韓國海岸海洋工學發表論文集 (2003)
第14券, pp. 259-269

Changes in Free Oscillation Mode in Isahaya Bay Due to a Barrier

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1. INTRODUCTION

The necessary of predicting changes in tidal regime that would caused by large coastal engineering developments has been led to increased numerical modeling of tides on the continental shelf since 1970s (Flather, 1976; Choi, 1978; Greenberg, 1979). In additional to this requirement, in view of practical concerns for pollutants, oil spill dispersal, search and rescue operations at sea, and navigation, demands for accurate tidal predictions in both time and space are increasing. The aim of this study was to predict how the construction of a tidal barrier in the interior region of the Ariake Sea would disturb and/or alter the system's natural tidal state. Because of the possible environmental consequences, it is important that correct evaluations are made. The only practical way of obtaining this good approximate solution is to construct a mathematical model that simulates the behavior of the tidal system, which play the central role in the shelf sea, involving a set of equations of motion of the sea that are solved numerically to yield the tidal variation. The proposed changes in boundary configuration due to barrier scheme can then be inserted in the model and the resultant effects on the system estimated. The degree of confidence of these approximations is a function of accuracy with which the model reproduces the real system. During the past years, this approach has been widely used for the studies of barrier schemes in the Bristol Channel (Heaps, 1972; Miles, 1979; Owen and Heaps, 1979), the Bay of Fundy (Garett, 1972; Greenberg, 1979; Duff, 1979), the west coast of Korea (Choi, 1978, 1981, 2001) and Isahaya Bay in the Ariake Sea (Kim and Yamashita, 2002; Kyozuka, 2002; Nadaoka, 2002; Takikawa and Tabuchi, 2002). One of the most difficult and important tasks in this approach is that a sufficiently large region should be considered in the mathematical modeling since good results may only be expected by locating the open boundaries sufficiently far from the barrier sites beyond the barrier's influence. Some previous studied in this nature (Heaps and Greenberg, 1974; Garrett and Greenberg, 1977) indicate that unreasonable results may be obtained if too small a sea area is considered in the computations. However, the open boundaries of the existing models for estimating tidal changes in the Ariake Sea have been chosen arbitrarily in the previous studies. Here in this paper some of recent setting for accurate prediction of tide, conveniently termed as Regional Ocean Tide Simulator for the regional seas of Korean Peninsula is introduced and applications for simulation of barrier effects on perturbing the existing tidal regime due to constructions of Isahaya Bay dike in the Ariake Sea are briefly described.

2. NUMERICAL EXPERIMENT

2.1 Geographical Setting

The Ariake Sea is the long inner bay, 90 km in length, 17 km in average width, 1,700 km^2 in area, 20 m in average depth, and has the tidal flat area as shown in Fig. 1. As for one of the features of this bay, tidal range in Japan is the largest (Osamu, 2001). The sea connects with the East China Sea through the Hayasaki Straits.

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Vast tide land, formed in its innermost part by sediments from many small rivers such as Chikugo-gawa, Yabe-kawa, Shira-kawa, Midori-kawa, Rokkaku-gawa and Honmyo-gawa, has a width about 6~10 km outside the coast in ebb stage of spring tide (Isozaki and Kitahara, 1997). The Ariake Sea is the biggest cultivating ground of laver (seaweed) providing about two-fifth of the laver in Japan. In recent years, environmental problem has become serious in this area, such as frequent red tide, decrease of fish catches etc. Above all, the laver plants in the Ariake Sea were seriously damaged in the winter of 2000. It is not yet clear exactly what has caused such damage to the laver in the Ariake Sea. It has been suspected that the reclamation project (construction of tidal barrier) in Isahaya Bay at inner part of the Ariake Sea is a major contributing factor.

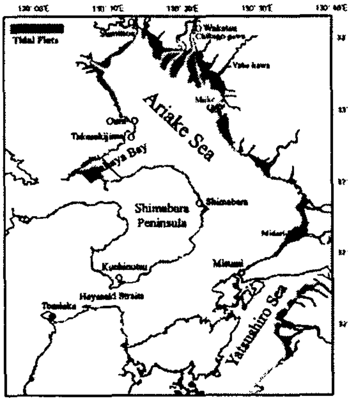


Fig. 1. Geographical location and tidal flats in the Ariake Sea.

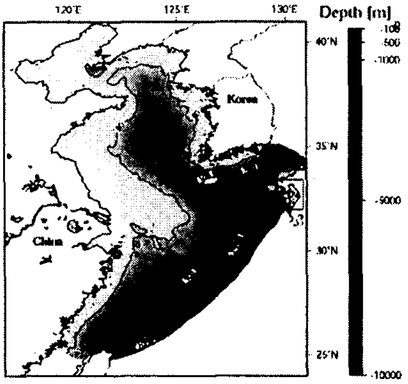


Fig. 2(a). Bathymetry of whole model domain including the Ariake Sea.

