the sea bottom to measure the current profile and 3-component ultrasonic anemometer is installed at the offshore top of TOP to measure the characteristic of sea surface wind. Joint observations with the Niigata Prefecture government were carried out in winter 1999. In the observations, waves and currents were measured at 13 stations (St.01−13) and TOP (Figs. 1 and 2).

The obtained observational results under the storm condition are summarized below. (1) Inside the surf zone, strong offshore-going currents (undertow) are observed intermittently and the occurrence of these currents coincides with high wave conditions. The intensity of offshore-going currents is extremely strong enough to transport sediment offshore. Remarkable is observed in the surf zone under high waves. (2) Outside the surf zone, the variation in long-shore currents is similar to that of wind speed. Long-shore currents induced by wind are widely generated in the coastal region. And its intensity is strong enough to transport sediment alongshore. Magnitude of longshore currents is much bigger than cross-shore current outside the surf zone. (3) Wind effects on the coastal currents are remarkable outside the surf zone, over a region of 10 or 15 m depth. Therefore, in planning large-scale coastal structures, such as harbor breakwaters and offshore reclamations, the estimation of wind and wave-induced currents and accompanied sediment transport in the coastal region is of great importance.

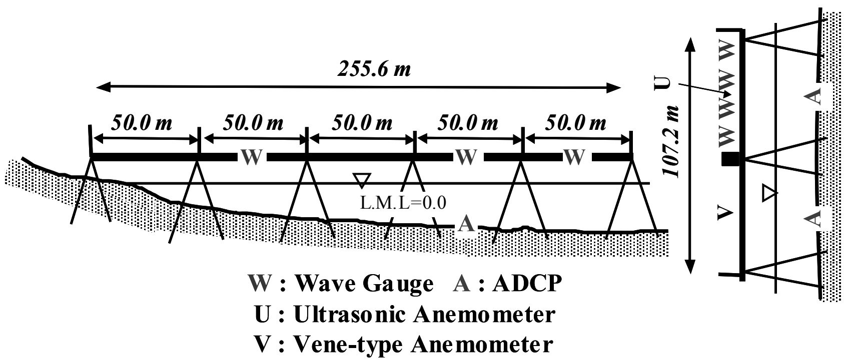


Fig. 1. Measuring instruments along TOP.

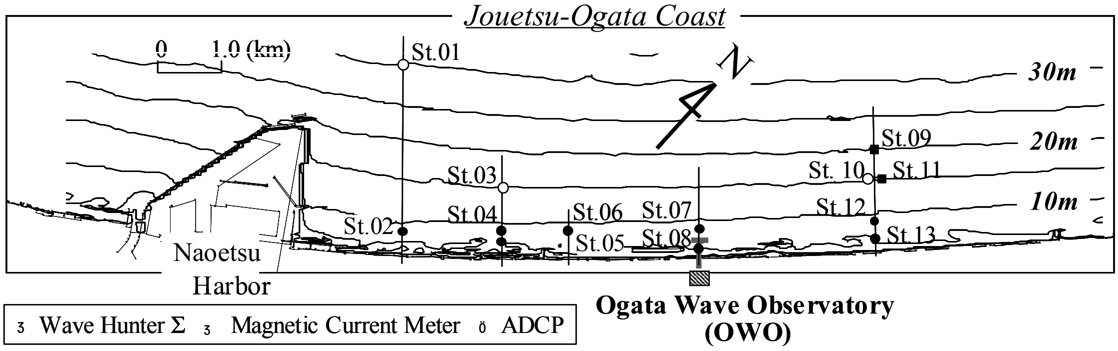


Fig. 2. Measuring stations (St.01 - St.13) at the joint observation in 1999.

