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DEVELOPMENT OF 3D BEACH EVOLUTION MODEL FOR SAND NOURISHMENTS AND ITS APPLICATION TO MORPHODYNAMICS AROUND COASTAL STRUCTURES

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ABSTRACT: A numerical model to predict three-dimensional (3D) beach evolution after sand nourishment was developed. The injection process of sand to near shoreline or offshore area was expressed by the sediment flux in the conservation equation associated with sediment transports and water depth changes, furthermore, sand dredging process was considered. In this study, First, computation of beach evolution around a coastal structure with and without nourishment was carried out. Secondly, the developed model was applied to the sand recycling project conducted at a field site, Kaike Coast, Tottori, Japan. Computed result was compared with the field data at Kaike Coast. Finally, the applicability of the developed model was investigated.

Keywords: Sand nourishment, beach evolution, sediment transport, nearshore current, numerical simulation.

INTRODUCTION

Human activities in Japan have concentrated in coastal area due to growing population. However we have many serious erosion problems in sandy beaches. Furthermore, we are in the face of serious environmental problems such as sea-level rise, climate change, extreme storm attacks due to the global warming effect. Especially, sandy beach erosion problems due to sea-level rise and extreme stormy wave attacks become more serious problems.

Conventionally, the causes of the sandy beach erosion are decrease of discharged sand material, interrupt of alongshore sediment transport due to construction of port, harbor, river mouth jetties. We have constructed coastal structures such as groins, detached breakwaters, and submerged breakwaters in order to protect the coastal area. However, moreover coastal erosion occurs in the other area. We need to take new countermeasures against the erosion problems.

Hence, sand nourishment as an alternative technique for beach erosion, which does not adapt coastal structures, is effective technique for recovering eroded beaches. For the last decade, many projects in the world have been performed (van Duin et al. 2004, Grunnet and Ruessink 2005, Ojeda et al. 2008, Bruno et al. 2009).

The purpose of this study is to develop a numerical model that can predict 3D morphodynamics after sand nourishment. In this study, the previous model presented by Kuroiwa et al.(2010) is modified so as to be capable to simulate the nourishing process of sand and the 3D morphodynamcs after the nourishment. A model test associated with sand bypassing system was carried out. Furthermore, the applicability of the presented model to a field site, which implements sand recycling project, was investigated.

NUMERICAL MODEL

The developed 3D model was based on the hybrid model proposed by Kuroiwa *et al.*(2006). The model consists of three modules, which are computations of (1) wave, (2) nearshore current, (3) sediment transport rate and water depth change, as shown in Fig. 1.

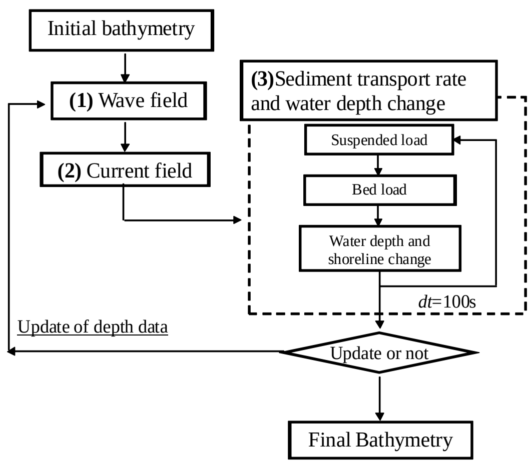

Fig. 1 Flowchart of 3D morphodynamc

Wave and Nearshore Current Modules

In computation of wave height distribution around coastal structures, the interaction due to coexistence of waves and currents should be considered. Kuroiwa et

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al.(2010) have proposed a 3D morphodynamic model with the interaction of waves and currents, based on the wave action balance equation proposed by Mase et al.(2004). However, iteration of wave and nearshore current computations is needed to obtain a steady state. The accuracy and applicability of the previous model in 2010 have not been still investigated. In prediction of morphodynamic in the long or medium term, to reduce the computation time is needed. In this study, as a first step in the development of 3D model associated with sand nourishment, a simple model for wave field computation, the energy balance equation with energy dissipation and diffraction terms (EBED) presented by Mase(2001), was employed.

Nearshore current field is determined by the Hybrid model proposed by Kuroiwa et al(2006).

