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Simulation of Wave Overtopping and Inundation over a Dike Caused by Typhoon Chaba at Marine City, Busan, Korea

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ABSTRACT

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This study follows up previous research on simulating the wave-induced overtopping of coastal dikes by incorporating the empirical formulas of EurOtop version 2007 into the storm surge model ADCIRC + SWAN. Hindcasting simulations were performed for the wave overtopping and inundation induced by Typhoon Chaba along the dike of Marine City, South Korea, in 2016. The simulation results showed that the wave overtopping and inundation lasted for at least three hours and were spread over the dike. Normal storm surge inundation was not seen because the dike crest height of 4.40 m was higher than the peak water surface elevation (WSE) of 1.13 m and significant wave height of 3.09 m. Near the dike, the wave overtopped maximum inundation height was ~0.7 m and decreased along the overland road to the upper zone, which agrees with the field survey results. This tendency was almost the same as that reported previously regardless of the dike dimensions and incoming wave heights. The reduction factor in EurOtop is an important influence in generating the inundation. Sensitivity tests indicated that a value of 0.63 is appropriate for combining a rising WSE with storm waves and filling gap effects on two-layer tetrapod slopes. This kind of approach to inundation vulnerability is more applicable than the prevailing storm surge inundation for natural or low-lying coastal areas because more than 50% of the South Korean coast is artificial and should help in developing early warning systems and/or vulnerability analyses of mitigation projects at other artificial coasts.

ADDITIONAL INDEX WORDS: *Storm surge, wave overtopping, artificial coast, coastal hazard, EurOtop.*

INTRODUCTION

In Korea, 54% of the coastline has already been equipped with various rigid treatment methods, so a large number of embankments capable of responding to high waves with a minimum return period of 50 years have been constructed. Thus, during typhoons, there are almost no occurrences of normal storm surge flooding in low-lying coastal areas. However, an overflowing flood, which occurs when the embankment is overtopped beyond the high tide, frequently arises when a typhoon passes by or lands. The problem is that the frequency of high waves during storm season near or above the height of the design wave has been increasing for properly constructed dikes in recent years. This has causes enormous damage to the social capital built inside coastal embankments. When Typhoon Chaba passed through the Korean Strait in 2016, the newly constructed Marine City at Busan suffered severe damage due to wave overtopping and flooding.

A similar case of wave overtopping and flooding beyond the levees occurred for a high-rise apartment complex near Marine City in Suyoung Bay when Typhoon Maemi passed through in

2003. Marine City was constructed after that; although it was designed according to the concept of a wave return period, the historical flooding when Typhoon Chaba passed through became a turning point to recognizing the importance of great waves causing overtopping and flooding. In general, the crest height of the bank should be set by considering the highest water level outside plus the safety margin during the design stage of coastal structures. The coastal road embankments of Marine City were designed and constructed according to the same standards. However, inundation damage was occurred due to insufficient consideration of wave overtopping.

In a previous study (Lee and Suh, 2016), the first version of EurOtop (Pullen *et al.*, 2007) was actively combined with the ADCIRC+SWAN model to overcome the limitations of the storm wave and tidal current coupling model, which cannot efficiently simulate wave overflow. The combined module was used to successfully simulate wave overtopping and flooding in Sooyoung Bay, Busan, during Typhoon Maemi in 2003 and showed good qualitative results compared with flooding marks. However, verification of the newly proposed method was difficult. Then, Marine City was inundated in 2016; this event can provide important clues to reviewing the importance of wave heights and direction. Moreover, it presented a good opportunity to validate the model with regard to wave overtopping coupling and simulations. Generally, the crest level height and scale of a dike

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for a waterfront like Marine City dike is set corresponding to the heights of waves with return periods of 50 or 100 years in frequency design. However, there has not been sufficient study on how the amount of overtopping influences the interior of the bank. In addition, the flooding and submersion risk caused by the typhoon has not been further investigated, despite being a potential reason for the inundation of Marine City during the typhoon.