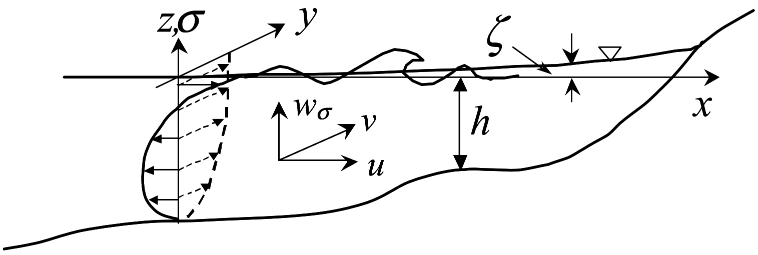


Fig. 3 Coordinate system and variables.

3. Numerical Model

The three dimensional model for coastal currents consists of three modules for mean current, waves and turbulence. In the vertical direction, σ-coordinate system is employed. The turbulence module works to evaluate the vertical eddy viscosity distribution and mean current profiles. The module of wave is employed to estimate the surface shear stresses due to wave breaking on the mean water level. The driving forces for mean currents are the surface shear stresses due to winds and breaking waves in this model. The coordinate system and variables are defined as Fig. 3.

3.1 Mean currents

The governing equations for the mean current in σ-coordinate system are as follows. The momentum conservation equation assumes hydrostatic pressure. The momentum equations, Eqs.(2) and (3), are solved for the horizontal velocities (u, v) caused by the shear stresses due to wind and breaking waves on the mean surface level. The mean surface elevation (ζ) is obtained by the vertically integrated equation for mass conservation equation, Eq.(4). The vertical velocity (w_σ) in σ-coordinate system is deduced from the mass conservation equation, Eq.(5), using the known variables (u, v, ζ).

$$\sigma = \frac{z - \zeta}{h + \zeta} \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w_\sigma\frac{\partial u}{\partial \sigma}-f\,v=-\frac{1}{\rho}\frac{\partial P_a}{\partial x}-g\frac{\partial \zeta}{\partial x}+\frac{\partial}{\partial x}\left(N_h\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(N_h\frac{\partial u}{\partial y}\right)+\frac{1}{D^2}\frac{\partial}{\partial \sigma}\left(N_z\frac{\partial u}{\partial \sigma}\right) \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w_\sigma\frac{\partial v}{\partial \sigma}+f\,u=-\frac{1}{\rho}\frac{\partial P_a}{\partial y}-g\frac{\partial \zeta}{\partial y}+\frac{\partial}{\partial x}\left(N_h\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(N_h\frac{\partial v}{\partial y}\right)+\frac{1}{D^2}\frac{\partial}{\partial \sigma}\left(N_z\frac{\partial v}{\partial \sigma}\right) \tag{3}$$

$$\frac{\partial \zeta}{\partial t}=-\int_{-1}^{0}\left(\frac{\partial uD}{\partial x}+\frac{\partial vD}{\partial y}\right)d\sigma \tag{4}$$

$$\frac{\partial uD}{\partial x}+\frac{\partial vD}{\partial y}+D\frac{\partial w_\sigma}{\partial \sigma}+\frac{\partial \zeta}{\partial t}=0 \tag{5}$$

where D (= h + ζ) is the total depth, h is the still water level, f is the Coriolis parameter, ρ is the water density, P_a is the pressure on the mean water surface, g is the acceleration of the gravity, N_h and N_z are the horizontal and the vertical eddy viscosities respectively. The surface shear stresses due to winds and breaking waves are considered as the surface boundary condition in the last term of the right side of Eqs.(2) and (3).

3.2 Waves

Time-averaged wave energy balance equation (Battjes and Janssen, 1978), Eq.(6), and surface roller energy balance equation (Nairn et al., 1992), Eq.(7), are used to derive the wave field and to calculate the dissipation ($Diss$) of surface roller (SR) energy due to wave breaking. It is assumed that energy dissipation due to breaking changes to surface shear stress (τ_{wave}) at the mean surface level expressed by Eq.(8).

$$\frac{\partial}{\partial x}\left(E\,C_g\cos\theta\right)+\frac{\partial}{\partial y}\left(E\,C_g\sin\theta\right)=-D_w-D_f \tag{6}$$

$$\frac{\partial}{\partial x}\left(2\,E_r C\cos\theta\right)=D_w-Diss \tag{7}$$

$$\tau_{wave}=\frac{Diss}{C} \tag{8}$$

where E is the wave energy based on linear wave theory, C_g is the wave group velocity, θ is the wave direction (the angle of incidence from x direction), D_w and D_f are the dissipation of wave energy due to wave breaking and bottom friction, C is the wave speed, E_r is the total kinetic energy in SR.

