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Source: Journal of Coastal Research, 85(sp1) : 186-190

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/SI85-038.1

Journal of Coastal Research	SI	85	186–190	Coconut Creek, Florida	2018

Efficient Real-time Erosion Early Warning System and Artificial Sand Dune Breaching on Haeundae Beach, Korea

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ABSTRACT

Seok, J.-S. and Suh, S.-W., 2018. Efficient real-time erosion early warning system and artificial sand dune breaching on Haeundae Beach, Korea. *In:* Shim, J.-S.; Chun, I., and Lim, H.S. (eds.), *Proceedings from the International Coastal Symposium (ICS) 2018* (Busan, Republic of Korea). *Journal of Coastal Research*, Special Issue No. 85, pp. 186–190. Coconut Creek (Florida), ISSN 0749-0208.

An attempt to simulate real-time erosion on Haeundae Beach, Korea, was suggested in a previous study. The present paper is a sequential study comparing coastal sediment spatiotemporal changes on sandy beaches for horizontal and selected transects over a 2-m threshold wave height set with reference to Typhoon Chaba of 2016. It was found that erosion persisted for more than 17 h during the overall typhoon passage. By coupling heterogeneous models created with Perl script, Advanced Circulation (ADCIRC) + Simulating Waves Nearshore (SWAN) + XBeach, it is possible to satisfactorily predict beach morphology changes 12 h before onslaught, with both qualitative and quantitative accuracy. Moreover, this proposed scheme can be effectively extended for operational purposes. In addition, a series of numerical simulations hindcasting the breaching and downfall of an artificial coastal dune were performed. An artificial sand dune constructed on Haeundae Beach in 2012 breached and collapsed due to storm contact. Here, simulation results indicate that the weak points of the sand dune responded differently to the storm. In addition, the collapsing procedure and magnitude changes occurred differently along the dune. Thus, it can be concluded that precise pre-design of artificial-sand dune location and size is very important, and must be performed for a target storm return period.

ADDITIONAL INDEX WORDS: *Early warning system, morphological change, heterogeneous models.*

INTRODUCTION

Beach morphological changes occur continuously, but abrupt alterations manifest during severe storm events. Although attempts to predict such changes using numerical schemes have been made, they are hindered by various problems. The most challenging problem may be treatment of the sand material shapes and diameters, which are spatio-temporally unevenly distributed, as having some typical value (such as mean diameter) throughout the entire region. To overcome this difficulty, some studies have considered integrated models of circulation under severe wave conditions with morphological changes. Kuiry *et al*. (2014) have introduced a process-based supercritical coastal flow model to simulate overflow and overwash due to rapid currents driven by storm surges and waves through a coastal inlet, as well as morphological changes in the inlet and barrier islands. Those researchers treated supercritical flow to enable the integrated coastal process model to simulate both overflow and overwash flow induced by storm surges and waves. Further, Suh *et al*. (2017) have demonstrated an efficient early warning system (EWS) for a sand beach constructed via loose coupling of the Advanced Circulation (ADCIRC) + Simulating Waves Nearshore (SWAN) and XBeach models using Perl script. Numerical hindcasting for comparison of the suggested scheme with the observed field morphological changes induced by historical storms has been performed for two representative typhoons, Maemi (TY0314) and Sanba (TY1216), on Haeundae Beach. Although those researchers proposed a well-designed beach erosion framework, there was insufficient verification based on field measurements in the study (Suh *et al*., 2017).

In 2016, Typhoon Chaba moved through the Korean Straits (from 2016-10-04 16:00Z to 2016-10-05 06:00Z) and directly influenced morphological changes at Haeundae Beach. Measurement of sea-bottom bathymetry around the beach area was performed in May 2016, *i.e.*, before the typhoon, and in October 2016, after the typhoon. As Harley and Ciavola (2013) have noted, one of the most significant challenges with regard to operating a real-time forecast model of coastal risk is the need for reasonably up-to-date topographic and bathymetric information. Thus, it is very meaningful that most of the processes inducing morphological reactions at Haeundae Beach have been verified through comparison with actual bathymetric data. At this location, some waves exceeding the threshold value affected the beach morphology, which changed with time due to passage of Typhoon Chaba.