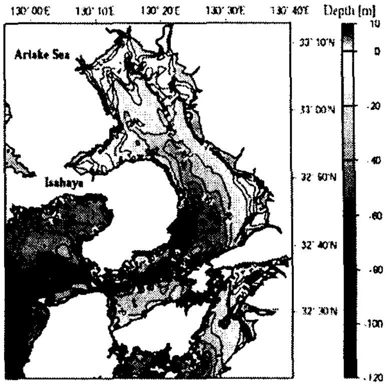


Fig. 2(b). Bathymetry of the Ariake Sea.

2.2 Regional Tide and Surge Simulator

A modeling technique that converts the model equations to be a discrete form and allows computation over irregular, spatially unstructured meshes has been used to set up as a main component of regional ocean tide simulator taking the advantage of more accurate representation of the coastlines, coastal structures and topographic features. Rather than refining dynamic grid nesting technique retaining the finite difference scheme we decided instead to adopt finite element technique permitting more flexibility in fitting regular coastline and bathymetry to be fitted with elements of an arbitrary size, shape and orientation (in particular barrier positioning). We made our own version of GUI based code for partitioning of unstructured meshes in semi-automatic manner to resolve the detailed variation of bottom topography and coastline topography permitting easy editing and can be merged into larger domain of base models, of which the open boundary conditions were prescribed previously with a series of adjustment runs. A dataset we created is detailed coastline dataset for Korean Peninsula comprising over million points and implemented on GUI based code for modification of coastline, updating and coordinate conversion. Considering the importance of setting up a proper model area, three versions of base models are created covering the YS (Yellow Sea and the East China Sea continental shelf), YS/ES (including the Japan and East Sea), YS/ES/NWP (extending to outer east Japanese coast). With this simulator design, detailed meshes in the coastal and estuarine regions can be resolved and computations can be manageable with parallel structures, demonstrating easiness of relocatablity within the base model regions. By taking time-stepping approach (Luettich et al., 1992) the method can accommodate the transient response to non-periodic (e.g. wind) forcing in additional to tides contrasting with harmonic approach and can be extended to three-dimensional flow computations subsequently. We have started external mode equations using parametric relationships for bottom friction and momentum dispersion. Key features of the external mode solution include the use of a generalized wave-continuity equation formulation (Lynch and Gray, 1979; Kinnmark, 1985) using finite element discretization.

2.3 Refined Grid System for the Ariake Sea

The simulation system for tides, wind and ocean circulation in the neighboring area of Korean peninsula was designed to cover broad area in scope and size yet providing high degree of resolution in nearshore area. Fig. 3 shows the mesh system used for Isahaya Bay simulation and regionally refined 61,000 elements was patched over coarser 73,000 elements of the larger area system thus totaling 134,000 elements. Approximate mesh sizes in region of interest were formulated as a few tens of meters and the bathymetry of tidal flat area was described, thus enabled detailed evaluation of changes in the tidal regime. Fig. 5 shows the decompressed domains for parallel computations of the a base model (simulator) used for Isahaya dike simulations employing in-laboratory PC-based cluster connected with 100 Mbps FastEthernet among 64 PCs running Linux using switching hubs (Fig. 4). It also has an interface to the RAID system of 2 Terra byte storage, keeping converted outputs with NetCDF files for prompt visualizations (e.g., IVS Fledermaus and Xvision software).

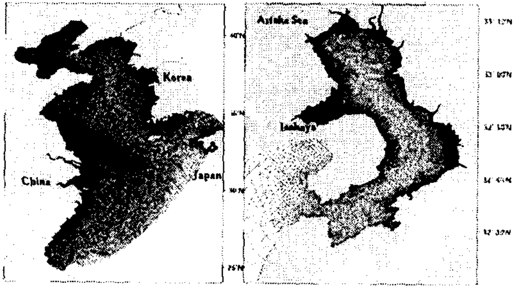


Fig. 3. Overall mesh and details at the Isahaya barrier.

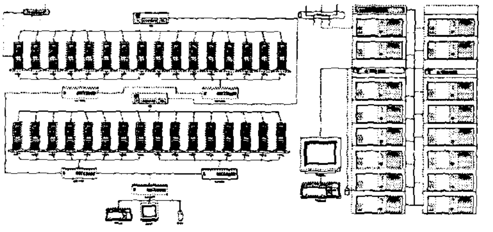


Fig. 4. Low cost in-laboratory linux-based parallel clustering computer system.