The principle of the roller model in this module is to convert wave energy dissipated by breaking into the breaking shear stress and the turbulence production near the surface through the roller. The breaking shear stress (τ_{wave}) on the mean water surface works as the driving force to generate the shear flow near the surface together with wind shear stress. Moreover, by assuming that the scale of SR has relation to the turbulence scale near the surface, the turbulence production near the surface due to breaking is considered.

3.3 Turbulences

To evaluate the vertical eddy viscosity, 2.5 level turbulence closure model proposed by Mellor and Yamada (1974,1982) are employed. This model has been used in Princeton Ocean Model (POM) that works as the circulation model for ocean, lake and estuary etc. all over the world. The surface boundary condition is related to the wave energy dissipation and the length of SR considering the turbulence production near the surface due to waves.

4. Hindcast of Coastal Currents

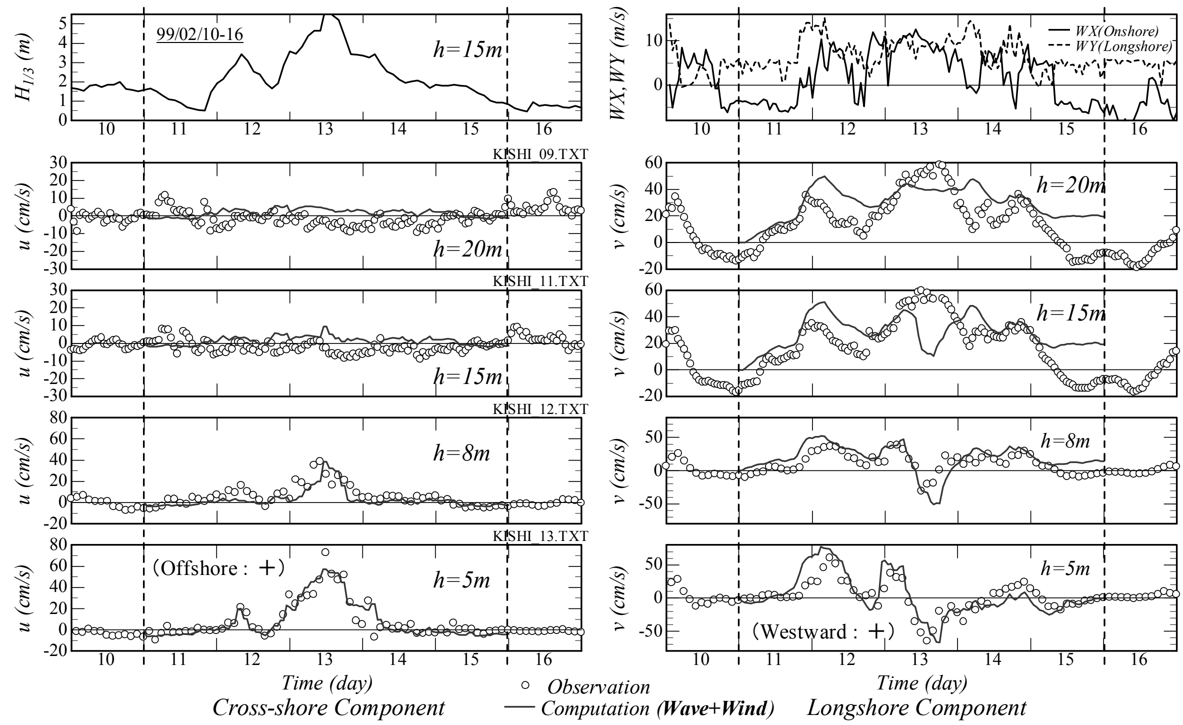
It can be seen from Fig. 2 that the topographical feature of Jouetsu-Ogata Coast has smooth and uniform parallel contours along the coast except an area near the Naoetsu Harbor. The measuring stations of Sts.09-13 distributing in the area of 7km alongshore are little influenced by Naoetsu Harbor in their observed data. Therefore, a beach profile along the line of Sts.09-13 is used as a representative topography of computational domain. Three components of currents (u, v, w) are computed. The maximum water depth is 40m at the offshore boundary and the minimum depth of 4m is assumed at the coastline. The grid spacing in the cross-shore direction is 100m and the number of vertical layer is 5. Observed wind at the TOP and wave data at St.11 are used in the computation as driving forces of coastal currents.

