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Authors: Lim, Hak Soo, Chun, Insik, Shim, Jae-Seol, and Kim, Chang S.

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Wave-induced current simulated by wave–current coupled model in Haeundae

Hak Soo Lim[†*], Insik Chun[‡], Jae-Seol Shim[†], and Chang S. Kim[†]

[†]Operational Oceanography Research Center
Korea Institute of Ocean Science and Technology
Ansan 15627, Korea

[‡]Department of Civil Engineering
Kokuk University
Seoul 426-744, Korea

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ABSTRACT

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The wave-induced current in Haeundae, at the southeastern end of the Korean Peninsula, is one of the main causes of beach erosion. The Korean government recently initiated a beach restoration project for Haeundae beach to protect the famous beach against wave-induced currents generated by waves during summer and winter. To mitigate beach erosion, two submerged breakwaters and a sand nourishment program were initiated in 2013. With the support of the Korean government, we have also started an R&D project to develop coastal erosion control technology in order to understand the processes of beach erosion by measuring sediment transport and hydrodynamics in Haeundae coastal waters, including the development of a numerical simulation method. The aim of this study is to understand the main processes of wave-induced currents that cause erosion at Haeundae beach by considering wave and tide interactions, using a wave–current coupled model compared with long-term observed wave and current data. We found that the cross-shore current during summer is mainly caused by the eddies produced by wave-induced currents generated by strong high waves during a Typhoon approaching from the SSW and S directions. During other seasons, a longshore current is produced by swell waves coming from the E and ESE directions. In comparisons with the measured data, we also found that the wave-induced current is well simulated by a wave–tide coupled model in Haeundae with a coastal environment of wave and tide interaction.

ADDITIONAL INDEX WORDS: *Wave-induced current, wave-tide interaction, coastal processes, beach erosion.*

INTRODUCTION

Haeundae, located at the southeastern end of the Korean Peninsula, has a 1.6 km long coastline with a 60 m wide famous sand beach facing Tsushima Island and the Korea Strait. Haeundae has shallow water (<30 m), small tidal range (<1.2 m), and weak tidal currents (<1 m/s), waves (H_s < 4 m), and winds (<15 m/s) which vary seasonally. The end of the pocket-like beach is surrounded by Dongbaek Island at the western end of the coast, and Dalmaji hill, at the eastern end. The Chuncheon stream, once located in the middle of the beach, supplied fresh water and suspended sediment transport through the 1940s until it lost functionality due to coastal area development.

The beach is currently being eroded mainly by the recent ongoing coastal development, such as the construction of Mipo Port at the eastern end of the beach near Dalmaji hill, and revetments near the beach, as well as the disruption of river sediment inflow into the beach. Additionally, the beach has retreated due to high waves developed by nearby Typhoons during summer and fall, and the swell waves propagated by strong winds from the northwest and northeast during winter (Lim *et al.*, 2014). The Korean government recently started a restoration project in 2013 to mitigate beach erosion via a massive beach nourishment program and two submerged breakwaters at both ends of the beach to prevent offshore flow of sediment. To support the restoration project, in July 2013, we initiated a long-term observation and numerical simulation as part of the government R&D project to develop a coastal erosion control system.

The wave-induced current prediction software package HAECOM (Kim *et al.*, 2010) was developed recently with the goal of preventing people from being swept away by rip currents in Haeundae in the summer. The GUI-based forecasting system predicts rip currents generated by wave-induced currents simulated by one-way coupled hydrodynamic and wave models. To predict sediment transport in Haeundae coastal waters by high waves in summer and winter, the numerical simulation system CST3D (Kim *et al.*, 2013) was adopted to reproduce the bathymetric change during the period of beach erosion in 2007. The wave-induced current was simulated by the EFDC hydrodynamic one-way model, linked to the SWAN wave model for wave information, to calculate the radiation stress in the momentum equation of the flow model.

Recently, Lim *et al.* (2014) analyzed the variability of waves and currents in Haeundae using the long-term wave and current measurements observed by Acoustic Wave and Current meters (AWACs) near the beach, together with a wave–tide coupled nearshore current simulation using the ROMS-SWAN modeling system.