Recent operational models for storm surge forecasting incorporate waves, tides, and meteorological variations to simulate surges from the ocean to estuaries and rivers with the aid of flexible grid structures. However, these models are still limited at simulating vertical docks or steep sloped dikes, which are common for coastal levees and dikes used to protect against storm inundation, because of mathematical singularities or numerical instabilities near the steep bottom gradient. In addition, wave run-up and overtopping of the crest of a dike cannot easily be simulated with a model, even with state-of-the-art circulation models, because of the difficulty with treating diverse canopy materials at the abrupt gradient variations along the dikes. To overcome such unresolved problems with wave mechanics over dikes, an efficient approach that uses the EurOtop module has been proposed (Suh and Lee, 2015; Lee and Suh, 2016). The main concept was to incorporate the incoming time-variant storm wave direction and heights, which are computed in SWAN, in front of a dike to calculate the wave overtopping rates. All numerical computations were done according to an active decision tree technique to choose the proper type of overtop formula for the corresponding external wave conditions.

Anyhow, the following remains to be resolved in the simulation of a serial physical process of wave overtopping and inundation: (1) if the wave run-up and overtopping occur because of high waves during a storm invasion; (2) if they occur, what would be the amount under different conditions; (3) if the amount of overtopping for a unit time span is sufficient for inundation or will just cause wetting; (4) if the overtopping rate is enough for inundation to spread landward, then how does the overland elevation affect this; (5) can the surface canopy conditions be provided to properly represent buildings and pavements; and (6) what is the optimal grid spacing to resolve wave overtopping and overland flow simulations.

METHODS

In order to inform and trigger the EurOtop computation of overtopping rates, the temporal variation of the water surface elevation (WSE) and incoming wave heights and direction at 20 m in front of the dike were reproduced for the simulation of Typhoon Chaba with the ADCIRC+SWAN coupled model. The numerical grids were based on NWP-G116k, like those used in Suh *et al.* (2015). This covers the Northwestern Pacific (NWP) but was modified to fit the Marine City simulation with the shortest grid spacing of 5 m for LiDAR data and design charts, as shown in Figure 1. Owing to the small grid spacing, the time increment for numerical integration was also adjusted to 0.1 s to satisfy stability criteria. The bottom roughness coefficients were set to Manning's n for the coastal area representing bed materials and depth variation. However, 0.023 was applied in front of the study area of Marine City. The overland paved road was set to 0.016.

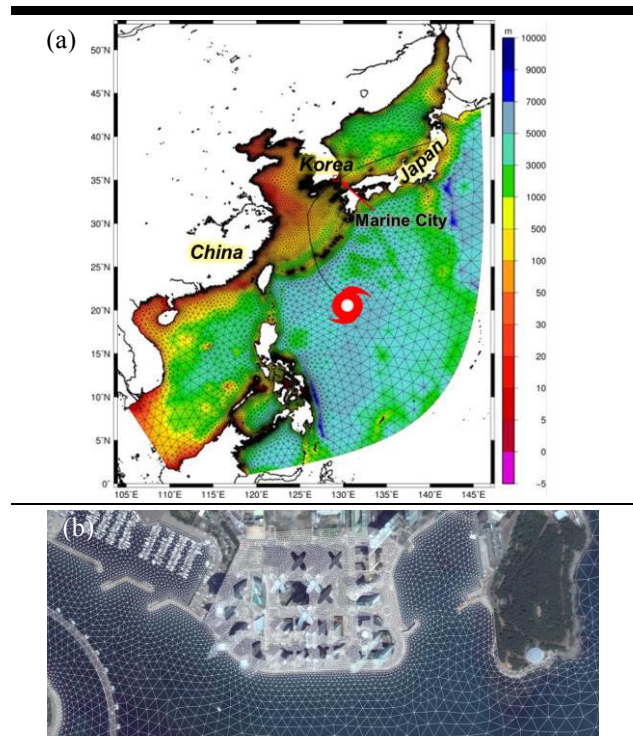


Figure 1. (a) Map showing the study area including the NWP typhoon storm surge modeling area; (b) refined grid structure with a minimum spacing of 5 m for the overland area of Marine City, Busan, Korea.