Fig. 4 (a) shows a comparison of computed currents and observations at Sts.09-13, together with the observation of significant wave height ($H_{1/3}$) and wind speed components (Wx,Wy). Circles indicate observed data and solid lines are computations. The strong offshore-going currents (undertow) and the variation of longshore component of coastal currents are simulated with good agreement inside the surf zone where water depth is less than 10m (Sts.12 and 13). In the offshore region, Sts.11 and 09, alongshore currents are computed in the same order of magnitude and the direction, however the peak positions are not always predicted. Fig. 4 (b) shows a same comparison of currents under the different external force condition, in which wind shear stress are not considered. In the nearshore zone, both cross-shore and longshore component of currents are simulated with the same accuracy as Fig. 4 (a). However, no longshore currents outside the surf zone are simulated at Sts.09 and 11. It is found that the variation of longshore currents inside surf zone is also accurately computed when both wave and wind are considered as external forces (Fig. 4 (a)). These results conclude that wind effect is of great importance for longshore currents in the offshore region, and the external condition of only wave forcing is insufficient for a simulation of coastal current. It is also concluded that the developed model improves the accuracy of simulations of currents in the coastal region.

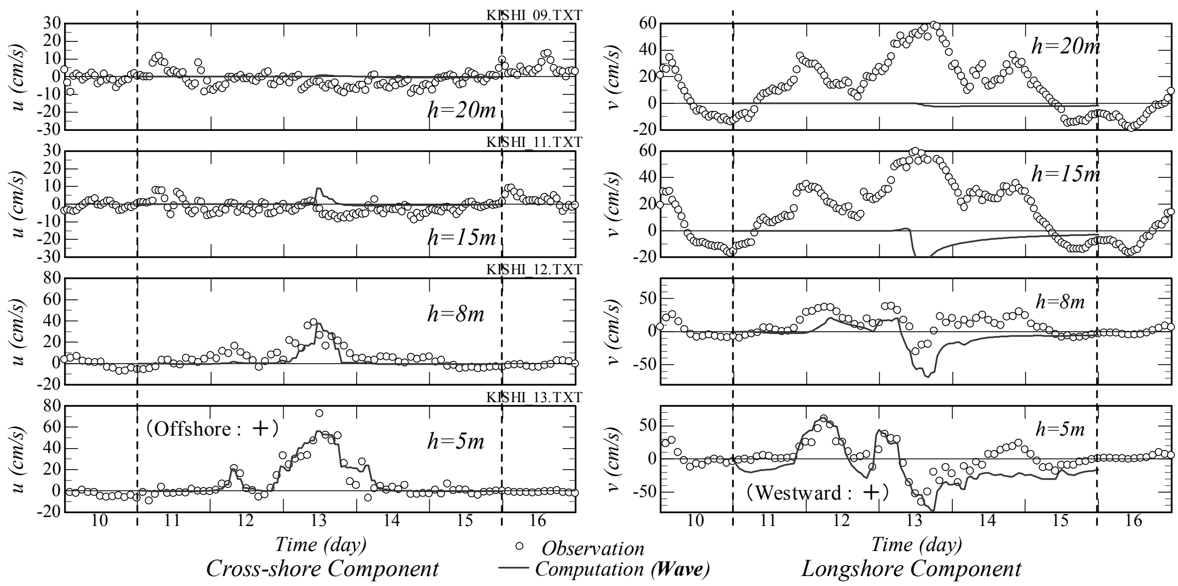
For some differences in longshore current velocities in the offshore region, it is supposed that overestimated computation of undertows extends offshore over the region of 15-20m deep. It may come from the grid size of 100m, which is not enough resolution to consider wave effects or wave breaking process in the computation of breaking wave model.