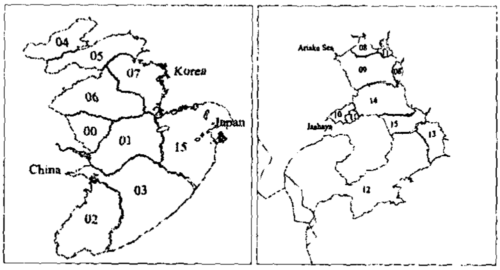


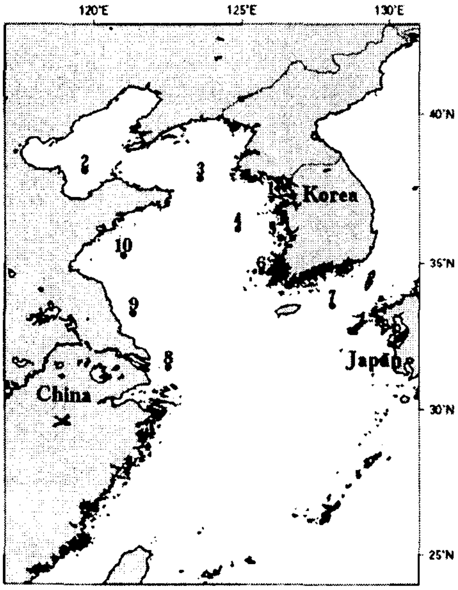
Fig. 5. Partitioned domain for parallel computations showing details of decompressed domains at Isahaya Bay.

3. NUMERICAL SIMULATION

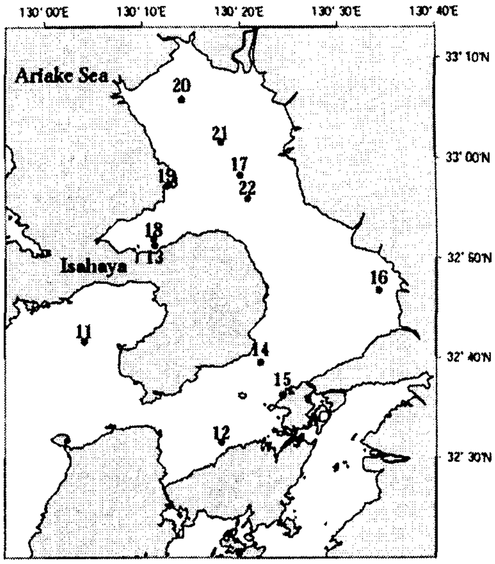
3.1 Free Oscillation Experiment

The free oscillation modes of the M_2 tide in the system were studied by free oscillation experiment using Platzman resonant iteration scheme. The model was run for 50 days from an initial state of motion with open boundary elevations of the shelf model permanently set to zero and those interior to the boundary initially set to 2 m. The first two days of data were discarded leaving 48 days of 10 minute data. Figs. 7 and 8 show time series of elevation at the selected stations shown in Fig. 6. Frequency spectra has been calculated at the selected stations in Fig. 6 using Blackman-Turkey method. The power spectra thus analyzed are showed in Figs. 9 and 10. The changes due to Isahaya barrier in the Yellow Sea and the East China Sea are very small, thus may be negligible. The largest peak at the stations in the Yellow Sea and the East China Sea (Fig. 6(a)) occurs at frequency (period) of Table. 1. Oscillations with a peak period about 10.42 hours were only calculated for Incheon Bay. This period is close to M_2 tidal frequency, and may thus be responsible for near-resonance in the

Kyoenggi Bay. The 10.42 hour period in Incheon Bay may also be obtained from Merian's formula adopting a basin length of 100 km with an average depth of 10 m (An, 1977; Choi, 1980). Choi (1980) performed the experiment of free oscillation mode in the Yellow Sea and East China Sea using the maximum entropy method (Lacoss, 1971) involving the construction of optimum numerical filters. Fig. 11 illustrates distribution of peaks in power spectra performed by Choi (1980) at the points in Fig. 10. Comparing model generated power spectra with the one of Choi (1980), there is good agreement between the two power spectra in the Gulf of Bohai, near Qingdao and in Incheon Bay. Especially, near-resonant characteristic of Incheon Bay which responds to semidiurnal tidal period is reproduced very well. Free oscillation with period about 10 hour in the Ariake Sea is calculated at all stations in Fig. 6(b), and this period is also near-resonant characteristic of the bay which is close to M_2 tide. The reduction in period of free oscillation is computed after the construction of Isahaya barrier (Table 2) and the magnitude of period is about 25 minutes. The computed result is similar to the one performed by Takikawa and Tabuchi (2002). Takikawa and Tabuchi (2002) investigated the reduction of 20 minutes in the period of free oscillation after the construction of Isahaya barrier by numerical experiment.



(a)



(b)

Fig. 6. The stations of comparison.