Scattered buildings on the overland area were regarded as imaginary islands with fixed boundaries, and dikes along the coastal road were treated as internal barriers in ADCIRC. The dimensions of the dike and field topological data were gathered through design reports and charts in order to represent the actual situation with good accuracy. Figure 2(a) presents a schematic for wave overtopping of a dike. The dike is a composite type with a slope of 0.67. It is covered with tetrapods, has a berm width of 4 m in the offshore direction, and has a parapet crest level of 4.40 m, as shown in Figure 2(b). A positive freeboard condition with high waves was applied to EurOtop to compute the overtopping, and a negative freeboard situation with broad weir treatment and free overflow over the dike was also applied. The overtopping rates were estimated at every time step according to the automatic decision tree concept, as shown in Figure 2(c). To calculate overtopping over the tetrapods, the reduction factor γ_f was modified after several sensitivity tests to consider the roughness coefficient.

In the previous hindcasting simulation of Typhoon Maemi in 2003 (Lee and Suh, 2016), the overtopping rates were relatively small, and the computing resources were not enough to calculate every time step of the wave overtopping rates. Thus, a numerical treatment of making a sufficient amount of overland flows was considered by adding every period, approximately 12 s, to the wave overtopping volume for 10 min. This coincided with the time span of the wave information for coupling ADCIRC+SWAN. However, in the simulation of Typhoon Chaba, the computing

resources were enhanced from 64 CPU cores to 120 CPU cores. In addition, the calculated rates were much bigger than the previous computation, so the rates did not need to be summed. Thus, every time step (0.1 s) of the ADCIRC+SWAN output was used by EurOtop to compute the flow rate, but the total simulation time was not increased owing to hardware improvements.