In addition to use of a sand-beach EWS, coastal zone management (CZM) is also performed through construction of temporary artificial dunes, which are used as buffers against high water levels and waves during the winter storm period. However, these dunes are constructed in a relatively haphazard manner, based on local experience and with little knowledge of

DOI: 10.2112/SI85-038.1 received 30 November 2017; accepted in revision 10 February 2018.
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their ability to sustain the effects of different storm types. As such, despite the existence of offshore wave and water-level predictions, the management response to dune failure and subsequent inundation is mostly reactive rather than proactive (Harley and Ciavola, 2013). At Haeundae Beach, an artificial sand dune was constructed in 2012; however, it collapsed during the passage of Typhoon Chaba. Although, limited data are available on artificial sand dunes, such as their general size and shape. The detailed specifications are unknown, which poses difficulties for analysis of dune collapse or breaching.

This paper first reinforces the numerical verification of the previous study by Suh *et al*. (2017) and then examines the cause and effect of dune breaching and collapse through hindcasting simulations. That is, the collapse shape and size of the artificial sand dune in response to the external force at the time of the typhoon are quantitatively reproduced via numerical experiments in this study. This knowledge is important to facilitate proper beach management. Further, this approach can be applied in future designs, for example, for 50- or 100-year return periods, to provide adequate artificial sand dunes or coastal barrier protection that can withstand typhoons.

METHODS

First, real-time morphological change forecasting for Haeundae Beach, the target area, due to typhoons that may affect Korea is considered. As the numerical scheme, a circulation model incorporating storm waves ADCIRC+SWAN (Dietrich *et al*., 2012) is coupled with the XBeach model (Roelvink *et al*., 2009); this coupled scheme has been described in detail in the previous paper (Suh *et al*., 2017). According to previous studies (Kim and Suh, 2016; Suh *et al*., 2017), most characteristics of typhoons affecting Korea can be accurately determined as they pass through the Ryukyu islands, which lie between Taiwan and Japan. The typhoon forecast is captured every 6 h, and the storm surge model is automatically initiated when the center of the typhoon penetrates those islands, entering the continental shelves. This is almost directly north of 25 degrees of latitude, which is referred to as region of interest (ROI)-1. The storm surge model is triggered using a set of command sequences written in Perl script.

The aim of real-time morphological forecasting is prompt and early release of simulated results to the relevant agencies, prior to typhoon passage or landfall. To achieve this aim for Typhoon Chaba in 2016, three advisories, which were released in advance as the typhoon approached the target area, were applied to both storm surge forecasting for ROI-1 and XBeach coupling simulations for the beach morphological change area, labeled ROI-2. In accordance with the temporal forcing variations, the Haeundae Beach responses were uploaded to a webpage in the form of animations and text indicating the spatially varying tendencies. Moreover, the occurrence times and magnitudes of the maximum erosion and deposition with possible maximum storm surge elevations along the Korean coast were automatically published online immediately after simulation.

The real-time simulation was initiated based on determination of the impact of the typhoon crossing over the Ryuku islands. To maintain numerical efficiency in the real-time morphological simulation, the computation was only performed when the computed wave height in ROI-2 exceeded the threshold value H_{th} of 2 m and lasted to the end of the typhoon passage, when the significant wave height H_s was greater than H_{th}.

Typically, coastlines are protected by levees or barrier islands. During overflow, the tops are over-washed by currents induced by storm surges. Thus, levee crests may be eroded by overwash flow (Kuiry *et al*., 2014). To prevent sand loss at east-coast beaches and Haeundae Beach, some soft treatments have been applied. For soft treatment, sand nourishment and artificial sand dunes are typically used to provide protection against severe erosion. In the second part of this study, artificial sand dune collapse was simulated. A trapezoidal shape was assumed along the Haeundae-Beach frontal region. This assumption was necessary because detailed design or construction dimensions were unavailable. The construction was performed by heavy-vehicle drivers using bulldozers. This field-adopted beach modification approach is somewhat popular for restoration or mitigation activities for CZM. For example, beach scraping of the Emilia-Romagna (E-R) coast in Italy is usually directed by field decisions of bulldozer drivers (Harley *et al*., 2016).

