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UNDERSTANDING COASTAL EROSION PROCESSES AT THE KOREAN EAST COAST

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Abstract

Coastal erosion is a serious issue for many beaches along the East coast of South Korea. In order to better understand and mitigate the coastal erosion a framework of data analysis techniques and numerical models has been set up. This framework is used to study the relevance of different coastal erosion processes acting on different temporal scales for the beaches of Anmok and Namhangjin. The results indicate that especially the construction of a port led to severe erosion at the down-drift beach. Nowadays this erosion is to a large extent mitigated by the construction of coastal protection measures. Nevertheless, changes of in the beach states in the foreshore of the Korean East coast as well as storm erosion during extreme events, can still lead to (temporal) coastline retreat in the order of 20-30 m. The interactions between the erosion processes and the design of effective protection measures require further investigation.

Key words: coastal erosion, human interventions, sediment transport, numerical modelling, Anmok Beach, South Korea

1. Introduction

Various beaches at the South Korean East coast experience erosion (Kim et al., 2013), which can result in considerable damage to coastal infrastructure as observed at Namae beach in 2007 (Kim et al., 2011). The expansion of cities along the coast in the last decade(s) has further increased the consequences of the erosion (Kim and Lee, 2011). Various authors suggest that man-made structures that have been developed over the years adversely affect the stability of the adjacent beaches (e.g. Kim et al., 2007, Kim et al., 2013; Oh and Bang, 2013; Kim et al, 2014). Kim and Lee (2007) question the effectiveness of hard structures along the Korean coast, as they protect only the considered section of the beach at the cost of erosion on the adjacent beaches.

To better understand and mitigate the coastal erosion along the Korean East coast, a framework of data analysis techniques and numerical models has been developed. The development of this framework is part of a 5-year research program named "CoMIDAS" launched by the Korean government in 2013. The coastal system of the Korean East coast poses many challenges to numerical (or physical) modelling as a result of complex bathymetries with rip-bar configurations (Cho et al., 2014), spatially varying sediment characteristics and rocks (e.g. Oh and Bang, 2013), changes in sediment supply by rivers (Kim and Lee, 2007), the presence of numerous coastal interventions and environmental conditions which are influenced by wind and swell waves as well as occasional typhoon events (Kim et al, 2007). Individual numerical modelling techniques often focus on one or a few physical processes and could individually not easily provide answers for the Korean context. In this paper we present a framework of different data analysis techniques and numerical models covering the relevant spatial (km to m) and temporal scales (days to decades) for the Korean East coast. The framework is applied to the beaches of Anmok and Namhangjin (Figure 1) in order to investigate the importance of (1) large-scale coastline reorientation, (2) port construction, (3) beach state dynamics and (4) swash processes under storm conditions on the coastal erosion experienced at these beaches.

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2. Study area

The Korean East coast is characterized by a rocky coastline interrupted by numerous sandy, often pocket-type beaches. Many coastal developments are present along the coast, often consisting of breakwaters associated with local port developments. The beaches of Anmok and Namhangjin (see Figure 1), representing typical developments along the Korean East coast, are selected as a pilot location for field surveys and numerical modelling. These beaches are located near the city of Gangneung and separated by a local fishing port (constructed in several stages between 1992 and 2006). The beaches experience localized erosion, which resulted in damage of the coastal infrastructure backing the beach. Over time a sequence of mitigation measures (e.g. submerged breakwaters, groynes, revetments and beach nourishments) has been implemented in order to mitigate the erosion (see Figure 1 and Table 1). Often these measures decreased erosion locally, but shifted the problem to adjacent beach sections.

Figure 1. Location of Anmok and Namhangjin beaches at the Korean East coast with an overview of the human interventions that have taken place over time.

Table 1. Overview of coastal interventions at the beaches of Anmok and Namhangjin, including their (estimated) time of implementation and main dimensions. The numbers in the first column correspond to the numbers in Figure 1.

#	Year (finished)	Intervention	Dimensions
1	End 2002	Breakwater Gangneung port (North)	Total length 734m
2	Mid 2005	Groyne at Namdae river outlet	Length ~200m
3	End 2006	Breakwater Gangneung port (South)	Total length 335m
4	Mid 2012	Nourishment Namhangjin	Volume 35,700m^3
5	Mid 2012	Terminal groyne runway	Length ~125m
6	End 2012	SBW 5	Crest length ~100m, height -2.7m MSL
7	End 2013	SBW 1-4	Crest lengths ~190..150..150..150m Crest heights ~-4.4..-3.7..-4.8..-3.0m MSL
8	End 2013	Nourishment Namhangjin	Volume 179,200m^3
9	Mid 2014	SBW Anmok	Crest length ~250m, height -0.5m MSL
10	Mid 2014	Nourishment Anmok	Volume 11,000m^3