5. Numerical Experiment of Influence of Large- scale Coastal Structure on Current and Sediment System

The influence of a large-scale structure on coastal currents (and sediment transport) is examined by numerical experiment with the idealized conditions. Fig. 5 shows the computational domain with a straight coastline, a uniform bottom slope, 1/100, in the cross-shore direction. The minimum water depth is 5m at the coastline, the maximum depth is 50m at the offshore boundary. The horizontal grid size is 100m in the cross-shore direction and 200m in alongshore direction. A 1.5km-long breakwater is set perpendicular to the coastline. Its offshore end depth is 20m deep. Imposed wind direction is parallel to the coast and its speed is 15m/s. Wind field is assumed to be uniform and constant. Fig. 6 indicates current vectors near the bottom after



(a) Wave and wind effects



(b) Only wave effects

Fig. 4. Comparison of observation and computation at Sts.09, 11, 12 and 13.

duration of one day. An affected area of current field is about 10km lee side of the breakwater. The circulation is generated behind a breakwater. A distribution of shields parameter φ defined by Eq. (9) is computed using simulated currents as illustrated in Fig. 7.

$$\varphi = \frac{\tau_b}{s\rho g d} \tag{9}$$

where, τ_b is bottom shear stress, s is the specific density of sand in the water (= 1.65) and d is the grain size (= 0.1mm). In the case of no structure, the uniform longshore currents are computed in a whole domain. This means that sediment transport rate does not have a significant gradient in space resulting in small topography changes, even though current speed is enough to transport sediment alongshore.

It has not been considered that currents near the bottom generate active sediment transport in the offshore region even under storm conditions. Because very few observations of currents and topography changes have not been carried out in the wide area of coastal region. Therefore, it has been expected that the extension of structures to the deeper region, e.g. over 20m in depth, or the construction of detached structures in the offshore region are appropriate to the condition that does not disturb the current and sediment transport. Then it may be possible to reduce the influence of coastal structures to the neighboring coast. However, wind-induced coastal currents are generated in the whole coastal region to produce sediment transport in the deeper region. Then a large-scale structure constructed in the coastal region will destroy the balance of sediment transport in space as shown in Fig.s 6 and 7. This may cause slow-acting coastal erosion over a large lee-side area of the structure. Fig. 8 illustrates the particle tracers transported by the currents shown in Fig. 6 after one day duration. The particle injected near the coastline (circle) moves to the backside of a breakwater and its traveling distance during one day is shorter than that of other particles. The particle injected at the top of a breakwater (cross) is trapped in the circulation lee-side of the breakwater. It is shown that the material / sediment moving alongshore is interrupted by a structure. It was made clear that assessment of coastal currents and sediment transport in the wide area of coastal region (from the nearshore zone to offshore region) is necessary when large-scale structures will be constructed.

6. Conclusions

A three-dimensional numerical model for coastal currents was developed based on the observational findings. That was currents in the nearshore region were generated by both waves and wind. The model consists of three modules, mean current, wave and vertical turbulence. Hindcast of coastal currents in Jouetsu-Ogata Coast was carried out. Strong offshore-going currents including undertow in the nearshore zone and continuous longshore currents in the offshore region were simulated by the model. The verification of the model by comparing simulation and observation showed that wind effects on the generation of coastal currents in the offshore region was important to simulate coastal current system.