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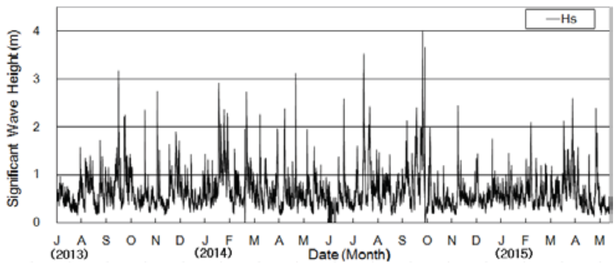
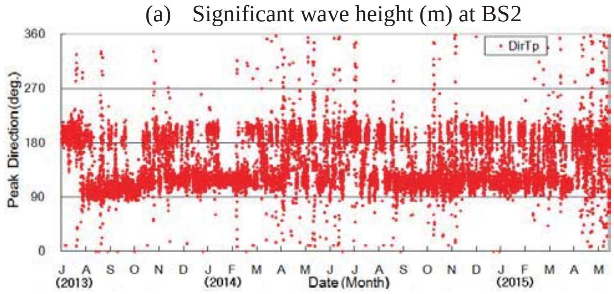
*Corresponding author: hslim@kiost.ac.kr

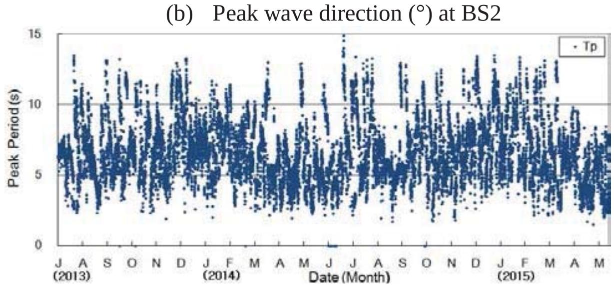
Figure 1. Location of study area. Observation stations and periods of AWAC wave and current measurements in Haeundae coastal waters at the southeastern end of the Korean Peninsula.



(a) Significant wave height (m) at BS2



(b) Peak wave direction (°) at BS2



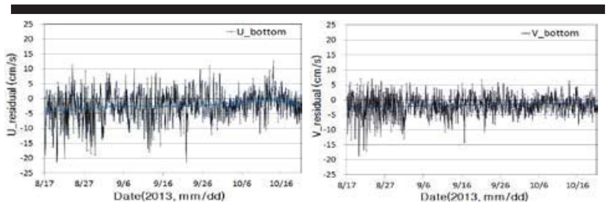
(c) Peak wave period (s) at BS2

Figure 2. Time series of (a) significant wave height, (b) peak wave direction, and (c) peak wave period at station BS2 from long-term observation by an AWAC from July 25, 2013 to June 10, 2015.

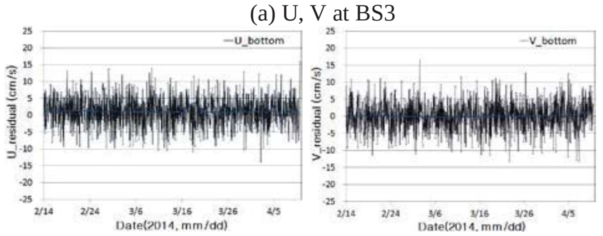
METHODS

In order to understand the coastal water processes, wave and current data were measured and analyzed to calibrate the wave and current coupled modeling system and validate the model results. Long-term field observations were designed and conducted in Haeundae coastal waters (Figure 1) as part of the measurements for the development of a coastal erosion control system. At station BS2, which was deployed at the mean water depth of 22 m, wave and currents have been observed by an AWAC since July 25, 2013. Figure 2 shows the significant wave height, peak wave direction, and peak wave period estimated from observed data from July 26, 2013 to June 10, 2014. At station BS3, which was deployed at the western part of Haeundae, with a mean water depth of 8 m, an AWAC measured the waves and currents from August 17 to October 21, 2013. At stations BS4 and BS5, with mean water depths of 6 m and 4 m, respectively, the waves and currents were also measured in winter and summer of 2014.

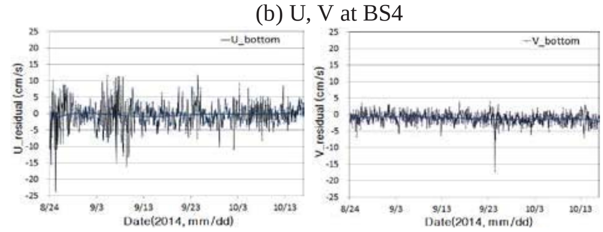
We estimated the residual currents from the current data observed nearshore of Haeundae beach for comparison with simulated wave-induced currents. The IOS Tidal Package, T_TIDE (Pawlowicz *et al.*, 2002) was used to estimate the residual current, eliminating the predicted tidal current from the observed raw current. Figure 3 shows the time series of the bottom residual current and regression curve for the residual current based on the bottom current measured at stations BS3, BS4, and BS5.