The Korean East Coast is a micro-tidal, wave-dominated environment with the wave climate dominated by winter swells coming from the north-northeast. The observed current magnitudes are generally low (in the order of 0.1 – 0.2 m/s). The average significant wave height in deep water at the Korean East coast is about 1 m with a wave period of 6 s (Kim et al., 2011b). Occasionally, the coast is hit by typhoons. A significant wave height of about 7 m and wave period of 12 s was recorded in December 2010 at Gangneung (Oh and Jeong, 2013). A maximum significant wave height of 9.7 m was even recorded in 2006 at Sokcho (Kim et al., 2007; Oh and Jeong, 2013).

Anmok and Namhangjin beach are characterized as reflective beaches with 1:10 to 1:20 slopes at the waterline which gradually become gentler in the active surf zone (MSL-4m to MSL) to about 1:50. The beach shape and position can, however, change considerably on relatively small time scales. Changes in dry beach volume of Anmok beach (from MSL to MSL+7m) were, for example, in the order of 10 m3/m/month for September to October 2010 (Lee et al., 2011). Bathymetric measurements in the period from 2007 to 2009 at Anmok and Namhangjin beach (Oh and Bang, 2013) showed erosion at the waterline and in deeper water (MSL -5m to MSL-10m), while accretion was observed in intermediate water depth (MSL -2m to MSL -5m), which indicates that cross-shore variability of the beach is present at a seasonal to multi-year timescale. The median grain size (D_{50}) of the coastal sediment varies between 1000 μm at the shoreline to 200 μm in deeper water at about MSL -10m (Oh and Bang, 2013). Some seasonal variation in sediment composition is observed South of Gangneung port with coarser sediment in winter.

Figure 2. Presence of crescentic bars at Anmok beach with an indication of the locations where rip currents occur. The yellow rectangle represents the submerged breakwater that was constructed in 2014 at Anmok beach.

It is believed that the construction of Gangneung fishing port is one of the major causes of the coastal erosion experienced at Namhangjin beach. Another potential cause is large-scale coastline reorientation as a result of longshore transport gradients, possibly affected by decreased sediment supply from rivers. Furthermore, observations highlighted the presence of rhythmic crescentic bar patterns resulting in rip cells that may have caused local beach erosion (Figure 2). Also swash induced sediment transport can be relatively important due to the relative steep beach profiles, the coarse sediment and the regular occurrence of swell waves. The objective of this study is to investigate the importance of these processes for the coastal erosion experienced at Anmok and Namhangjin beach.

3. Methodology

The processes which affect the natural shoreline variability (and erosion) of the beaches of Anmok and Namhangjin act on different time-scales: large-scale coastline reorientation and impacts of port constructions typically take place on large timescales (e.g. years to decades), whereas bar states can affect the coastline position on intermediate time-scales (e.g. months to years) and storm run-up and wave impact at even shorter time-scales (e.g. hours to days). A framework of data analysis techniques and different numerical models has been set up to effectively study the relevance of the identified erosion processes on these different scales (see Table 2).

Table 2. Applied relevant coastal processes for Anmok beach, associated temporal scales and model investigations

Physical component	Temporal scale	Model
Large-scale coastline reorientation	Years to decades	Data Analysis & UNIBEST-CL+
Port construction	Years to decades	
Beach position fluctuations due to beach state dynamics	Months to years	Data Analysis
Storm erosion	Hours to days	XBeach

Boundary conditions for the morphological models are derived from a Delft3D-wave model, which transforms offshore waves to the nearshore with the wave energy transport model SWAN (Booij et al., 1999). A three-stage nesting approach is used to obtain sufficient grid resolution in the nearshore with grid resolution increasing from 2km offshore to 166m for the intermediate grid and 20m in the nearshore. Offshore wave data from the WAM (Wave Modeling Group) wave model for the period 1979 to 2008 are classified into 241 wave classes (i.e. based on wave height, wave direction, wave steepness and wind direction) at 19 locations along the offshore boundary of the SWAN wave model.