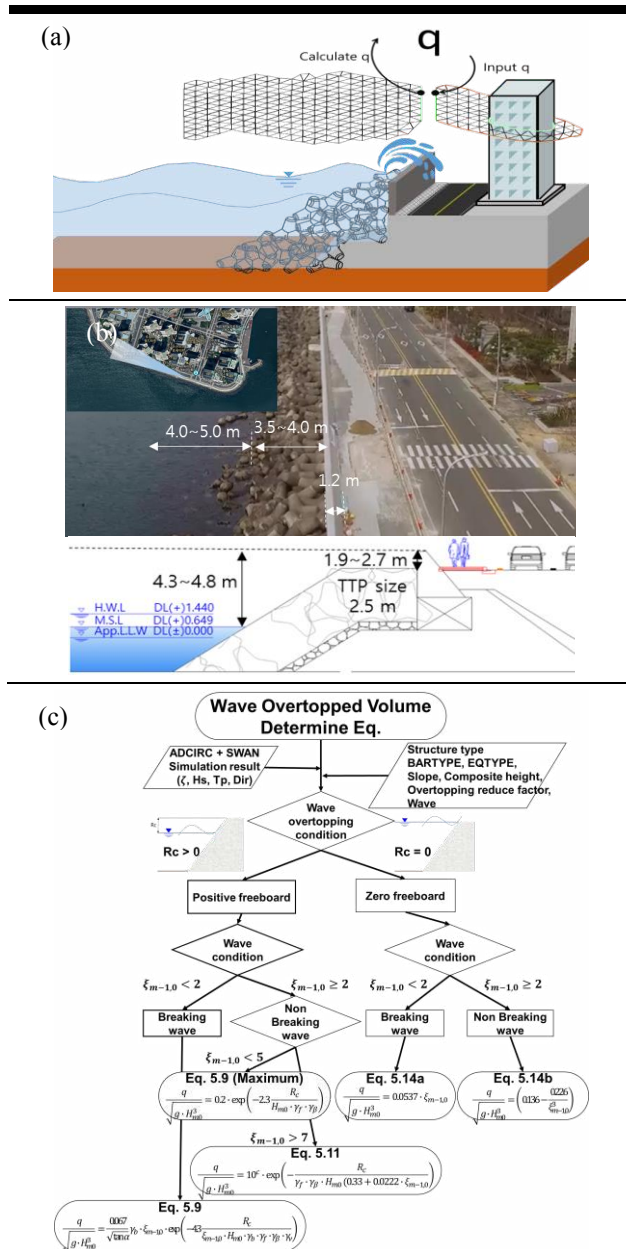


Figure 2. (a) Schematic diagram of wave overtopping induced by temporal storm wave forcing conditions; (b) Photo showing Marine City coastal road with typical cross-sectional dimensions; (c) Associated decision tree considering the external temporal variation of wave conditions for calculating the overtopping volume with EurOtop.

RESULTS

Typhoon advisories are renewed based on updated meteorological information. Consequently, later advisories normally gives better results with regard to storm surge simulations. However, most of a typhoon's information is known when it crosses over the Ryuku Islands (Suh *et al.*, 2015). Thus, an earlier advisory can be applied for real-time forecasting to realize an early warning system (EWS). Typhoon Chaba caused not only wave overtopping and inundation but also beach erosion in the Busan area. In another study on beach erosion analysis, advisories #25, #26, and #28 were introduced for real-time morphological forecasting.

The simulation results showed that inundation due to wave run-up and overtopping occurred at 2016-10-05 00:20Z, and lasted for 5 h. However, significant overtopping occurred for 3 h. During that time, the highest WSE was 1.13 m, while the peak significant wave height (H_s) was 3.09 m. Even though H_s does not represent the maximum height, the linear addition of two maximum heights could not cause a traditional storm surge because the lowest crest level of the dike was 4.40 m, as shown in Figure 3. Wave-induced overtopping continued for several hours under the positive freeboard. According to the simulation results, the incident wave direction was SSE for the whole length of the dike, as shown in Figure 4. However, the direction actually varied continuously counterclockwise as Typhoon Chaba passed through.

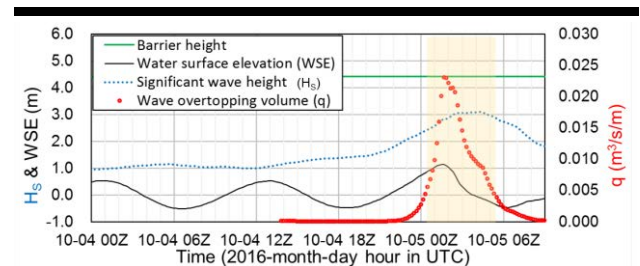


Figure 3. Computed hydrographs of the overtopped volume (red circles), H_s (blue dots), and WSE (black line). Significant wave overtopping occurred during the shaded time interval of about 5 h.



Figure 4. Snapshots of wave trains show the incoming direction, run-up, and resulting overtopping of the dike. Video was recorded at 3-s intervals to determine wave periods.

The simulated wave heights and direction were found to be a major factor in wave overtopping. In fact, the peak wave height of approximately 3.09 m occurred at 2016-10-05 04:10Z. However, the peak surge elevation, which is the sum of the water

level and surge-induced wave height, did not yield the traditional surge inundation. Simulated overtopping rates were estimated from 2016-10-05 00:20Z at least 4 h earlier to the peak wave heights. Thus, any H_s with a threshold momentum value from run-up and overtopping can cause similar inundation over a low-crested dike. Variations in the incoming wave direction should be precisely investigated because most inundation occurs when train waves are activated along the dike. This tendency is almost coincident with the video taken during the inundation, as shown in Figure 4.