Table 1. Period (frequency) of the free oscillation mode for the largest peaks in power spectra at the stations in Fig. 6(a)

Station No.	Frequency (cph)	Period (h)
1	0.096	10.42
2	0.017	57.58
3	0.017	57.58
4	0.017	57.58
5	0.013	76.78
6	0.013	76.78
7	0.009	115.17
8	0.013	76.78
9	0.017	57.58
10	0.017	57.58

Table 2. Comparison of free oscillation period at all stations (11-22) between before and after the construction of Isahaya barrier

	Before the construction of Isahaya barrier	After the construction of Isahaya barrier
Frequency (cph)	0.100	0.104
Period (hour)	10.01	9.60

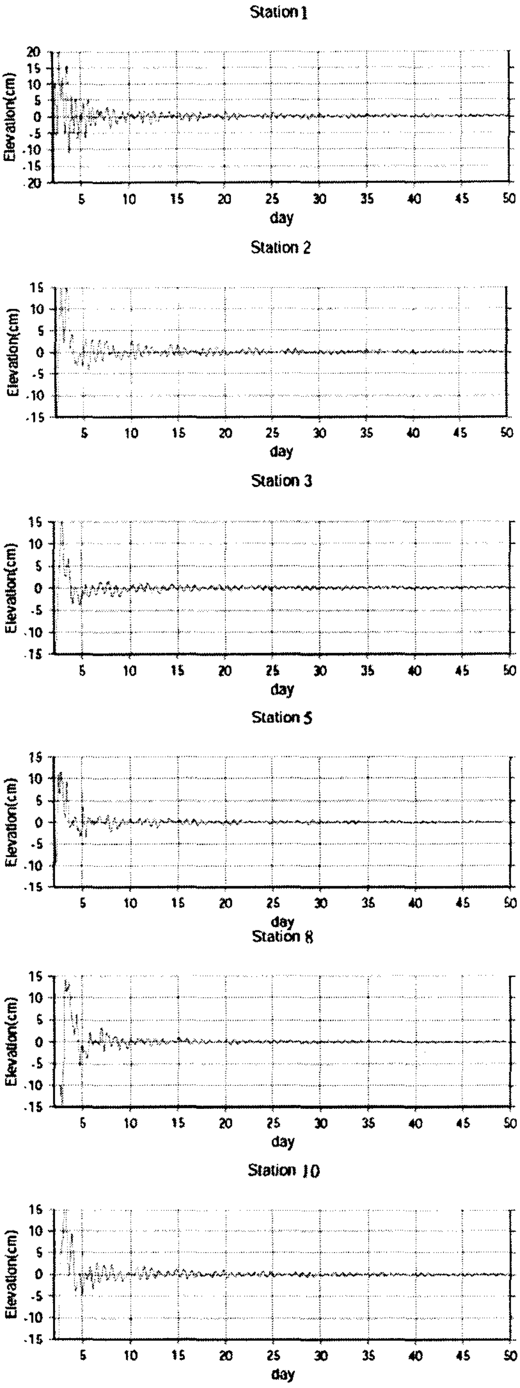


Fig. 7. Time series of elevation at the stations in Fig. 6(a) before the construction of Isahaya barrier.