Sediment Transport and Water Depth Change Modules

The total sediment transport considers the bed load and suspended load. The suspended load is determined by flux model, which is based on the two-dimensional advection diffusion equation, proposed by Sawaragi et al.(1984). The bed load is determined by the model based on Kuroiwa et al.(2000). In this model, the sediment transport rate due to the alongshore steady current in the run-up region is taken into account in order to predict the shoreline change.

To consider the sand dredging and discharge associated with the sand bypassing or back-passing system, the dredging sediment flux q_d and discharged sediment flux q_i are added to the sand mass conservation equation, as follows;

$$\frac{\partial h}{\partial t}=\frac{Q_s}{1-\lambda}+\frac{1}{1-\lambda}\left\{\frac{\partial}{\partial x}\left(q_{bx}+\varepsilon_s|q_{bx}|\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(q_{by}+\varepsilon_s|q_{by}|\frac{\partial h}{\partial y}\right)\right\}+q_d-q_i \quad (1)$$

where, h is the water depth, t is time, q_{bx} and q_{by} are bed load due to steady currents. ε_s is the dimensionless coefficient. Qs is the difference between the settling flux $w_f C$ and the picking-up flux F_z of bed material, as given by

$$Q_s=F_z-w_f C \quad (2)$$

$$F_z=(1-\gamma)C_0\alpha w_f\left(\frac{u_*}{w_f}-1\right)\quad \begin{pmatrix} u_*\geq w_f:\gamma=0\\ u_*\leq w_f:\gamma=1\end{pmatrix} \quad (3)$$

where α is the dimensionless coefficient, C_0 is the concentration at reference point, $C_0=0.347N_c^{1.77}$.

$$N_c=\frac{0.688\hat{u}_w^2}{1.13(s-1)gw_f T} \quad (4)$$

$\hat{u}_w$ is the maximum orbital velocity at bottom, s is the specific gravity of sand, T is the wave period. C is determined by solving the following advection diffusion equation, as given by,

$$\frac{\partial C}{\partial t}+U\frac{\partial C}{\partial x}+V\frac{\partial C}{\partial y}=\frac{\partial}{\partial x}\left(k_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial C}{\partial y}\right)+\frac{Q_s}{\overline{\eta}+h} \quad (5)$$

where, k_x and k_y are the diffusion coefficients, which are determined as a function of current velocity and water depth.

MODEL TEST FOR SAND NOURISMNET

A model test associated with sand dredging and discharging, which is a sand bypassing test around a port was carried out in order to investigate the performance of the developed model.

A Model Test without Sand Nourishment

In case that alongshore sediment transports are interrupted due to construction of groins, port and so on, beach erosion is occurred at the down-drifting area of the sediment transport. Fig.2 shows a model case that a port is constructed as interrupting alongshore sediment transport. Firstly, we computed bathymetry change after 150days without sand dredging at the entrance of port and sand nourishment. Until obtained the final bathymetry, the bathymetry was updated every 2days, namely the computations of wave and nearshore current modules were done 60 times. The grid size Δx and Δy in the computations were set to 10m. The significant wave height and period were set to 1.5m and 7.0s, respectively.

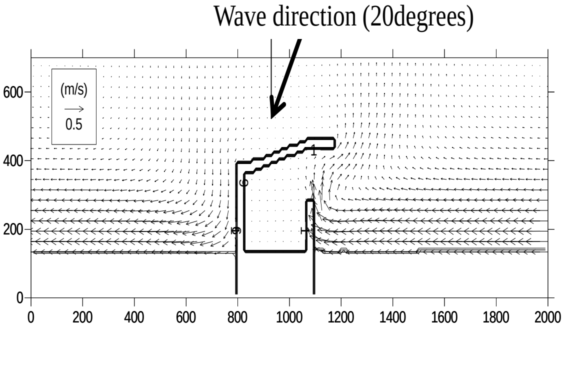


Fig. 2 Computational domain and computed nearshore current vectors(Hs=1.5m, Ts=7.0s).

Fig.3 demonstrates the computed bathymetry change after 120days. The computed result shows that the port mouth in the up-drifting side remarkably occurred accretion of bed material, in the contrary, the left side of the port occurred erosion and shoreline was retreated.