A numerical simulation of the time immediately after Typhoon Chaba passed through was performed based on advisory #28, which was almost the last advisory when the typhoon passed through in 2016. The computed results did not greatly deviate with other results based on the earlier advisories #25 and #26. The best track of Typhoon Chaba was released in 2017 with newer information on the track location and associated typhoon characteristics. Although the effects of wind characteristics according to advisory information were compared, the differences between the best track and advisories were not great. The simulated total overtopping volume for advisory #28 with $\gamma_f = 0.6$ was $46.9 \times 10^3 \text{ m}^3$. The volume calculated by using the best track with the same reduction factor was an order of magnitude smaller at $6.4 \times 10^3 \text{ m}^3$. However, applying a slight smoother value of 0.63 resulted in almost the same volume at $45.1 \times 10^3 \text{ m}^3$. Thus, this sensitivity test showed that the wave overtopping volume is highly sensitive to γ_f . These calculated amounts can be compared with the assumed real inundation volume based on the field survey, as shown in Figure 5. The real inundation volume was estimated to be $45.9 \times 10^3 \text{ m}^3$ for a period of 5 h.

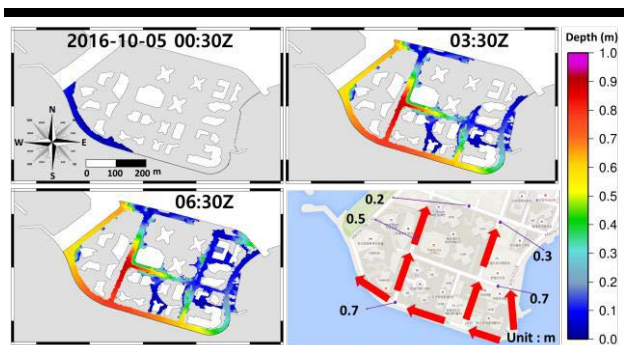


Figure 5. Simulated wave overtopping and inundation spreading pattern with the maximum depth (m) and the field survey results (lower right image).

Field surveys were conducted just after the inundation hazards to determine the maximum inundation depth, area, and spreading pattern for paved overland flows. According to the survey, the initial overtopping occurred at the middle of the dike to yield an inundation depth of 0.7 m. From that point, flooding flowed landward of Marine City with a depth of 0.3 m at the farthest inland inundated part. The simulation results of the inundation as shown in Figure 5 almost coincided with the survey results.

In previous research (Lee and Suh, 2016), hindcasting was qualitatively compared with inundation marks from data more

than 12 years old. In this study, however, the computed results were compared with not only precise field flooding marks but also several videos captured from different viewpoints during the inundation event. The overall overtopping pattern and inundation area were confirmed to be effectively captured with the proposed scheme. Thus, the wave overtopping module can be satisfactorily applied to other coastal levee structures.

DISCUSSION

When the typhoon approached Marine City, the WSE increased and marked a peak value of 1.13 m. It was 0.52 m at the previous high tide 12 h ago. Because the crest level of the dike was 4.40 m, which is much higher than the peak WSE, there were no possibility of storm surge inundation even though WSE anomalies increased because of the typhoon. At the time corresponding to the peak WSE, H_s was 2.80 m, which was not the peak value. The peak value of 3.09 m occurred approximately 2.8 h later at 2016-10-05 04:10Z. Wave overtopping occurred as H_s increased to over 2.4 m regardless of the WSE. The magnitude was not significant, but it grew when combined with the WSE to cause flooding, which started from 2016-10-05 00:20Z. According to these simulation results, wave overtopping and inundation at Marine City arose because of the combined effects of a rising tide and incoming storm waves. Thus, for a storm surge EWS, a combined circulation and wave model such as ADCIRC+SWAN can be applied to simulate wave overtopping with the suggested coupling of the EurOtop module.

A key issue in wave overtopping is how to properly define the surface reduction effect due to armoring and incoming wave conditions. Reduction factors are always derived as the difference between a structure with and without an influence factor, such as the roughness, berm, vertical wall, and obliqueness (Van Doorslaer *et al.*, 2016). Aydoğan *et al.* (2016) presented γ_f depending on the wave steepness. The factor is very sensitive to not only the ambient conditions but also the structural dimensions. Van Doorslaer *et al.* (2016) suggested a new version of EurOtop to introduce a newly adjusted reduction factor and replace the first version from 2007.