Several numerical simulations were performed to elucidate the behaviors during Typhoon Chaba in 2012, where the dunes finally collapsed and were breached due to wave forces exceeding the threshold value. The typical sand-dune dimensions are shown in Figure 1 (a). Note the 7-m heights immediately in front of the central park and tourist information center, which decreased slightly at both dune wings, to 5 m. To model the artificial dunes, a boundary-fitted orthogonal curvilinear grid with minimum spacing of 5 m was used to adequately describe the concave-shaped beach layout and to effectively simulate dune breaching, as shown in Figure 1 (b). This flexible grid structure can elucidate both dune collapse and beach modification with good accuracy. Some degree of computational cost was unavoidable for these simulations, because of the small grid size and relatively large number of cells.

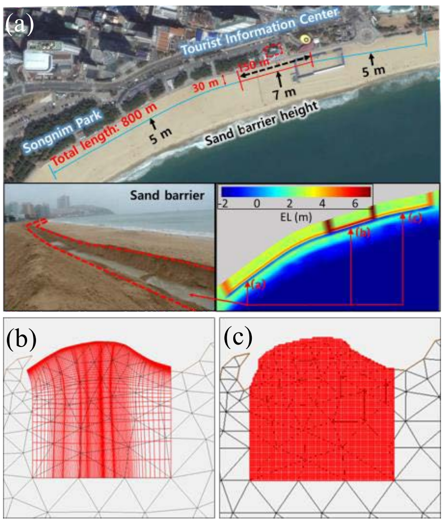
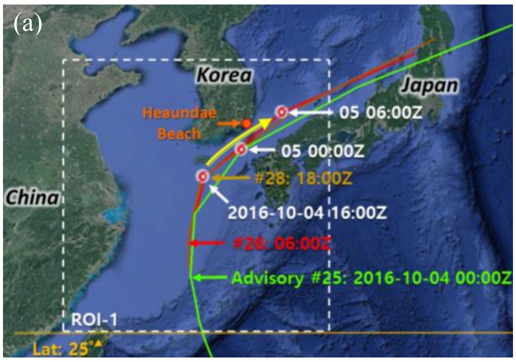


Figure 1. (a) Sand barrier specifications, (b) orthogonal curvilinear grid with minimum size of 5 m for simulation of barrier breaching, and (c) rectilinear grid for real-time forecasting with grid size of 30 m.

RESULTS

In this successive study, the loosely coupled beach erosion model proposed in a previous study (Suh *et al*., 2017) was calibrated against the measured post-storm profile for Typhoon Chaba. To analyze the effectiveness of the data on the near real-time morphological changes based on early forecasted typhoon advisories, five transect lines were selected, as shown in Figure 2. For those lines, the computed results for the three advisory forecasts were compared with the observed differences between May and October 2016. In addition, the area between transects from Dongbaek Island in the west to Mipo Harbor at the easternmost point was divided into even segments. At the beach face, the transect segments spanned 100 and 500 m in the backshore and nearshore directions, with 8-m depth. Hence, the region affected by erosion and sedimentation, especially swash and surf zones, during severe storm events was found.



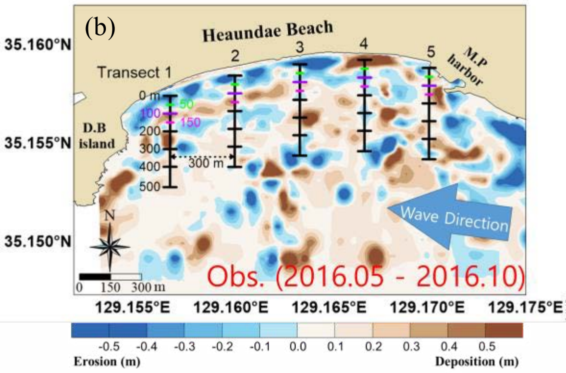


Figure 2. (a) Typhoon Chaba tracks and locations of released advisories. The beach morphology varied during the times for 17 h indicated by the yellow arrow. (b) Spatial beach changes induced by storms. The transect lines are shown in black.