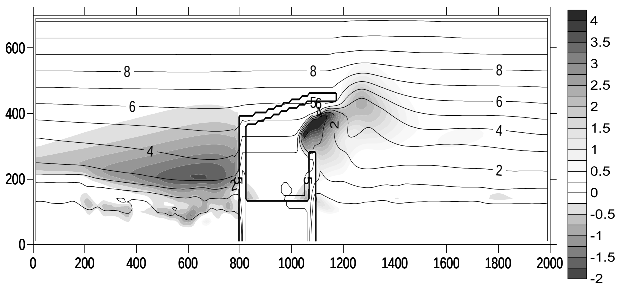


Fig. 3 Computed bathymetry change after 120days without sand dredging and injection in sand bypassing.

A Sand Bypassing Test around a Port

Secondly, bathymetry change due to sand bypassing was computed. By using time variation of incident waves as shown in Fig.4, computation with sand bypassing process for sand dredging around the mouth of the port mouth and sand nourishment at the down-drifting side was carried out. The sand bypassing was performed after 120days. As the bathymetry was remarkably changed, the bathymetry was updated, and the wave and nearshore current fields were recomputed.

Fig.5(a) demonstrates computed bathymetry change at 160days. In this figure, blue area and red area represent sand dredging and injection area, respectively. Those values are the deference of computed water depth at 120days. Fig.5(b) shows computed result for bathymetry at 180 days. Figs.6(a) and (b) shows beach profile changes at dreading area and injection area, respectively. These computed results show that sand bypassing is appropriate measures for beach erosion and port mouth deposition problems. We found that the developed model gives qualitatively available computed results.

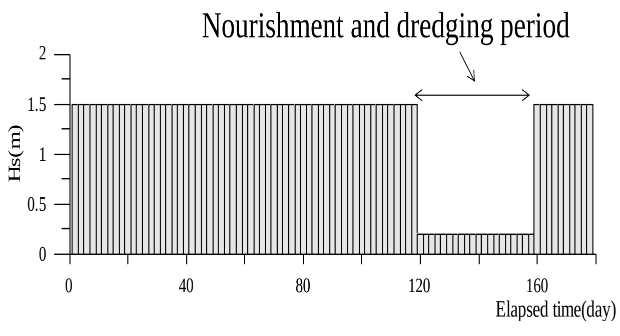
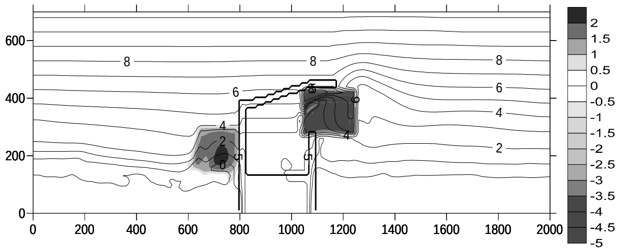
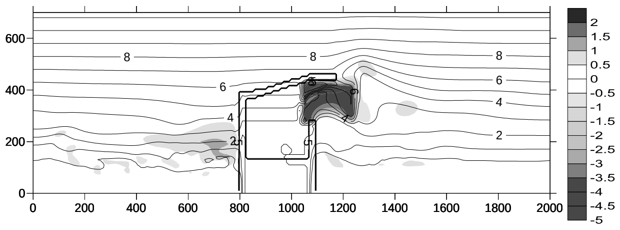


Fig. 4 Time series of incident significant wave height H_S.



(a) Computed bathymetry at 40 days later at the end of dredging and sand nourishment(t=160days)



(b) Computed bathymetry at 60 days later after starting dredging and sand nourishment(t=180days).

Fig. 5 Computed bathymetry changes after starting sand bypassing

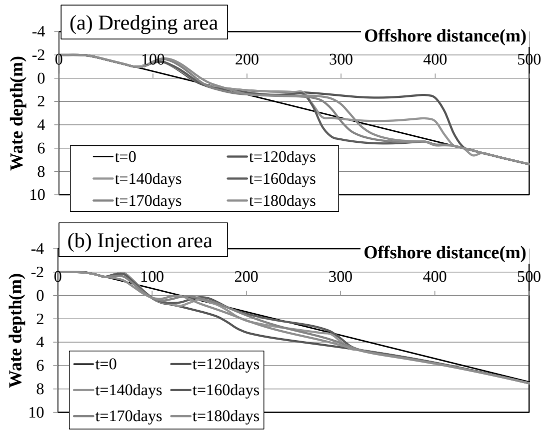


Fig. 6 Computed beach profile changes in sand dredging area and sand injection area.