The relevance of large-scale coastline reorientation for coastal erosion is investigated by means of data analysis of shoreline observations and numerical modeling simulations with coastline model UNIBEST-CL+ (Ruggiero et al., 2010; Deltares, 2011). UNIBEST-CL+ evaluates coastline changes as a result of gradients in sediment transport on the basis of a computation of the wave transformation, longshore currents and sediment transport with the Transpor2004 formulation (Van Rijn, 2007a and 2007b). For small coastline disturbances the UNIBEST model will provide a similar result as the diffusion equation of Pelnard-Considère (1956), but the model also accounts for non-linear influence of wave refraction on the foreshore (i.e. it can take a different orientation of the active surf zone and foreshore) which improves accuracy for more pronounced coastline perturbations. The coastline position in 2002, just after the finalization of the first port breakwater, is taken as a starting point for the model simulations. In order to assess the impacts of Gangneung port the UNIBEST-CL+ model is run both with and without the presence of the port. Wave conditions are derived at 44 locations along the Anmok and Namhangjin beach at a depth of 4 m which is determined based on an estimate of the depth-of-closure (Hallermeier, 1983). Cross-shore profiles are also derived at these locations. The active height of the beach profiles is set at 5 m. Nourishments at Anmok and Namhangjin beach are included as source and sink terms. It is noted that reduced sediment supply from rivers may also have contributed to the coastal erosion at the Korean East coast in the past (Kim and Lee, 2007). However, due to limited availability of historic data on river discharges and sediment loads, this aspect was not further investigated in this study. Nowadays, the discharge of the local Namdae River, just south of Gangneung, is small (Chikamori, 2005). Therefore, the sediment contribution of the Namdae River was not accounted for in the UNIBEST-CL+ model computations. Based on observations a calibration of the coastline orientation of 1.5° is made for a beach section at Anmok near Gangneung port.

The relevance of natural rip-bar patterns for (temporary) retreat in the shoreline position is assessed based on data analysis of available satellite imagery from Landsat 4, 5, 7 and 8 and Sentinel 2 missions (roughly bi-weekly from 1985 to 2016) complemented with 5 high quality aerial images and 8 bathymetric surveys between 2007 and 2015. Satellite images on which the bar patterns or shoreline positions could not be clearly identified, for example due to the presence of clouds, are excluded from the analysis. The extraction of the bar and shoreline patterns from satellite imagery is performed manually based on visual inspection of the images. The shoreline extraction is repeated several times to account for potential bias in the manual procedure of the shoreline extraction. A selection of detected shorelines is compared to the bar patterns found in a bathymetric survey close to the date of the satellite image (see example in Figure 3). The bias in the bar position was generally found to be of similar magnitude as the pixel resolution of the satellite image (~30m). As we are mainly interested in the intermediate scale bar dynamics, this bias is considered acceptable.

The extracted bar positions are analyzed to obtain the cross-shore position (x) and alongshore position (y) of the bars. This required a straightening of the bar pattern by means of a rotation with the coastline orientation and removal of larger scale coastline undulations by means of the subtraction of a 6^{th} order polynomial fit (Figure 4). The shoreward perturbations of the sandbar are defined as horns, while the seaward perturbations are defined as bays. The same procedure is followed to analyze the shoreline characteristics and repeated for all selected images. However, as the shoreline perturbations are generally much smaller than the bar perturbations, the accuracy of the shoreline detection is affected more by the pixel resolution. The number of shorelines that could be detected in time is therefore much smaller than the number of bar patterns. The correlation between the bar and shoreline patterns is assessed for the timestamps where both detected bar patterns and shorelines are available.

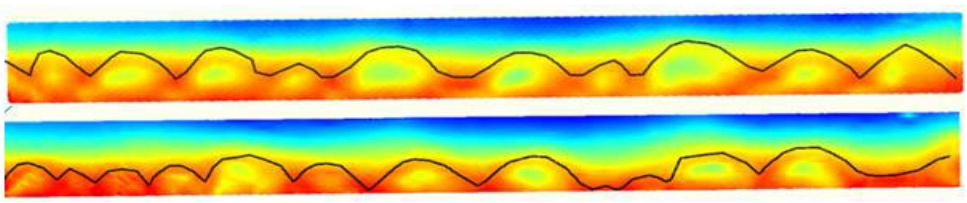

Figure 3. Example of the verification of the identified bar patterns from satellite imagery (black lines) with bathymetric surveys from September 2013 (upper panel) and June 2015 (lower panel).

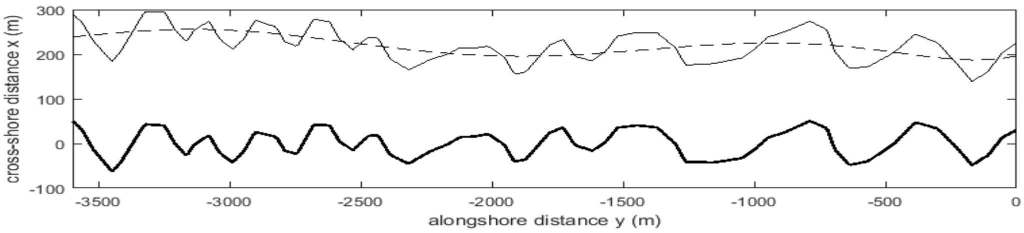

Figure 4. Example of the extracted sand bar position after correction for the coastline orientation (upper thin line), the 6th order polynomial fit (dashed line) and resulting sandbar perturbations (lower thick line) for a LANDSAT satellite image from 16/05/1985.