The numerical simulations were based on three advisories, from #25, where the center of the typhoon had just entered ROI-1 (crossing over the Ryukyu islands), to #26 and then # 28, as shown in Figure 2. The simulated results were qualitatively compared with the bathymetry observations performed before and after the typhoon. In addition, to understand the swash and surf zone variations quantitatively, comparisons were also made along the specific transects.

As the analyses had considerable dependence on the outer forcing variation, comparisons were performed according to the typhoon advisories. The simulation results shown in Figure 3 indicate that the morphological changes were mainly geological effects. For example, the most deposit-dominant zone appeared at Mipo Harbor, which is left of the headland; thus, it was within the shadow zone of the counterclockwise typhoon wind and wave incoming direction. As a result, along transects 4 and 5, sedimentation occurred on the swash zone. On the other hand, erosion dominated the swash zone of transects 1–3, where the shading effect was eliminated. The erosion and deposition magnitudes were approximately 0.5 m and, thus, may not be important in the context of the overall morphological variations. However, the tendencies did not vary even under adoption of the earlier advisory, #25. Thus, the availability of earlier versions of meteorological information would provide sufficient time for prompt preparedness to achieve beach protection.

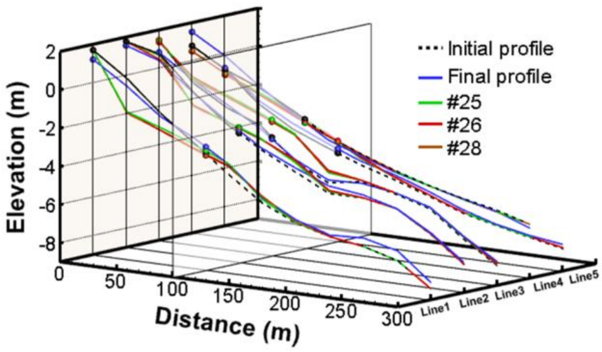


Figure 3. Morphological changes along transect lines in accordance with typhoon advisories.

The spatial variations of the morphological changes in accordance with the updated advisories were also compared against field observation results, as shown in Figure 4. As apparent from the figure, the spatial erosion and deposition on the surf and swash zones according to XBeach were satisfactorily similar to observation, except at the eastern part of the beach between the center and Mipo Harbor due to shadow zone effect of headland, which may not be clearly resolved in numerical simulation. There, deposition dominated the real-world behavior, whereas Xbeach indicated erosion. Regardless, the results based on the earliest advisory were almost identical to those of the subsequent advisories. It was also noted that the maximum erosion (deposition) levels were 1.98 (0.97), 1.87 (1.08), and 1.75 (0.98) m for advisories #25, #26, and #28, respectively.

Overall, erosion and deposition occurred in the swash and surf zones within the 150-m banded area along the beach face of the study area. This general tendency did not change under the revised typhoon advisories. Those simulated results exhibited almost the same trends and magnitudes as the measured field data, especially in the surf and swash zones. This clearly indicates that the beach responded when H_s exceeded the threshold value for morphological change (Suh *et al*., 2017). However, the value of H_{th} is dependent on the site and external forcing; thus, it should be verified with observed field data. Based on analyses of serial storm clustering in the UK, Dissanayake *et al*. (2015) have suggested a H_s value of 2.5 m, which is slightly higher than that reported for the target area considered in this study. Regardless, the results indicate that the EWS developed by coupling XBeach with ADCIRC+SWAN using external Perl script to form a coupled model of beach morphological change can be efficiently applied in CZM.