APPLICATION TO A FIELD SITE

Field Site

The presented model was applied to a field observation associated with a sand recycling project conducted in Yumigahama Coast, Tottori, Japan. Fig.7 shows Yumigama Coast, which is sandy beach with a distance of 16km, facing the Sea of Japan. Yumigahama Coast was formed with sand sourced from Hino river. The dominant direction of alongshore sediment is from Hiro river to Sakai-minato marina(St.B). Retreat of shoreline on the west side of Hino River started around 1960, caused by decreasing of sand supplied from Hino river. In the erosion area, breakwaters and groins were constructed to recover the retreated shoreline. However, the erosion area was more extended at Tomimasu area on the western side of those coastal area. On the other hand, alongshore sediment has been trapped at Sakai-minato Marina at the end of Yumigahama coast and extreme accretion has been occurred. In order to solve both problems of beach erosion at Tomimasu area and deposition around the marina, a sand recycling project, which transports sand dredged around Sakami-minato Marina into Tominasu area by trucks, has started since 1992. The sand volume is an average of 30,000 m^3 per year. Despite of such sand nourishment project, the maintenance of shoreline was insufficient. In order to maintain the eroded shoreline, four submerged breakwaters, which are called " artificial reefs", were constructed, as shown the left picture in Fig.7. Photos 1 and 2 show sand dredging area at Sakaminato Marina and erosion area at Tominasu Area

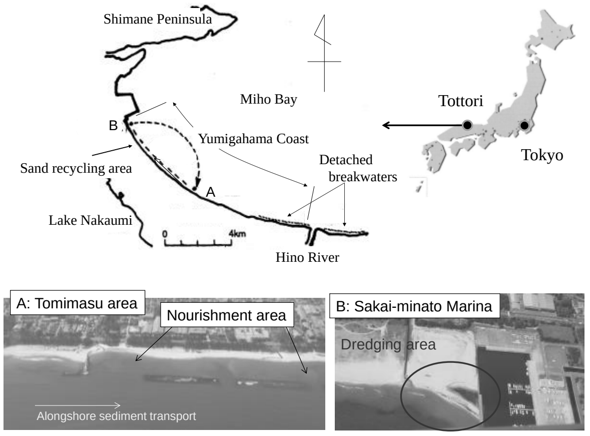


Fig. 7 Sand recycling project in Yumigahama Coast. The sand recycling is performed from Sakai-minato Marina to Tomimasu area.

(a) Sand deposition (b) Sand dredging

Photo. 1 Sakai-minato Marina, taken in Dec.,2012.

(a) Beach erosion (b) Sand nourishment

Photo. 2 Tominasu Area, taken in Dec.,2012(a) and Mar.,2013(b).

Computational Conditions

The developed model was applied to a field survey result associated with the sand recycling project conducted in Yumigahama Coast, in order to investigate the applicability of the model. In this study, to apply the model into the whole area of the sand recycling project is difficult because of many run time and computation capacity. Therefore, the model was applied to Tominasu area of sand nourishment with 2.3km long in the alongshore direction. Fig. 8 shows the computational domain and the measured bathymetry in July,2009. In 2009, four artificial reefs had been already constructed to protect Tomimasu area. The bathymetry result was employed as an initial bathymetry in the computation. Fig.9 shows bathymetry measured in 2010. In this figure, red area and blue area present erosion area and deposition area, respectively, described from the difference of the measured water depth for one year from 2009 to 2010.

The bathymetry change after 1 year was reproduced using the developed model to investigate the model performance. In this period, total sand volume nourished at Tomimasu area was approximately 15,000m^3 from January to March, in 2010. The red square in Fig.8 represents nourishment area. Fig.10 shows time series of significant wave height *H*s used in this computation, which was arranged the wave data sets observed Tottori Port and Tomimasu offshore observatory station at the water depth of 10m. The detailed value of the wave height and period are shown in Table1. The computations of the wave and current modules were roughly 75 times to reach the 150 days. The sand injection was carried out for 40 days as shown in Fig.10. The wave direction was set to -10 degrees at offshore boundary. The median diameter of sand particle was 0.2mm.