The relevance of storms for coastal erosion on the short time scale is evaluated with the XBeach model (Roelvink et al., 2009), which computes storm erosion as a result of water level setup, undertow currents and wave-group forcing (Herbers et al., 1994; Van Dongeren et al., 2003). A time-series of wave conditions from 1979 until 2007 at 129.00°E, 37.83°N is analyzed with the Peak-Over-Threshold (POT) method to identify storm events (see Figure 5), from which three representative extreme storm events were selected. This is a 1/150 year storm with a significant wave height (H_S) of 7.8m and Tp=12 s (October 2006 storm), a 1/2 year storm event with an Hs of 5.2m (Tp=12 s) which is representative for the other storms with a wave height above 4 m and a storm event with an Hs of 3.1m (Tp=9 s) which has an associated 1/1 year frequency. Spectral wave boundary condition time series for all four storms are imposed on the offshore boundary of the XBeach model at 22 m water depth, which were derived from the Delft3D-wave model. The Daly et al. (2012) breaker formulation is used with default parameter settings. In the case of the stationary wave mode, the Janssen and Battjes (2007) breaker formulation is used with a breaker coefficient of 0.78. A uniform grain size of 0.4 mm is used in all models. To simulate onshore transport of sediment under skewed and asymmetric waves, the XBeach parameters facSk and facAs set to 0.10 and 0.25, respectively, based on experiences with beaches with similar grain size in the USA (De Vet et al., 2015).

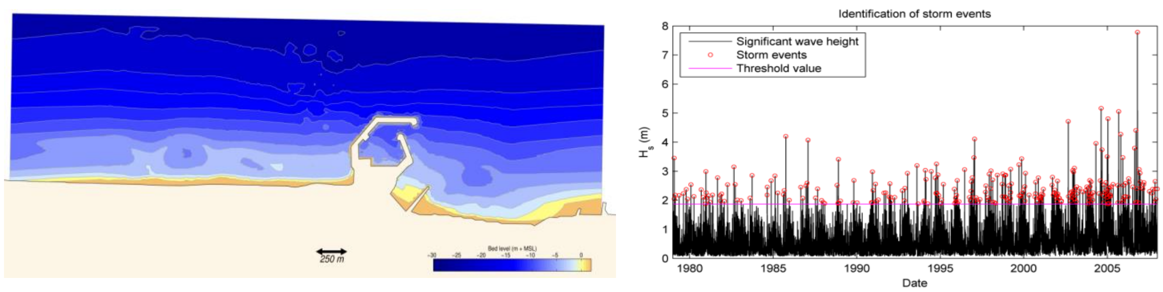

Figure 5. XBeach model bathymetry (left panel) and time-series of significant wave height at the nearshore location close to Gangneung (129.00°E, 37.83°N) used for identification of storm peaks (right panel).