(a) U, V at BS3



(b) U, V at BS4



(c) U, V at BS5

Figure 3. Time series of bottom residual current at (a) BS3, (b) BS4, and (c) BS5 observed nearshore of the beach, derived from measured current data, eliminating predicted tidal current estimated by T_TIDE.

Wave and current coupled modeling

A numerical simulation using a wave and current coupled model, ROMS-SWAN (Warner *et al.*, 2008), was conducted to determine the wave-induced current in Haeundae with a typical condition of swell waves (H_s: 2.5 m, T_p: 12 s) coming from SSW in summer, and ESE in winter. The two-way coupled model has been used for a variety of applications in Korean coastal waters, especially by the Korea Operational Oceanographic System (KOOS) to provide predicted data on a 72-hour basis to the public for the prevention of coastal disasters and safe navigation in harbors and ports (Lim *et al*., 2013a).

The down-scaled Haeundae hydrodynamic model ROMS (Haidvogel *et al.*, 2008; Lim *et al*., 2013b) uses a high-resolution grid (288 × 144) with a cell size of 15 m horizontally and 5 layers vertically covering 129.15–129.19°E and 35.14–35.16°N. Figure 4 shows the computational model domain and bathymetry in Haeundae. In the middle of the Haeundae coastal waters near the beach, two parallel shoals are located orthogonally to the coastline. For the open tidal boundary, we used 10 major tidal constituents, including semi-diurnal tidal constituents (K_1, O_1, P_1, and Q_1) and diurnal tidal constituents (M_2, S_2, N_2, and K_2) derived from a global model of ocean tides, TPXO7 (Egbert *et al.*, 2002). The detailed model configuration was described by Lim *et al.* (2014). The phase-averaged spectral wave model SWAN (Booij *et al*., 1999) two-way coupled with ROMS at the interval of 4 min also used the same model domain and bathymetry for the wave and current interaction. Figure 5 shows the simulated significant wave height and the direction of the swell waves coming from SSW in summer and ESE in winter estimated by long-term observed wave data at station BS2. Most of the waves coming from SSW reach the middle of Haeundae beach, especially behind the shoals, because of the wave breaking and shoaling effect. However, the waves coming from ESE are significantly decreased near the shallow waters because of wave breaking and refraction.

In this paper, we simulated a wave-induced current to investigate the coastal processes and beach erosion by swell waves. We compared the results of a wave and tide coupled simulation with the results of a wave only simulation to examine the effect of wave–current interaction, and validated the results using the estimated residual currents observed by AWACs.

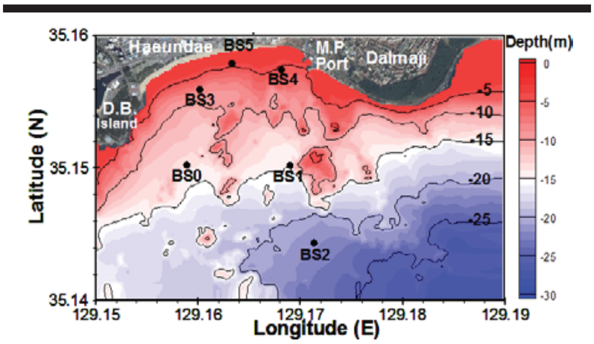


Figure 4. Computational domain and bathymetry of Haeundae coastal waters for the simulation of wave-induced current using ROMS-SWAN.

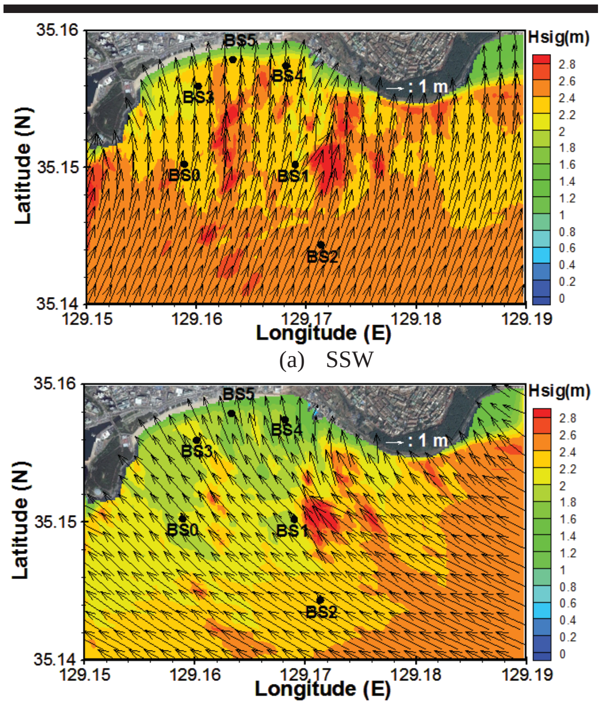


Figure 5. Significant wave height and direction simulated by SWAN model for swell waves (H_s: 2.5 m, T_p: 12 s) coming from (a) SSW in summer, and (b) ESE in winter.