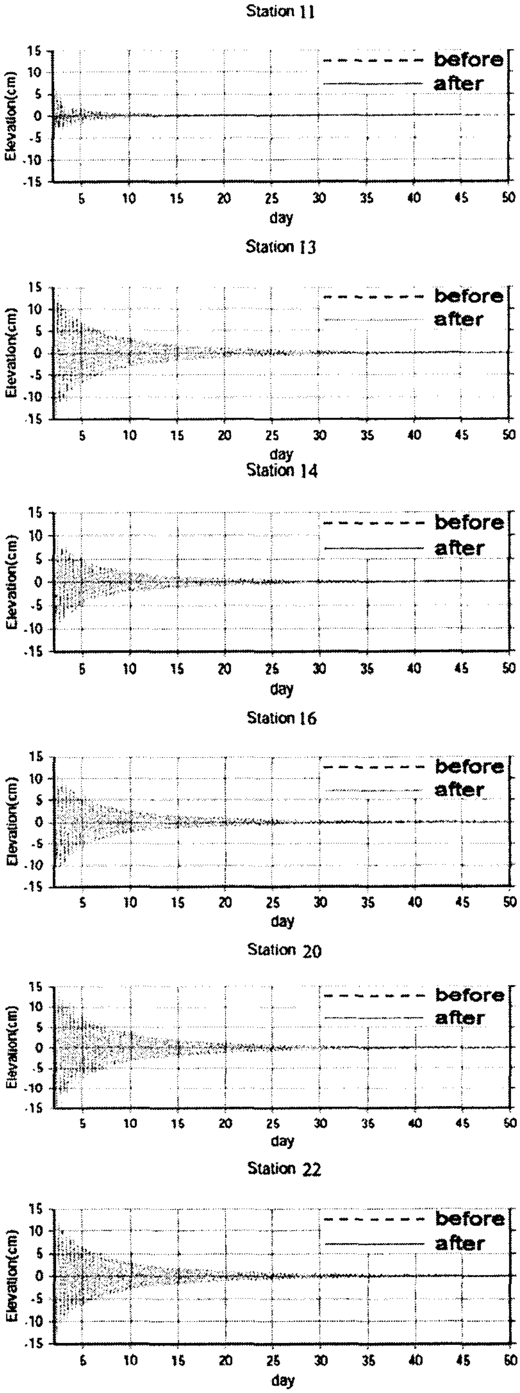


Fig. 8. Time series of elevation at the stations in Fig. 6(b) between before and after the construction of Isahaya barrier.

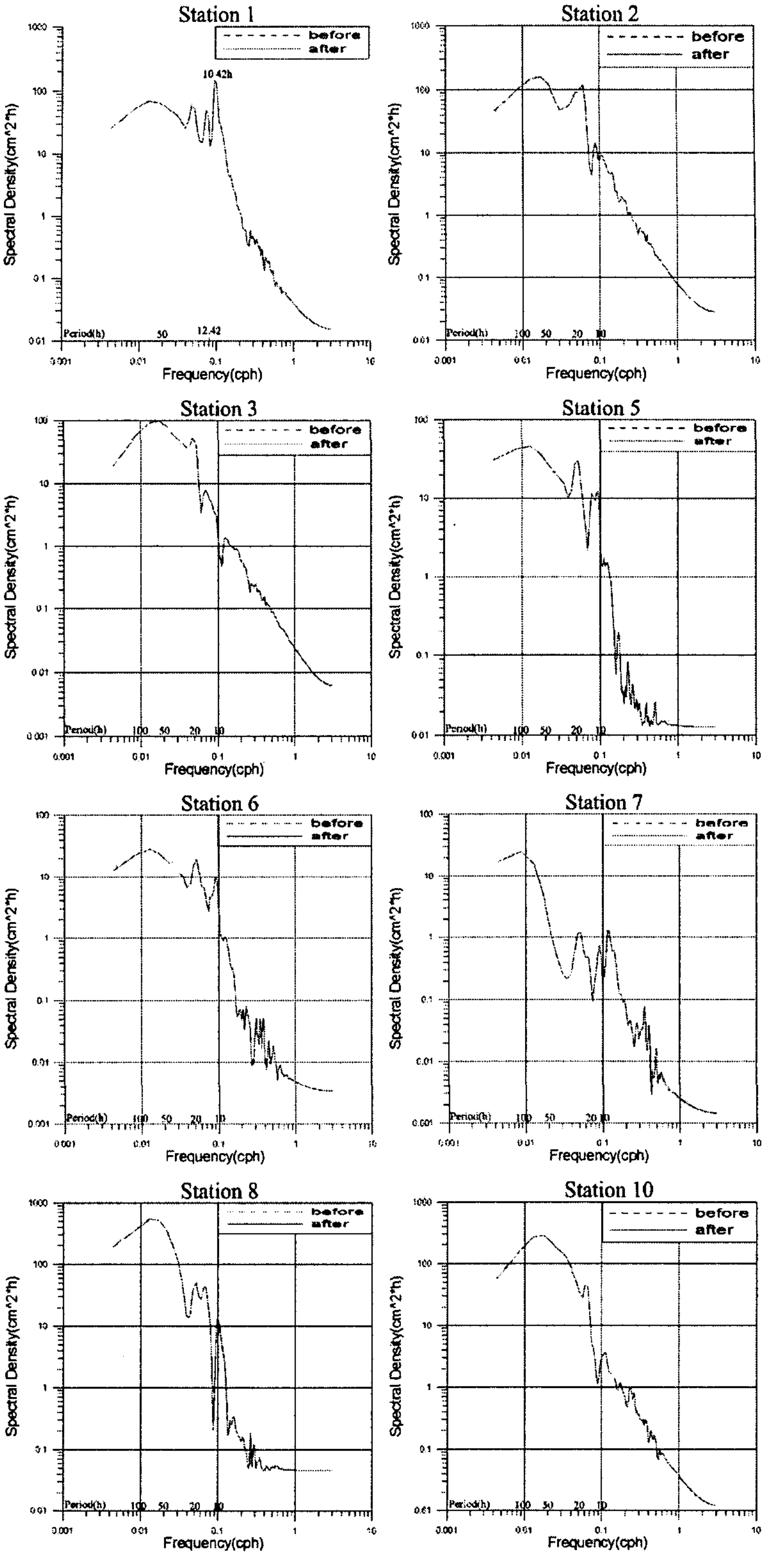


Fig. 9. Power spectra for selected points in the Yellow Sea and the East China Sea from oscillation experiment.