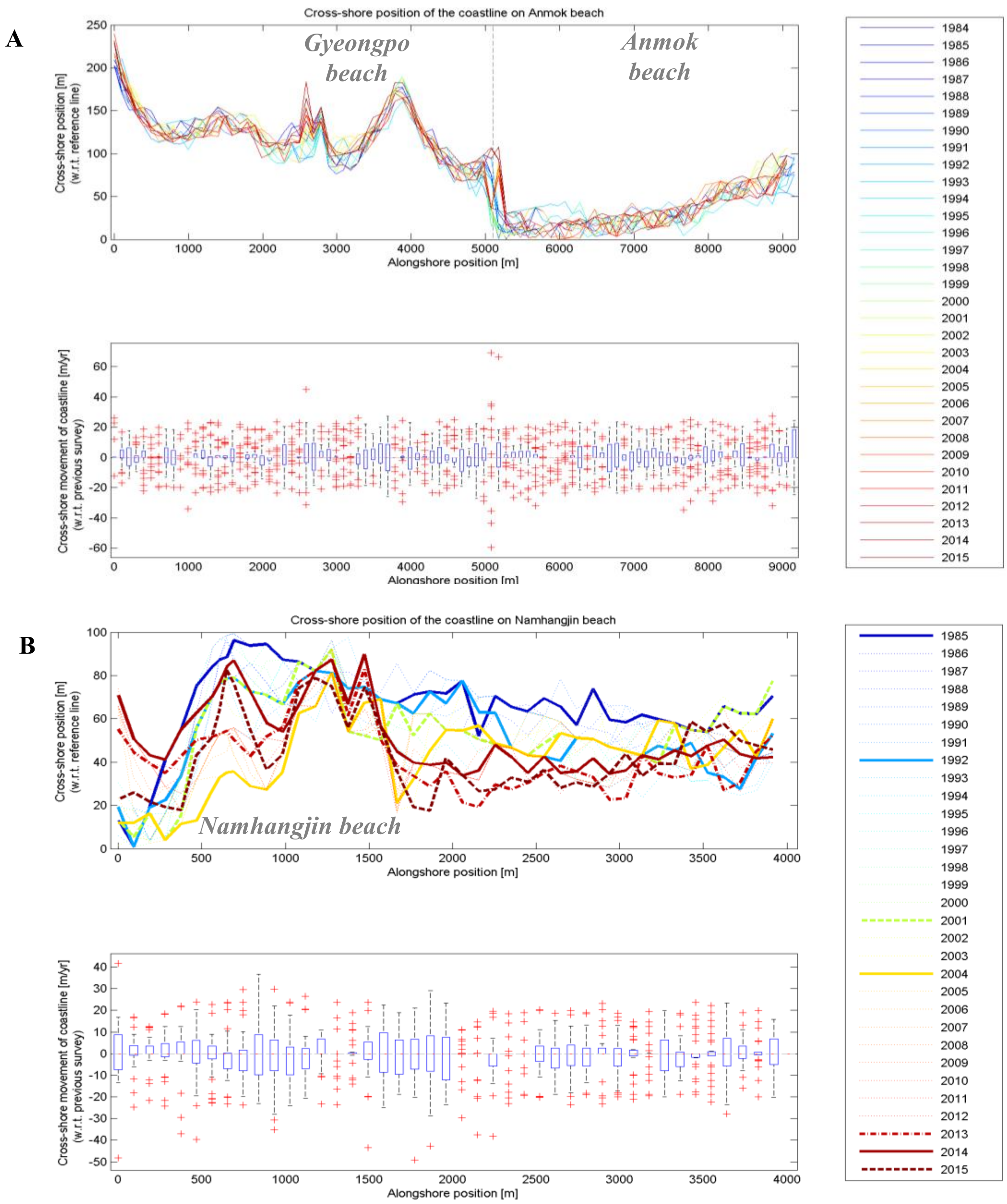

Figure 6. Overview of temporal variability of cross-shore coastline positions in time for the Anmok (A) and Namhangjin (B) coastline (positive x-direction from NW to SE). Upper plot: Shoreline positions from satellite imagery over the period from 1984 until 2015. Lower plot: Box plot of average annual variability in-between surveys (red markers), 25 percentile, mean and 75 percentile change over the considered period (lower, middle and top of blue box) and 5% and 95% confidence interval (i.e. lower and upper end of black lines).

4. Results

4.1 *Observed coastline changes*

Shoreline position measurements at Anmok beach (Figure 6A) show considerable seasonal variations in cross-shore shoreline positions, while changes in coastline position due to long-term coastline reorientation are much smaller. Yearly cross-shore variations are typically between -20 and +20 m (see lower plot of Figure 6A), but can be larger for some locations along the coast. Long-term redistribution of sediment from one side of the beach to the other, as a result of wave-driven longshore transport, is not distinguishable in the measurements since the natural variability dominates the changes. Only a small-scale impact is observed from x=8800 to 9000m in 2014 and 2015 as a result of the construction of a submerged breakwater at Anmok beach.

Large annual variations in shoreline position of about -40 to 40 m/yr are also observed at Namhangjin beach (Figure 6B). These changes are for a large extent related to large-scale coastline changes as a result of the construction of Gangneung port (between 1992 and 2006), a terminal groyne at Namdae river outlet (in 2005) and an offshore breakwater (in 2012 and 2013) and local beach nourishments (in 2012 and 2013). A large retreat in the coastline position of about 20 to 60 m is, for example, observed between 2001 and 2004 at Namhangjin beach (x=400 to 1200m) as a result of the construction of the port breakwaters. Considerable accretion (about 60 m) was then observed at the Namdae terminal groyne from 2004 to 2014 (at x=0m), which provided a sheltered region where sediment could accumulate. Sand nourishments in 2012 and 2013 resulted in additional accretion of about 30 to 50m at Namhangjin beach (from x=200 to 1200m). The southern part of the beach (x=1500 to 4000 m) retreated over time. The causes for this erosion are unknown. Furthermore, the annual variability (+/-20 m/yr) in the shoreline position is present, which may relate to seasonal variation in the shoreline position and accuracy of the data.

In summary, Anmok beach (North of Gangneung port) shows annual variability in the shoreline positions (0 to 20 m/yr), but no clear structural/long-term changes as a result of the port construction. Namhangjin beach (South of the port), on the other hand, shows a clear response to the port structure and other interventions at the beach. A more detailed analysis of the reason(s) for the different responses at both beach sections is made in the following sections.