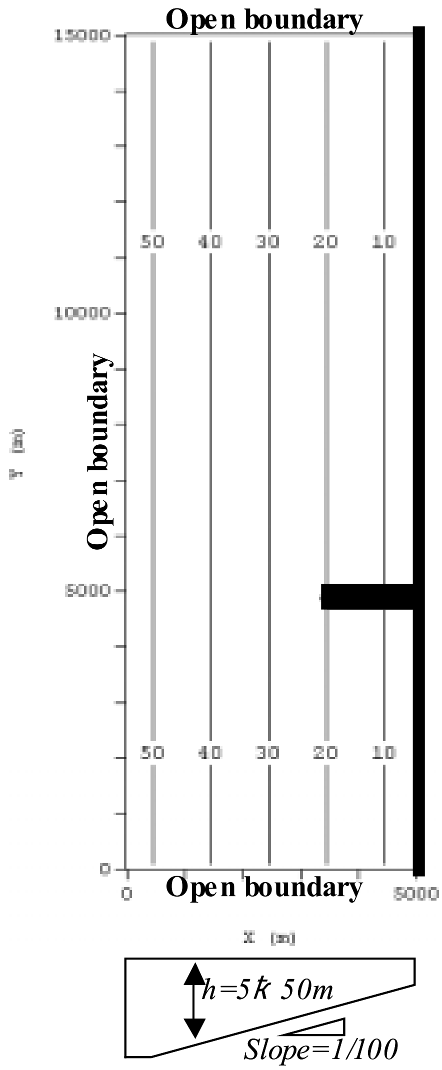


Fig. 5 Computational domain with parallel contour lines. Thick bar indicates a large-scale breakwater

Numerical experiment of coastal currents in the idealized beach was carried out to make clear the influence of a large-scale structure on currents and sediment transport. A large-scale coastal structure interrupts the continuity of material (sediment) transport in the longshore direction with slow-acting significant topography change in the neighboring coast. Therefore, it is necessary to assess coastal currents and sediment transport in the wide area of the coastal region when large structures.

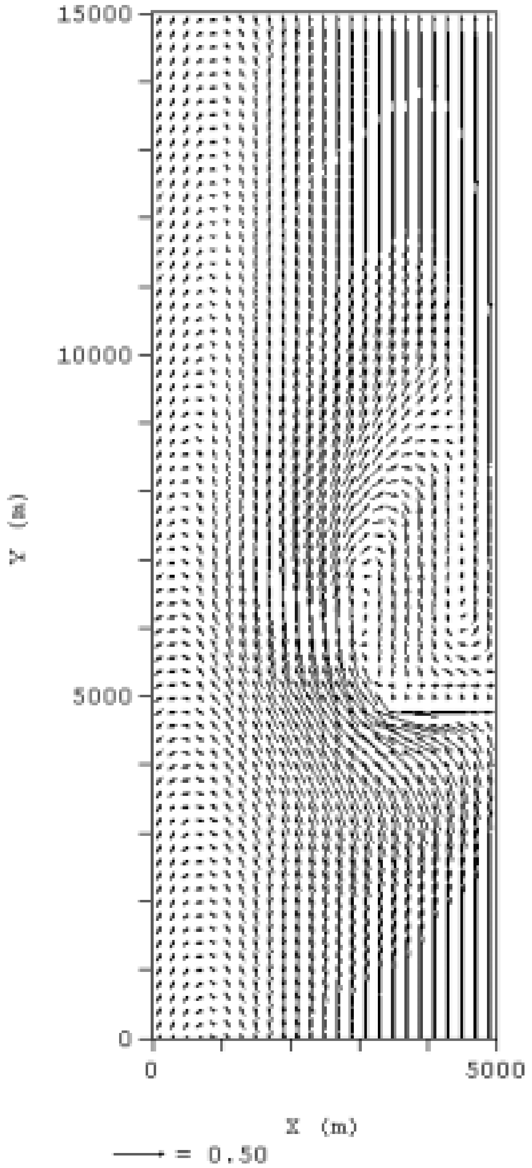


Fig. 6 Distribution of Current vectors of wind-induced coastal currents near the bottom after one day