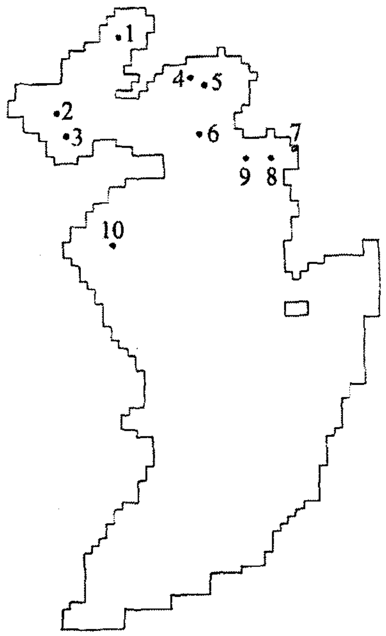


Fig. 10. Locations for free oscillation analyses (Choi, 1980).

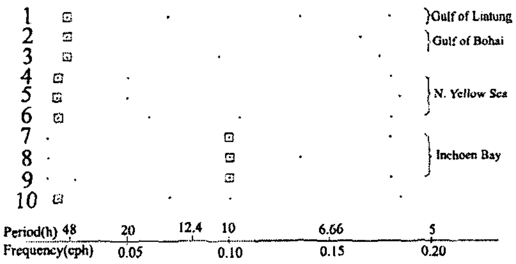
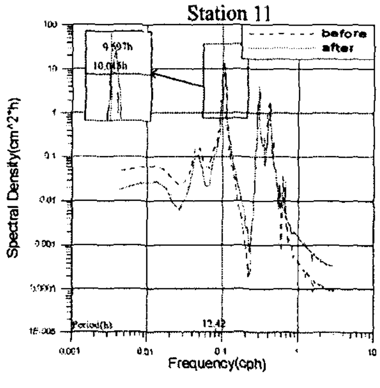


Fig. 11. Distribution of peaks in power spectra of points in the Yellow Sea (Choi, 1980).



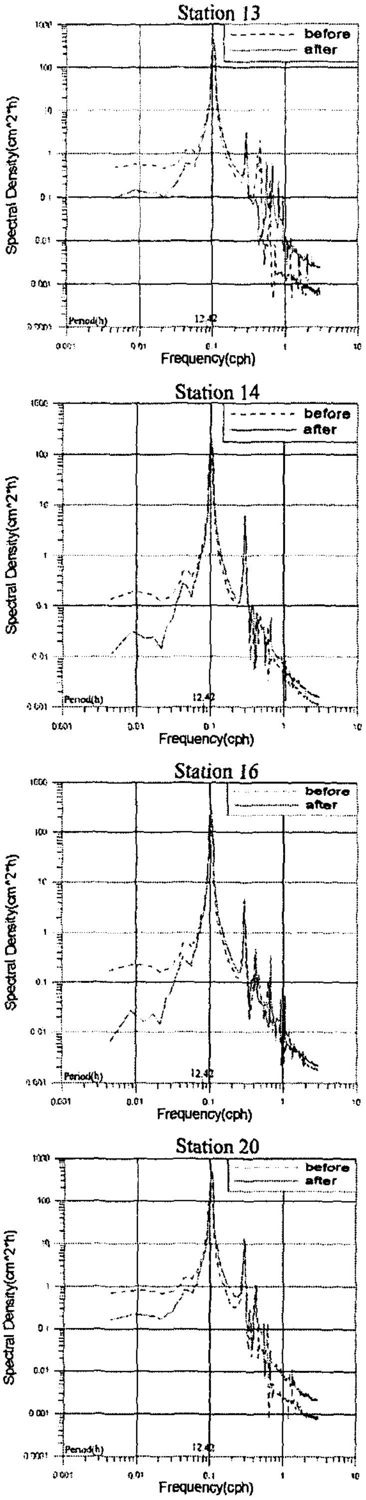


Fig. 12. Power spectra for selected points in the Ariake Sea from oscillation experiment.

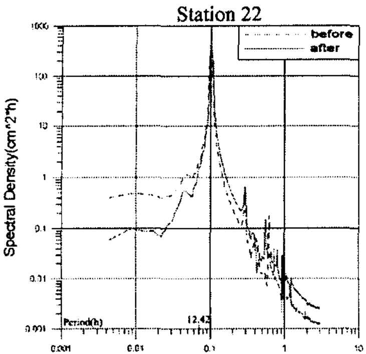


Fig. 12. Continued.