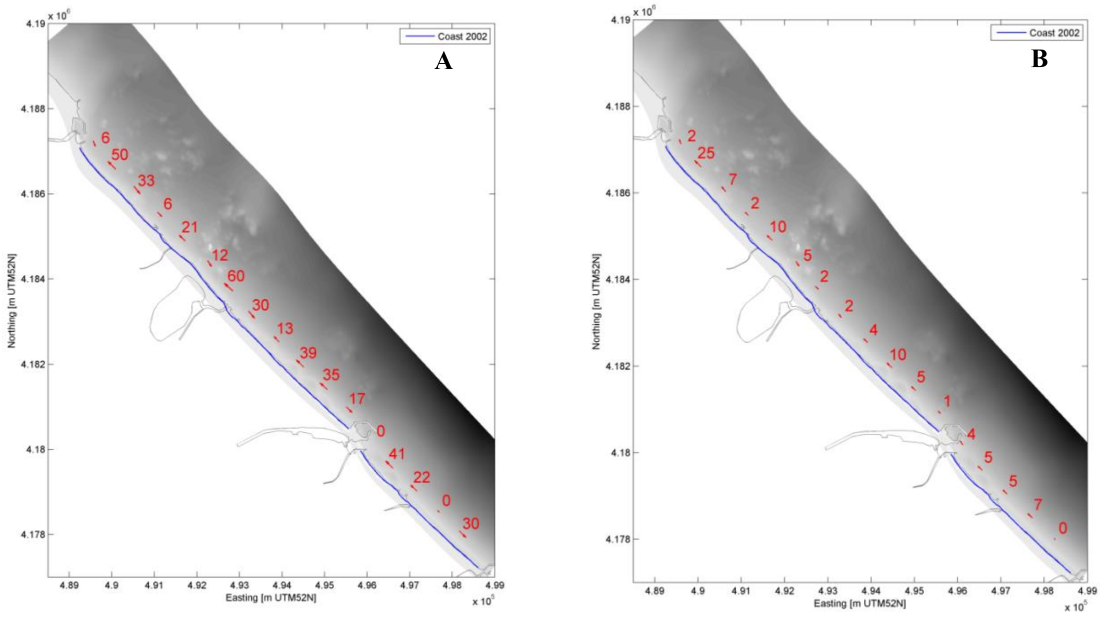

Figure 7. Autonomous net long-term alongshore transport rates at Anmok and Namhangjin beach for 2015 coastline. (A) Initial transport rates and (B) transport rates after 1 year of redistribution.

4.2 *Large-scale coastline reorientation*

The UNIBEST-CL+ coastline model confirms that large-scale coastline re-orientation is very small at the considered coastal sections, which is in agreement with the observations of the shoreline data (Figure 6). The model shows low initial transport rates in the order of 0 to 60,000 m^3/yr in both northern and southern direction (Figure 7), which reduce quickly to 0 to 25,000 m^3/yr as a result of shoreline adaptation after 1 year. Seasonal variations in the shoreline positions can, however, not be represented with the coastline model. These variations are investigated in Section 4.4.

4.3 *Impact of Gangneung port construction*

An investigation of the impact of wave sheltering of the Gangneung port was made with the UNIBEST-CL+ model. For this purpose, the model starts with the (relatively straight) 2002 shoreline and uses different wave conditions to account for the situation with and without the port construction. The wave conditions are derived from the Delft3D-wave model. The conditions at the southern side of the port can be affected considerably by the port structure for waves originating from the northern sector (see Figure 8).

The model results show that the orientation of the coast has not been influenced significantly at Anmok beach (North of the port), while a considerable impact is observed at Namhangjin beach (Figure 9). The shoreline at Namhangjin beach has locally advanced about 50 to 80 m in seaward direction and re-orientated towards the East, which was very similar to the observed coastline change.

A local curvature of the coast is present in the first 500 m on the southern side of the port, while the coastline orientation at some distance from the port is not affected. This also indicated by the computed sediment transport rates, which are directed towards the Gangneung port over a longer period of time (i.e. larger than 10,000 m^3/yr during the first year after construction of the port; see Figure 9). Transport rates in the vicinity of the Gangneung port are temporarily even of the order of 50,000 to 100,000 m^3/yr in the first months after construction of the port, which explains the required nourishment volumes for Namhangjin beach (i.e. in total about 200,000 m^3). The changes in coastline orientation at the southern side of Gangneung port are the result of the sheltering of the northern waves by the port breakwater. Consequently, the coast South of the port is influenced primarily by the waves from the East and South-East which induced the coastline reorientation.