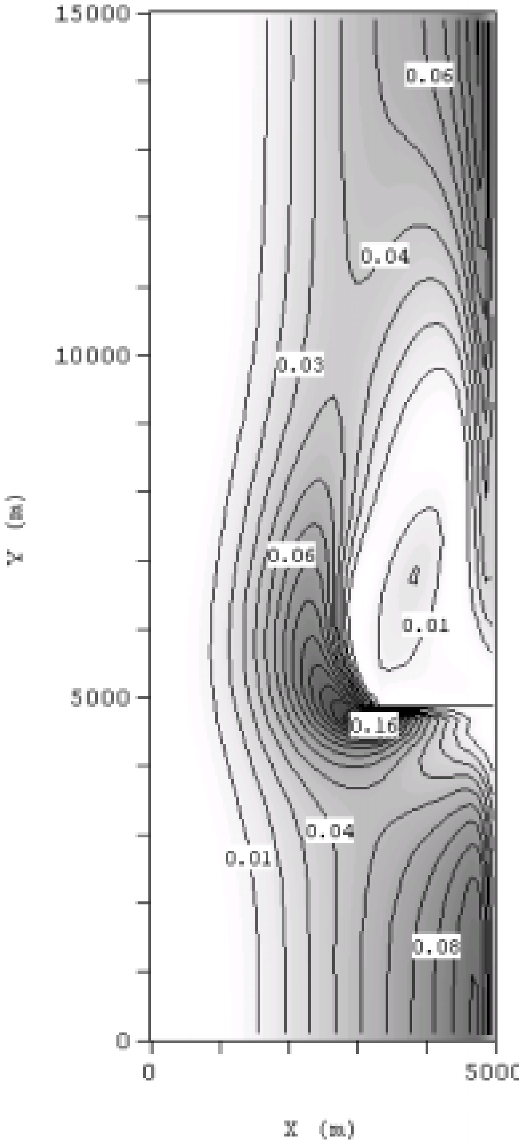


Fig. 7 Distribution of Shields parameter computed using currents in Fig. 6 (d=0.1mm)

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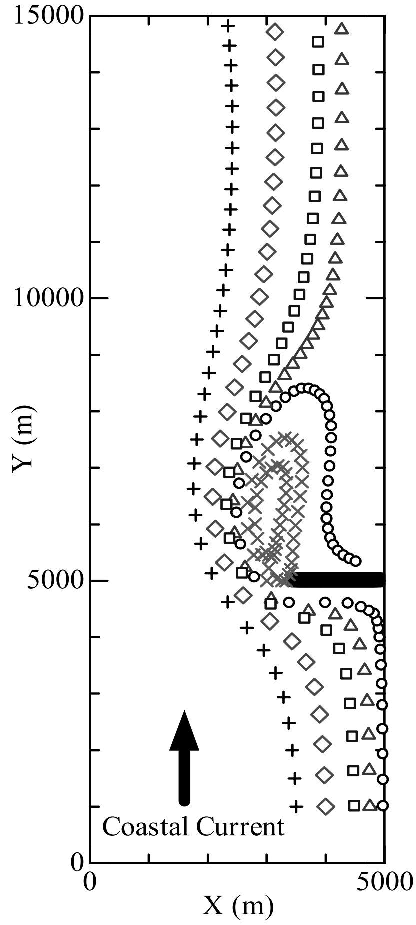

Fig. 8　Particle tracks by wind-induced coastal currents; influence of a structure in the coastal region

広域海浜流とその数値モデル

加藤　茂・山下隆男

要　旨

本研究では，1999 年冬季に上越・大潟海岸で行われた波・流れ・風の観測結果に基づいて，沿岸域での流れ（広域海浜流）の発生に及ぼす海上風の影響を考慮した３次元広域海浜流モデルを構築し，観測結果を追算することにより本モデルを現地海岸へ適用した。その結果，本モデルの現地への適用性が高いこと，広域海浜流の発生に砕波帯の沖合では風の影響が，砕波帯内では波の影響が重要であることが明らかとなった。また，数値実験により沿岸域の流れ，漂砂，地形変化に対する大規模構造物の影響について検討を行った。

キーワード：広域海浜流，波浪，3 次元数値モデル，海上風，漂砂