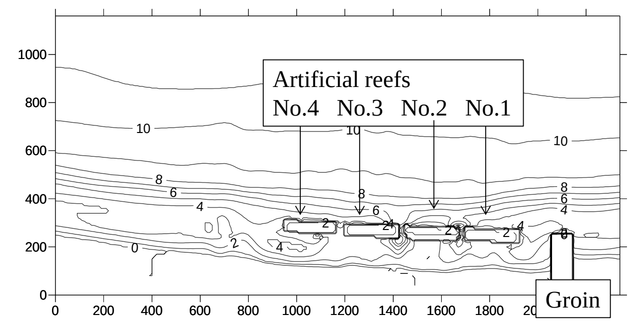


Fig. 8 Computational domain and measured bathymetry in July,2009.(Red square represents sand nourishment area)

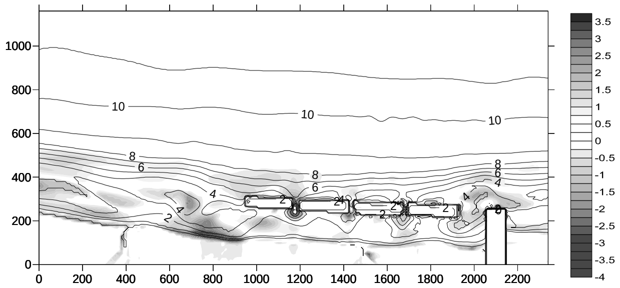


Fig. 9 Measured bathymetry in July,2010 (Red area : deposition, Blue area: erosion area)

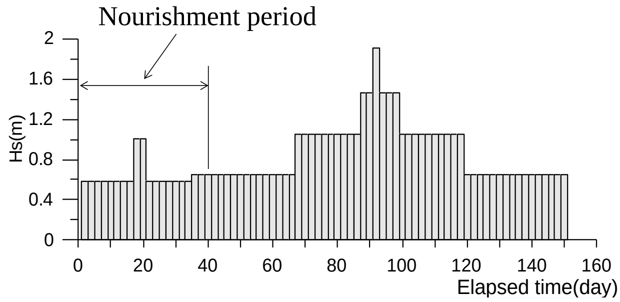


Fig. 10 Time series of incident significant wave height H_S with two stormy wave conditions.

Table 1 Wave conditions.

	Hs(m)	Ts(s)	days
Wave1	1.01	6.77	4
Wave2	0.58	5.51	30
Wave3	1.91	8.19	2
Wave4	1.46	7.52	10
Wave5	1.05	6.85	40
Wave6	0.65	6.04	64

Computed Results and Discussions

Applicability of the developed model

Fig.11 shows an example of computed nearshore current field. Strong currents occurred behind the artificial reefs and the direction of the currents at the left side of the reef No.4 is the North-East. The shoreward current on the reef No.4 was changed into the offshore direction.

Fig.12 shows (a) and (b) show computed bathymetry changes after 40days and 150days,respectively. Sand injection at the circle area as shown in Fig.12(a) was carried out for 40days. After implementation of nourishment, the injected sand behind the artificial reef No.4 was remained. However, the sand material was gradually decreased up to 150days. At the left side of the reef No.4, the sea bottom was eroded. The computed results around the reef No.4 qualitatively agree with the measured bathymetry in 2010 in Fig. 9.

Simulated results for influence of sand grain size into sand nourishment

Despite of the sand recycling implementation, beach around the artificial reefs in Tomimasu area has been eroded. The causes of the erosion are due to strong currents and grain size of nourished sand. As an attempt of countermeasures against the beach erosion around the artificial reefs, we examined the effect of sand grain size. Computations of three cases, which are sand nourishments with 0.2mm, 0.3mm and 0.4mm, were performed. The initial bathymetry, wave conditions and nourishment process are same as the conditions used in the computation shown in Fig.6.

Fig.13(a),(b) and (c) show computed bathymetry changes after 150days with 0.2mm, 0.3mm and 0.4mm, respectively. The nourished sand was injected into an area represented by black circle in Fig.13(a). This is the area the left side of the artificial reef No.4, which has been eroded. From Fig.13(a), we found that the nourished sand with grain size of 0.2mm was transported to offshore area and almost disappeared. As shown Fig.13(b) and (c), as the grain size become large, the nourished sand is remained. These computed results indicate that the nourished sand with a size of 0.3 or 0.4 mm is more effective than that with a size of 0.2mm.