RESULTS

We analyzed the seasonal variability of waves and currents using two-year long observations of waves and currents in Haeundae coastal waters. By statistical analysis, we found that swell waves (H_s: 2.5 m, T_p: 12 s) in the summer are propagated from SSW, generated in the South China Sea by typhoons passing nearby the Korean Peninsula. On the other hand, swell waves in fall and winter are propagated from ESE, generated in the East Sea by seasonal strong winds.

To estimate the average residual current from the observed current data, we applied a moving average method with a fortnightly data window, MSf (327.86 h) and two times MSf (Kim *et al.*, 2009; Lim *et al.*, 2014). Figure 6 shows the averaged bottom residual current, driven by a wave-induced current and eliminating the tidal current using a moving average method. The longshore currents measured in summer 2013 at station BS3, west of Haeundae beach, flows toward Dongbaek Island at a speed of 4–5 cm/s. The longshore current measured in summer 2014 at station BS5, in the middle of the beach, flows south at a speed of 2 cm/s. On the other hand, the longshore current measured in winter 2014 at station BS4, east of the beach near Mipo port, flows eastward at a speed of 3 cm/s. The offshore averaged residual current at stations BS1 and BS2

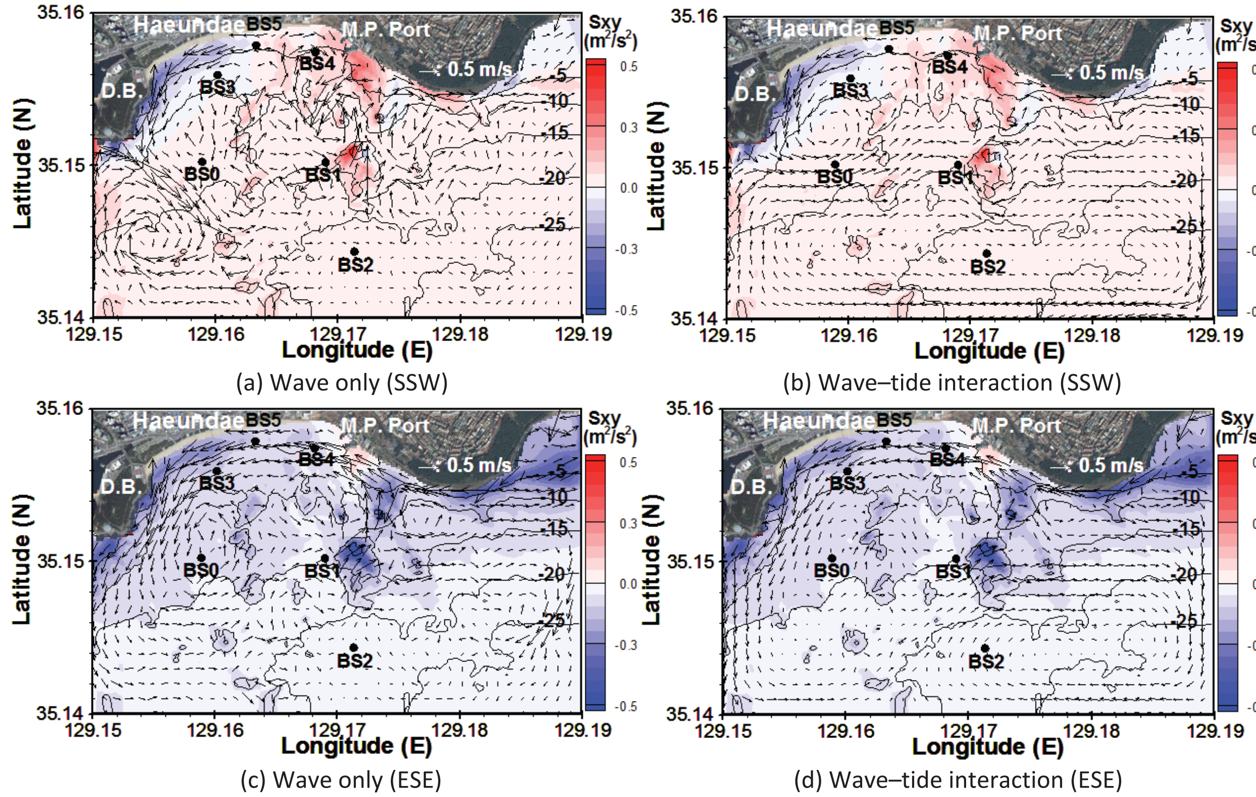


Figure 7. Bottom wave-induced current and horizontal radiation stress (S_{xy}) simulated by the ROMS-SWAN model under wave conditions of 2.5 m wave height and 12 s for different wave directions; (a, b) SSW and (c, d) ESE with/without wave–tide interaction.

flows northeast, similar to the ebb tide, at a speed of 9–10 cm/s. The flow direction at station BS0 during storms was opposite.

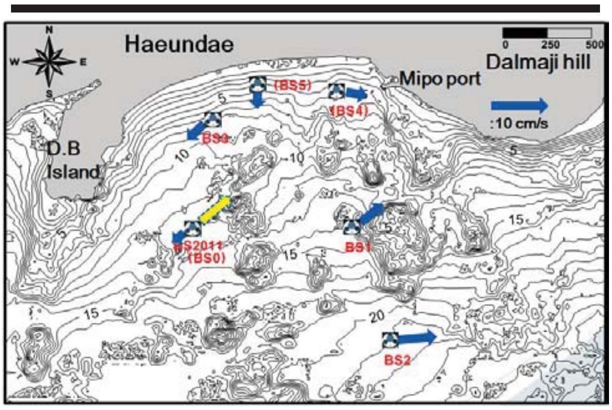


Figure 6. Averaged bottom residual currents in Haeundae coastal waters estimated by bottom-mounted AWAC flow data. Dotted arrow at the station BS0 means opposite residual current by storm waves in 2011.

Wave-induced current by wave–tide interaction

The wave-induced current was simulated separately using ROMS-SWAN, which is coupled through the Model Coupling Toolkit (MCT). SWAN provides the wave height, direction, and period to ROMS to calculate the radiation stresses, and ROMS also provides currents, surface elevation, and bathymetry to SWAN at certain intervals (Warner *et al.*, 2008). First, we simulated the wave-induced current without a tidal current boundary condition, calculating radiation stresses using the ROMS momentum equation using SWAN wave information every 4 min. Second, we simulated the wave-induced current using the ROMS model with a tidal current boundary condition, calculating the radiation stresses in ROMS using SWAN wave information. The ROMS-SWAN model exchange wave and flow information every 4 min for the wave–tide interaction.