Most tests on wave overtopping are based on the still water level in a laboratory flume, *i.e.*, static conditions. Thus, they do not properly account for real situations from the viewpoint of rising sea levels and the associated armored surface void gap closing effect. Hence, the overtopped volume can be increased by the smoothing effect. Flume tests are done under limited conditions that do not represent dynamic variations in the freeboard level and crest freeboard of the structure (R_c). In addition, the data used in analyzing γ_f are derived at the laboratory scale, not from field experiments. Thus, selecting an appropriate value of γ_f for application to real forecasting of the overtopping volume should be intensively studied. Moreover, in-depth studies on dynamic environmental conditions should be performed.

In real situations, the sea level continuously changes. In the case of Marine City, overtopping occurred for 5 h, and this constituted about half the semi-diurnal constituent periods. Overtopping increases during rising (spring) tidal periods. Thus, this kind of dynamic condition and its relation to the reduction factor should be further studied.

According to Van Doorslaer *et al.* (2016), the same γ_f in the newest version of EurOtop (Van der Meer *et al.*, 2016) gives a volume about 20% more than that calculated by the 2007 EurOtop (Pullen *et al.*, 2007). A possible issue with an increasing γ_f is the filling effect, as pointed out by Christensen *et al.* (2014). The mismatch is one of the reasons why the suggested γ_f of 0.4 cannot give a reasonable overtopping volume. Through a series of sensitivity tests, satisfactory results were obtained when applying γ_f of almost 0.6 for a two-layer tetrapod slope.

The overall computation was performed on a light parallel system with 120 cores. The numerical domain had a minimum grid resolution of 5 m for Marine City. The total simulation took 165 min to hindcast 3.75 days of tidal circulation, storm surge, and wave overtopping. Although the minimum time step of 0.1 s provided satisfactory numerical stability, it hindered numerical efficiency for real-time forecasting of the overland spread of wave overtopping. This method may be applied to real situations with several thousands of cores. If the purpose of forecasting is only to capture and predict possible overtopping and inundation, a real-time EWS can be promptly realized without having to refine the discretization for overland flows.

CONCLUSIONS

This paper presents a wave overtopping simulation for the inundation event of Marine City, Busan, Korea, caused by Typhoon Chaba. The overtopping rates due to temporal variation of the typhoon storm waves considering the incident direction were satisfactorily simulated by applying the empirical formulas of the EurOtop module to the ADCIRC+SWAN coupled model. The results were reasonable for the inundation tendency and spatial overland inundating propagation along the paved roads. In addition, the deepest inundation part and initial overtopped area were efficiently reproduced based on a comparison with field survey data. Thus, this proposed coupled modeling scheme, which treats diverse sloped or vertical dikes with surface armoring canopy conditions depending on the incident wave conditions, can calculate the wave run-up and overtopping volume without mathematical singularities around abrupt depth changes at the coast.

One of the most sensitive parameters, γ_f , which represents the surface armoring condition in EurOtop, should be precisely investigated and applied. Actually, γ_f is derived at the laboratory scale under limited conditions, such as still water with a static freeboard. Thus, applying a smoother coefficient with a value at least 50% higher than the suggested value of 0.4 can guarantee reliable simulation of real situations although the most dominant influence factors for run-up and overtopping are the slope of the dike and crest height. The approach in this study can be

successfully applied to other existing vulnerable coastal dikes in order to determine coastal vulnerability. Future studies should incorporate the sea level rise to reflect the decrease in the freeboard when the storm waves remain at the same strength. In addition, some moderate probabilistic vulnerable analyses should also be performed in dike overtopping and inundation simulation by generated synthetic typhoons introducing historical typhoon characteristics.

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