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Spatio-temporal variability of tidal asymmetry due to multiple coastal constructions along the west coast of Korea

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ABSTRACT

At least 19 remarkable dikes and land reclamations have been constructed since 1970 along the west coast of Korea, which resulted in a reduction in tidal flat area of almost 50%. Both the reduction in tidal flats and the artificially simplified coastal line have distorted the spatio-temporal tidal hydrodynamics; to quantify this, we analyzed and evaluated tidal asymmetry by phase differences of the principal semi-diurnal lunar constituent M_2 and its first over-tide M_4. Moreover, we applied the ADCIRC model to quantitatively investigate near- and far-field impacts on tidal variations using the gamma parameter, tidal energy flux, and dissipation rate. Through this study, we found that the tidal regime around the Incheon harbor area in Gyeonggi Bay has changed from ebb- to flood-dominant due to multiple nearby reclamations, in particular to the construction of the Siwha dike. The Saemangeum dike caused near-field de-amplification of M_2 but far-field amplification in the Shandong area of China. In addition to allowing a traditional asymmetry approach using phase difference, analyses based on the gamma parameter and tidal energy variations could distinctly improve spatial understanding of anthropogenic impacts on coastal tidal hydrodynamics.

1. Introduction

The Yellow Sea (YS) is surrounded by the Korean Peninsula and China and has a mean depth of 44 m. This remarkable shallowness makes tidal hydrodynamics complicated, especially in coastal regions. The spring tidal ranges along the west coast of Korea (WCK) from Incheon in Gyeonggi Bay (GGB) to Mokpo vary from 8.0 m to 3.8 m. The GGB is well known as one of the most remarkable macro tidal areas in the world. The tidal form factor, $F = (K_1 + O_1)/(M_2 + S_2)$, along the WCK is less than 0.20; thus, the WCK is a semi-diurnal dominant region. Moreover, it should be noted that the WCK is particularly shallow. Due to the complex coastal lines with shallow waters and a macro tidal range, tidal flats are well developed along the WCK and dissipate a lot of tidal energy. This yields non-linear shallow tides as a result of interaction through non-linear bottom friction and advection. One of the remarkable tidal characteristics of the YS is that about 8% of global tidal energy is systematically lost (Lefevre et al., 2000) in this small region, which awakens the importance of analyzing the feasibility of tidal power plants in semi-closed bays along the WCK. Song et al. (2013) showed that most of the tidal energy in the YS is dissipated via bottom friction in the west Korea Bay, GGB, the Mokpo Coastal Zone, the Jiangsu Shoal water and Hangzhou Bay. Moreover, they revealed that energy dissipation through horizontal diffusion is of significance in GGB, and found that tidal flats in GGB behave as energy-sink regions. Accordingly, destruction of tidal flats in this region would result in more serious local and far-field tidal effects.

Strong semi-diurnal forcing leads to relatively high over-tides and compound tides because of geo-morphological asymmetry. Previous studies on tidal asymmetry have focused on estuaries and channels. Speer and Aubrey (1985) found, via numerical modeling experiments, that increasing the ratio of tidal amplitude to water depth while keeping friction constant moved the inlet system in a flood-dominant direction and enhanced the growth of the M_4/M_2 ratio (characteristic values of the amplitude/depth ratio ranged from 0.1 to 0.5). Bolle et al. (2010) showed that tidal asymmetry arises from human-induced changes such as deepening of channels and dumping of sediments. Wang et al. (2002) assumed that the spatial change in tidal asymmetry in a certain part of the estuary, rather than at a specific location, should be related to the morphologic characteristics of the considered area. They characterized the tidal asymmetry of two stations as amplitude ratios and relative phase differences. Tidal asymmetry in an estuary was

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analyzed by examining the celerity differences of tides by Fortunato and Oliveria (2005). According to their results, tidal flats enhance ebb dominance, whereas large tidal amplitudes promote flood dominance. Their qualitative arguments indicate that friction also enhances flood dominance.

Several numerical modeling studies on tides in the YS have been accomplished. Choi (1980) used a coarse structured grid 2D Finite Difference Method (FDM) to reproduce major astronomical tides. Kantha et al. (1996) applied a model that showed M_4 could reach up to 10 cm due to shallow topography. Blain (1997) reproduced shallow tides using a 3D FDM model with a data assimilation technique. Kang et al. (1998) simulated the YS tidal regime with a 2D FDM with different bottom roughness Chezy coefficients. He et al. (2004) tried to enhance model reliability with the assimilation method, using Topex/Poseidon altimeter data from shallow tidal constituents. In addition to those FDM applications, unstructured Finite Element Method (FEM) models using fine resolution have been applied. Grid refinements using TIDE3D (Walters, 1987) and ADvanced CIRCulation (ADCIRC; Luettich et al., 1992) have been applied to reproduce tidal hydrodynamics (Suh, 2009, 2011). Song et al. (2013) clarified tidal changes caused by reclamation of the east coast of China. Its impacts spread so wide that they reached the WCK. Suh (2009) and Kang et al. (2013) dealt with tidal regime variations caused by the Saemangeum reclamation project. Their results showed a reduction in semi-diurnal amplitudes in the near-field area but a slight amplification in the far-field area on the Shandong Peninsula. Kang (1999) has shown ebb-dominance characteristics by examining tidal asymmetry due to dike construction of an estuarine dam in Mokpo. Although these previous studies dealt with site-specific anthropogenic impacts, the long-term variation induced by multiple reclamations over a wide range has not been investigated thoroughly. Thus, we examined the spatio-temporal tidal asymmetry variability due to multiple reclamations or dike constructions on the WCK for the last 4 decades using harmonic analyses of tidal record data at over 5 yearly intervals and numerical modeling using ADCIRC. This study aimed to understand and evaluate the existing relationship between coastal construction and tidal asymmetry along WCK. However, dredging of navigation channels was not considered in the bathymetry in the numerical modeling since assessing the impact of deepening channel depth on reducing flood dominance is beyond the scope of this study. Although the influence of summer monsoons on river outflows and meteorological forcing were not considered in this study, this simplification should be sufficient to assess the tidal-dominant impacts of human interference on the WCK.