Figure 7 shows the simulated bottom wave-induced current with swell waves coming from SSW and ESE, without and with wave–tide interaction. The simulated wave-induced current at station BS3 is well matched with the estimated averaged residual currents. Compared with the simulated results with swell waves coming from SSW in the summer, we found that the wave-induced current is separated at the station between BS5 and BS4, flowing westward and eastward. From the wave and current coupled simulation, we also found that the speed of the longshore current along the coastline increased because of eddies generated by wave–tide interactions.

CONCLUSIONS

A numerical simulation using a wave and current coupled model (ROMS-SWAN) was conducted to determine the wave-induced current, which is one of the major causes of beach erosion in Haeundae during summer and winter. The wave-induced current simulated by seasonal swell waves (H_s: 2.5 m, T_p: 12 s) come from SSW in summer and ESE in winter. We compared the wave-induced current with averaged residual currents observed by a bottom-mounted AWAC nearshore of the beach. The speed and direction of residual currents were obtained using IOS T_TIDE and a moving average method with a fortnightly period (MSf).

By comparing the measured and simulated results, we found that the cross-shore current generated by swell waves in summer is mainly caused by the eddy which is separated in the middle of the beach by wave-induced currents generated by strong high waves coming from the SSW and S directions. In other seasons, a longshore current from swell waves is caused by the wave-induced current generated by strong swell waves coming from the ESE and E directions. This is consistent with surveyed beach erosion near the surf zone in summer and the observed sediment transport toward Dongbaek Island on the western end of Haeundae beach in winter (Kim *et al.*, 2012), respectively.

The wave-induced current simulated by the wave–current coupled model generates a strong longshore current along the coastline in winter and also generates counter-clockwise strong eddies near Dongbaek Island in summer, which are consistent with observed data. The simulated results show that the wave-induced current needs to be simulated by a wave–current coupled model that considers wave–tide interaction where tides exist in Haeundae coastal waters.

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