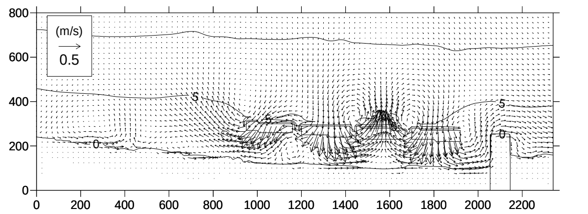


Fig. 11 An example of computed nearshore current field in Tominasu area.

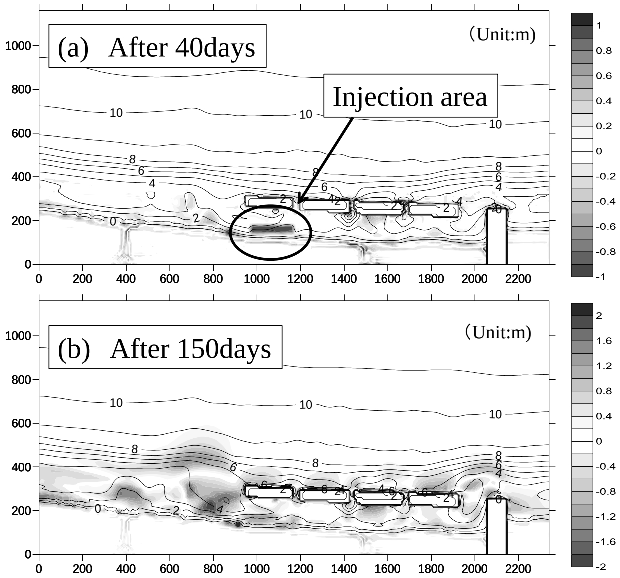


Fig. 12 Computed bathymetry changes

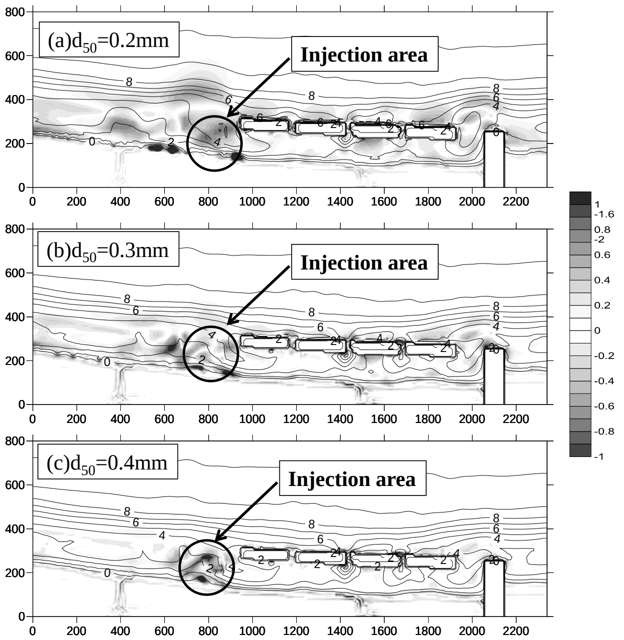


Fig. 13 Computed bathymetry changes after 40days and 80days.

CONCLUSIONS

In this study, a simple 3D model for predicting the beach evolution after sand nourishment was developed. Firstly, a model test associated with a sand bypassing system was carried out in order to investigate the performance of the model. Secondly, model verification against the field observation regarding to sand recycling project conducted at Kaike Coast,Tottori, Japan. From the computed results, some conclusions are derived as follows:

Model Test

A model test associated with sand dredging and discharging, which is a sand bypassing test around a port was carried out in order to investigate the performance of the developed model. The developed model gives qualitatively available computed results.

Application to a Field Site

The developed model was applied to a sand recycling project conducted by Kaike Coast, Tottori, Japan, in order to investigate the applicability of the model. Bathymetry change around artificial reef after sand nourishment was computed. The computed result qualitatively agreed with the measured bathymetry.

Problems of the Developed Model and Future Works

In this model, beach nourishment that sand material is placed at the berm area was not performed because shoreline changes are not sufficiently determined. In order to get more good accuracy of the prediction after sand nourishment, the model presented in this study should be modify so as to take account sediment transport in the run-up region.

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