2. Methods

Most of the coastal constructions on the shallow estuarine coastal region of the YS were constructed within a period of several years to 2 decades and reduced the tidal flat area dramatically. To assess the resulting tidal asymmetry changes, we adopted two methods: a comparison of harmonic constants, using the harmonic analysis tool TASK-2000 (Bell et al., 1999) to withdraw 63 tidal constituents for 366 days and application of numerical modeling for the years of the coastal construction events. We compared the situation before and after those constructions and their impacts to understand the physical spatio-temporal variations in tidal asymmetry.

2.1. Status of coastal constructions

Owing to rapid industrial development in Korea, the need to enlarge agricultural and manufacturing complex sites has increased intensively in recent decades. One easy and efficient way to enlarge these sites is the construction of tidal dikes for reclamation of land. As seen in Fig. 1, there are several large land reclamation constructions along the WCK. In the early stage of construction, from the mid-1970s to the late 1980s, dikes were constructed in the narrow entrances of estuaries. Meanwhile, large-scale land reclamations began in the mid-1980s. Among them, we pay particular attention to the following remarkable anthropogenic coastal constructions: the 33 km long Saemangeum dike construction (labeled P in Fig. 1, hereinafter referred to as [P]) and the Yeongjongdo reclamation [A] to allow building of Incheon International Airport. These coastal constructions resulted in tidal flat areas along WCK shrinking rapidly to less than 50% of their original area before these constructions were first implemented in the 1970s (Koh, 2001).

2.2. Analyses of recorded tidal data

There are 22 tidal stations along the WCK. We gathered hourly recorded tide data from 7 of these stations, which are the nearest stations for each construction for the period of 1970–2010; these stations are denoted by black dots with two initial capital letters (Incheon: IC, Mokpo: MP, Gunsan outer port: GO, Boryeong: BR, Anheung: AH, Pyeongtaek: PT, Wido: WD) in Fig. 1. To extract tidal constituents, TASK-2000 was applied at 5-yearly intervals and special years in which large coastal constructions were implemented. Analyzed amplitudes and phases referenced to Greenwich Mean Time (GMT) were investigated and are shown in Fig. 2 to help understand tidal asymmetrical magnitude and flood or ebb dominance. Among the tidal stations, IC station moved twice during the study period: in 1973, it moved from the inner dock to the outer Wolmi station by 2.032 km, adjacent to the passage of Incheon harbor; in 1998, it moved southward by 2.122 km along the passage. The effects of this movement shall be investigated in the following section with reference to the nearby coastal construction.

2.3. Numerical simulation

Coastal ocean circulation models have been intensively applied to the YS from the late 1970s to the present. Initially, a FDM with coarse grid resolution (Choi, 1980) was applied, while very fine-grid FDM, FEM, or Finite Volume Method (FVM) models have been applied to represent the complex geometry in recent years (Suh, 2009; Kang et al., 2013; Song et al., 2013). In this study, we took the FEM model ADCIRC.

Initially, a numerical model with the NWP-G57k grid structure was applied, denoting an extended grid of the North Western Pacific (NWP) with approximately 57k nodes (Suh, 2012). Although this grid had sufficient resolution in the shallow region, the resolution was not quite sufficient to resolve complex coastal lines, especially on the WCK. Thus, in the present study, finer gridding options referred to as NWP-G116k and NWP-G258k were developed. Since nodal distribution depends on how depth affects tidal hydrodynamic reproduction (Suh, 2011), 38% of the nodes were assigned to locations less than 10 m deep, and 14.5% to 10–20 m depths, i.e., more than 50% of total nodes were used to represent shallow coastal areas in NWP-G258k. As a result, the grid spacings around the major regions of interest associated with land reclamation, i.e., the Incheon, Gunsan, and Mokpo areas, were 420–1200 m, 310–1400 m, and 440–860 m, respectively, in NWP-G57k. These spacings were reduced to 290–1100 m (190–520 m), 290–1100 m (220–490 m), and 430–750 m (240–430 m), respectively, in NWP-G116k (NWP-G258k).

The coastal line was extracted from a worldwide shore line database, the Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) of the U.S. National Geophysical Data Center (NGDC; Wessel and Smith, 1996). Topological data