3.2 Changes in the Tide Due to Isahaya Barrier

Figs. 13~15 show the difference in amplitude and phase of the M_2, S_2 and K_1 tides indicating that disturbances due to the construction of barrier on tide occur over the whole model domain and the Ariake Sea respectively. As is seen in Figs. 13~15, tidal perturbation due to the Isahaya dike on the shelf system may be negligible in terms of their magnitude and only confined to the Ariake Sea due to its contracted narrow opening. After the construction of the Isahaya dike, the amplitude and phase decreased in the Ariake Sea (Figs. 13~15). The decrease of amplitude is the largest in Isahaya Bay in case of M_2, S_2 and K_1 tides. The magnitude of amplitude reduction occurs gradually from Isahaya Bay to the mouth of the Ariake Sea. The ebb current intensity for M_2, S_2 and K_1 tides in the Ariake Sea decreases after the construction of dike. Considerable reduction of the M_2 tide, current intensity during ebb situation is computed as shown in Fig. 16. The ebb current of M_2 tide at frontal region of the barrier was reduced up to 25 cm/s, also in the case of S_2 and K_1 tides, it is shown that the difference of ebb currents is the largest in Isahaya dike (Figs. 16~18).

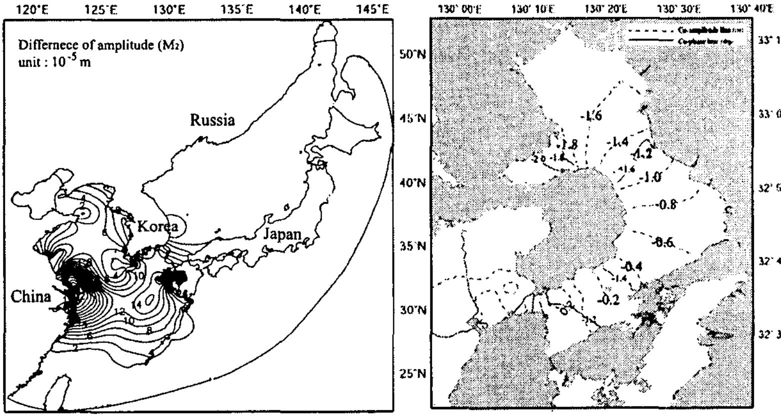


Fig. 13. Difference of amplitude and phase of the M_2 tide due to the construction of Isahaya Bay dike.

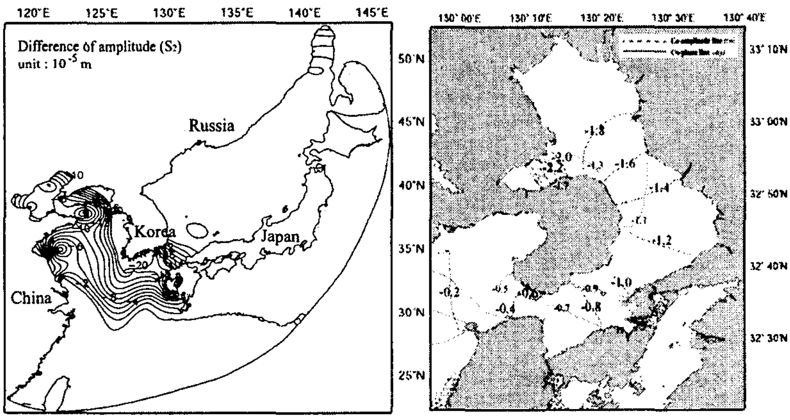


Fig. 14. Difference of amplitude and phase of the S_2 tide due to the construction of Isahaya Bay dike.

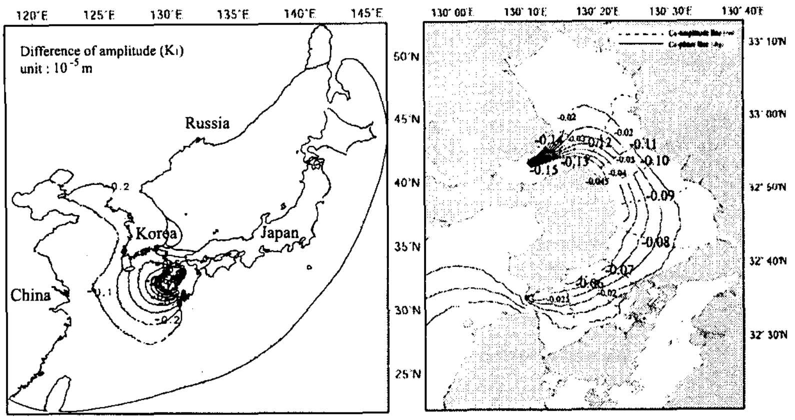


Fig. 15. Difference of amplitude and phase of the K_1 tide due to the construction of Isahaya Bay dike.