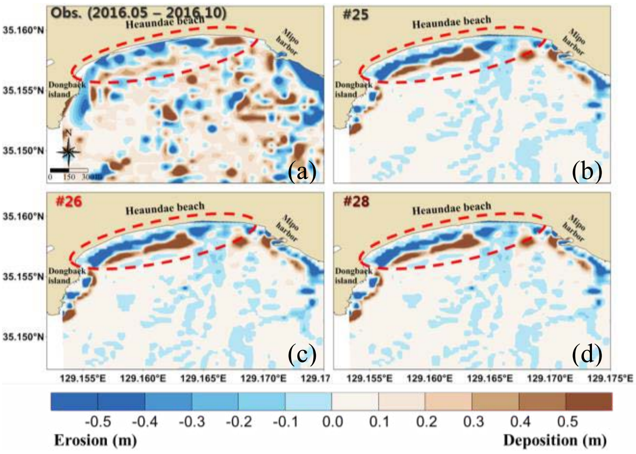


Figure 4. Morphological changes based on (a) field observation and (b)–(d) advisory numbers.

In the numerical experiments on artificial sand dune barrier breaching, it was assumed that the scale and physical properties of the beach material were those of the past conditions of Typhoon Sanba in 2012. The external conditions were assigned according to the storm wave.

According to the simulated hindcasting results for the artificial dune, there were no responding impacts when H_s was below 1.72 m. However, the generation during the typhoon of continuous waves having heights exceeding H_s = 1.78 m induced dune collapse (Figure 5). These wave behaviors began even 4.3 h prior to landfall (or passage) of the typhoon in the study area. Later, waves having considerably larger H_s values of 1.96 m were generated, with the dunes being breached. The total collapse process occurred over a period of 2.8 h. Comparison of the maximum water surface elevations indicates that the summation of the tidal elevation and peak H_s did not meet the crest elevation of 5–7 m; however, initial collapse occurred at the toe of the artificial dune and then spread to the main body.

These results are noteworthy for future design and construction of artificial sand dunes. For example, this study indicates the optimal location for detachment from the beach face to provide proper protection against incoming storm wave forcing. Thus, the model used in this research can be practically applied to the development of coastal protections, based on consideration of the design wave height of the target return periods. Moreover, it can be applied in a similar CZM tool designed to secure a moderate corridor width along the E-R shore (Harley *et al*., 2016), with the aim of protecting against forthcoming winter seasonal wave attacks.

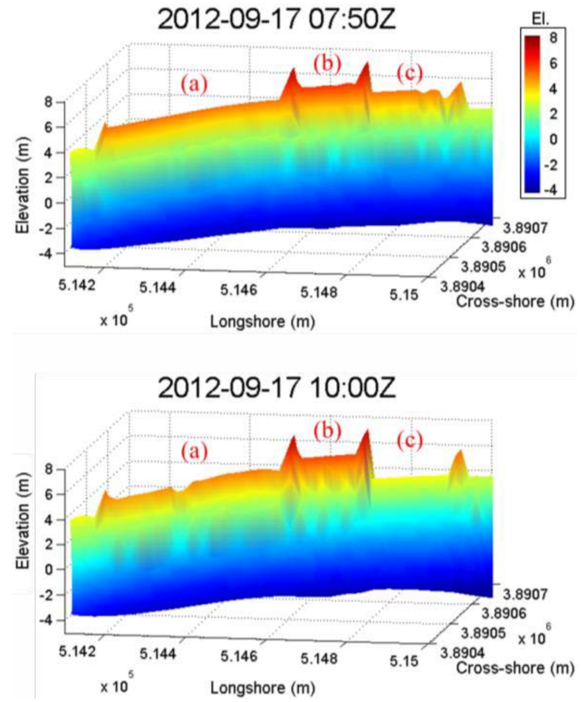


Figure 5. Artificial sand dune collapse induced by 2012 storm. Sectors (a)–(c) are shown in Figure 1.