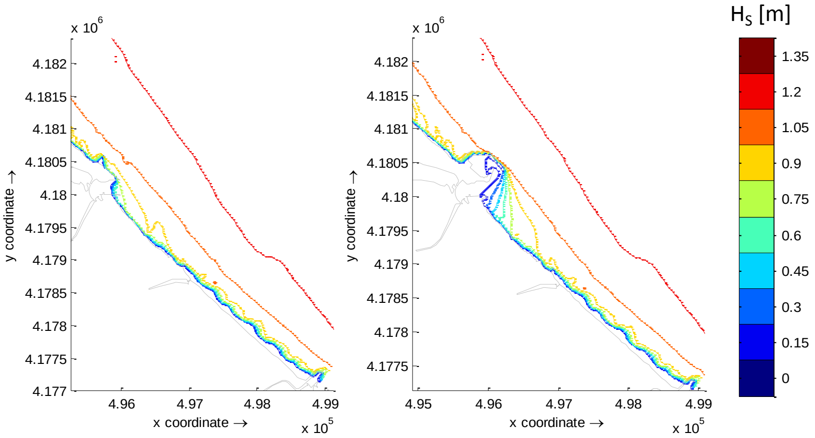

Figure 8. Computed impact of Gangneung port on the wave transformation (H_S) in the nearshore as computed with the Delft3D-wave model for an offshore wave condition with H_S of 1.4m and wave direction of 342 °N.

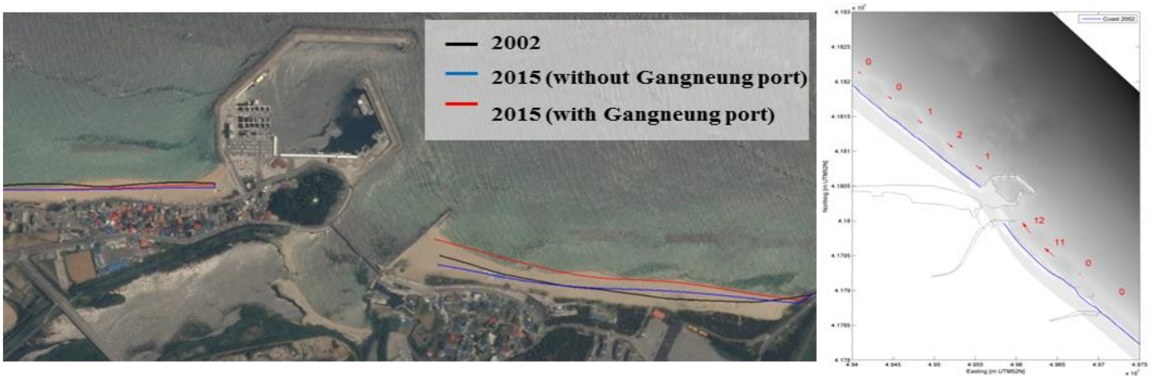

Figure 9. Computed shoreline impact and net transport rates (after 1 year) as a result of the construction of Gangneung port with the UNIBEST-CL+ model. Note that the satellite image shows the 2015 situation.