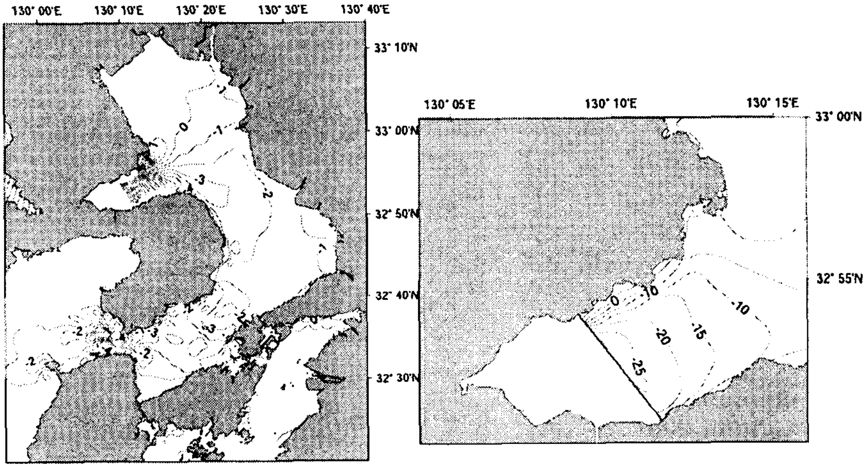


Fig. 16. Difference of ebb current intensity for M_2 tidal currents in the Ariake Sea and details at Isahaya dike (unit: cm/s).

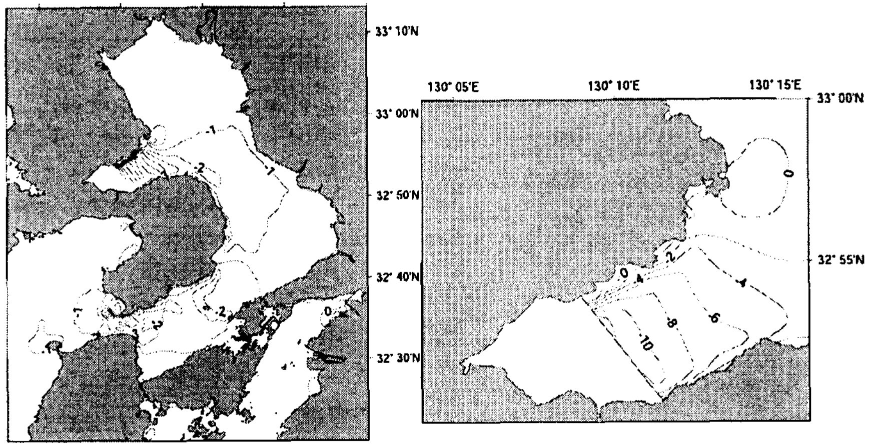


Fig. 17. Difference of ebb current intensity for S_2 tidal currents in the Ariake Sea and details at Isahaya dike (unit: cm/s).

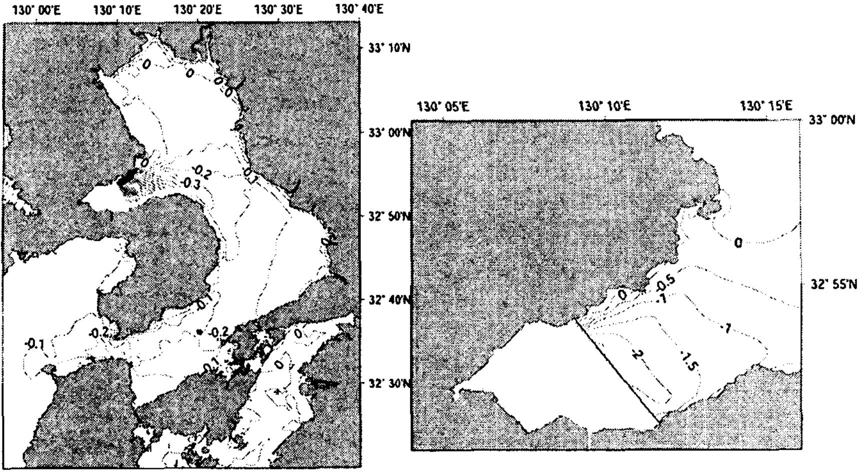


Fig. 18. Difference of ebb current intensity for K_1 tidal currents in the Ariake Sea and details at Isahaya dike (unit: cm/s).

4. CONCLUSIONS

Characteristic tidal period of free oscillation in the Ariake Sea, one of the most important factor, was investigated. According to the result from this simulation, the period of free oscillation decreased after the construction of Isahaya barrier, and the decreased period induces to reduction of tide. In this simulations of the Ariake Sea, it could be concluded that reduction of tide, which may be major contributing factor of the environmental problem in the Ariake Sea, is derived from the weaker resonance with period of free oscillation decreasing.

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