DISCUSSION

It was found that the most significant factor influencing beach morphological change during the passage of Typhoon Chaba in 2016 was the wave heights exceeding 2 m, which is the threshold value above which the exposed sand on Haeundae Beach is affected. Analysis of the simulated patterns with respect to the entire change period shows that the initial process in the surf zone may have a stronger influence than the final response, as the wave pattern can be classed as type-1, as defined in the previous research paper (Suh *et al*., 2017). Although the wave pattern type cannot be recognized in the EWS process, rapid determination of the pattern can indicate the initial erosion impact (or later erosion due to overwash) with good accuracy. As regards the simulations of artificial sand dune collapse, the time-variant wave pattern was classed as type-1. Thus, it can be assumed that initial erosion of the toe is the main cause of the overall dune failure. Thus, understanding of wave type is as important as detailed information on the typhoon characteristics of central pressure, maximum wind speed, and radius for simulation of beach morphological changes and dune failure.

In EWS application, either promptness or accuracy can be selected as the target during storm surge events (Suh *et al*., 2015). To secure promptness under the given computational facilities, a regular XBeach grid of 30-m spacing as shown in Figure 1 (c) was coupled with a relatively coarse unstructured grid covering the Northwest Pacific Ocean, *i.e.*, the NWP-57k grid. Overall

EWS computations were performed under a parallel system, *i.e.*, a 09-system with 84 cores, and a time of 109 min was required for a beach morphological simulation including 6 d of tidal ramp-up spindle and a 3.75-d period for typhoon storm passage.

To compare the accuracy depending on the advisory information, another simulation was performed by taking the last advisory (#28) with a finer XBeach domain, having a minimum distance of 5 m and comprising an orthogonal grid; this is the same grid as applied in the sand-dune breaching simulation. This computation required 260 min, *i.e.*, an increase of more than 151 min over the coarse grid calculation; however, quantitatively improved results were not obtained (not shown in detail here). Thus, a relatively coarse grid can be satisfactorily applied in an EWS with effectiveness and efficiency.

In terms of CZM, soft or hard treatments are implemented to mitigate coastal disasters. Along the east coast of Korea, coastal dikes or submerged breakwaters have been constructed as hard treatments to protect small fishing harbors from erosion, while soft treatments such as sand nourishment or bypasses have been applied on beaches. At some beaches, such as Haeundae Beach, artificial dune creation, beach reshaping, and beach scraping have occasionally been performed using heavy machinery such as bulldozers, as for E-R coastal reshaping (Harley and Ciavola, 2013). One of the serious problems in CZM involving beach rehabilitation is that such features are usually constructed within a short time using heavy mechanical assistance, without pre-estimation of the appropriate dimensions. Thus, availability of a model for effective design of coastal protections, such as that provided in this study, is essential.

Harley *et al*. (2016) have reported that, despite some limitations, EWS has overall benefits for a vulnerable coastline. Through a series of “what-if scenarios” with regards to emergency construction of artificial dunes, they illustrated that, if accurate forecasts had been available at the time, the rapidly constructed artificial dunes could potentially have withstood the elevated waves and water levels, significantly reducing the storm damage. Thus, the EWS using Perl script proposed in the previous study (Suh *et al*., 2017) could be applied satisfactorily to achieve rapid preparedness with preservation measures on the target beach a few days prior to storm arrival.

Erosion may be one of the problems induced by the passage of a storm. Wehof *et al*. (2014) have suggested a storm erosion index that incorporates both the storm tide and storm waves, as well as the storm duration. They performed a sensitivity analysis on the results and found that the wave steepness threshold used to separate erosion and accretion was particularly important. Hence, as reported above, early determination of wave type is very important for beach erosion simulation for EWS. In addition, this kind of quantitative approach using indexes will be helpful in assigning priority when a coastal mitigation program is required.

Finally, as the measured spatial depth data were employed in the verification conducted herein, the shortcomings of the previous study (Suh *et al*., 2017) were overcome in the present study.

CONCLUSION

In this study, numerical verification of the EWS based on loose coupling of the ADCIRC+SWAN model with XBeach reported previously by Suh *et al*. (2017) was performed, and dune breaching and collapsing behavior were examined through hindcasting simulations. It was found that the developed model can be used in practical design of coastal protections, and the EWS can be employed a few days prior to a storm to achieve rapid preparedness.

ACKNOWLEDGMENTS

This research was supported by the projects entitled “Development of Coastal Erosion Control Technology” funded by the Ministry of Oceans and Fisheries, Korea.

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