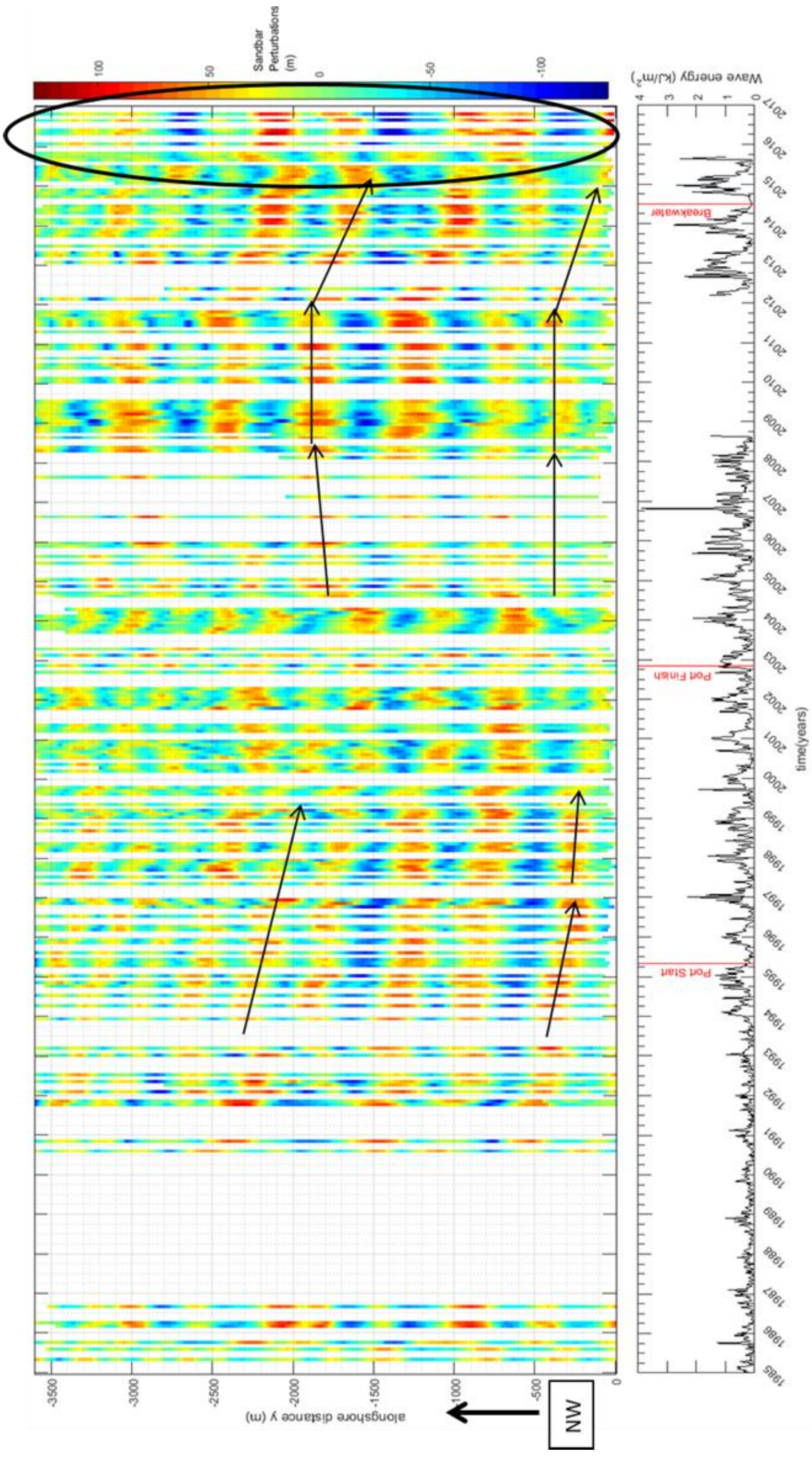

Figure 10. Time stack image of the sandbar perturbations in time (left) and ten-days averaged offshore wave energy, including the most important human interventions in red (right). Positive perturbations indicate sandbar bays and negative perturbations sandbar horns. The arrows indicate the bar migration directions. The highlighted part of the time-stack (end 2015-2016) indicates a sudden shift in the bar patterns, which still requires further investigation.

4.4 *Impact of crescentic bar dynamics*

The data analysis of the bar-shoreline dynamics at Anmok beach shows that the crescentic bars in the foreshore tend to migrate alongshore (Figure 10). The migration rates are in the order of 20 to 50 m/yr and direction and magnitude vary in time and space. The migration seems to be affected by the local wave climate and the construction of human interventions in time (Figure 10). However, the relations between these processes are not yet fully understood and require further investigation.

Furthermore, the analysis clearly shows that the crescentic bars are often in anti-phase with the shoreline (see for example Figure 11), which means that the shoreline shows shoreward perturbations in a sandbar bay (seaward perturbation) and, vice versa, seaward perturbations at the sandbar horns (landward perturbations). Due to the presence of the bars a typical variation in shoreline position of about -20 to +30 m is found (compared to the average coastline position which was subtracted from the perturbation with a 6th order polynomial fit). The migration of the beach states can therefore also lead to a temporal shoreline retreat in the order of about 20 m (with respect to the average coastline position).

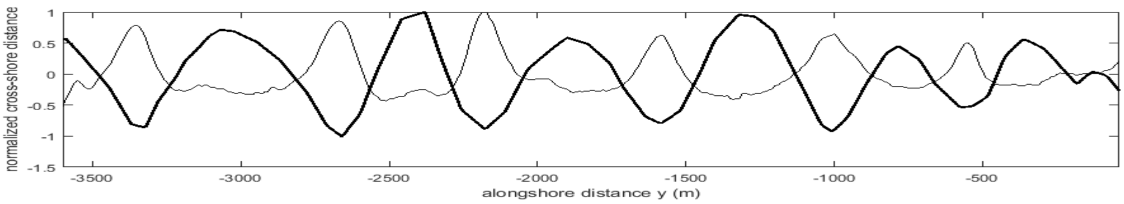

Figure 11. Bar position (thick line) and shoreline positions (thin line) at Anmok beach for a LANDSAT satellite image of 1 December 2008 (with a correlation of 0.87).

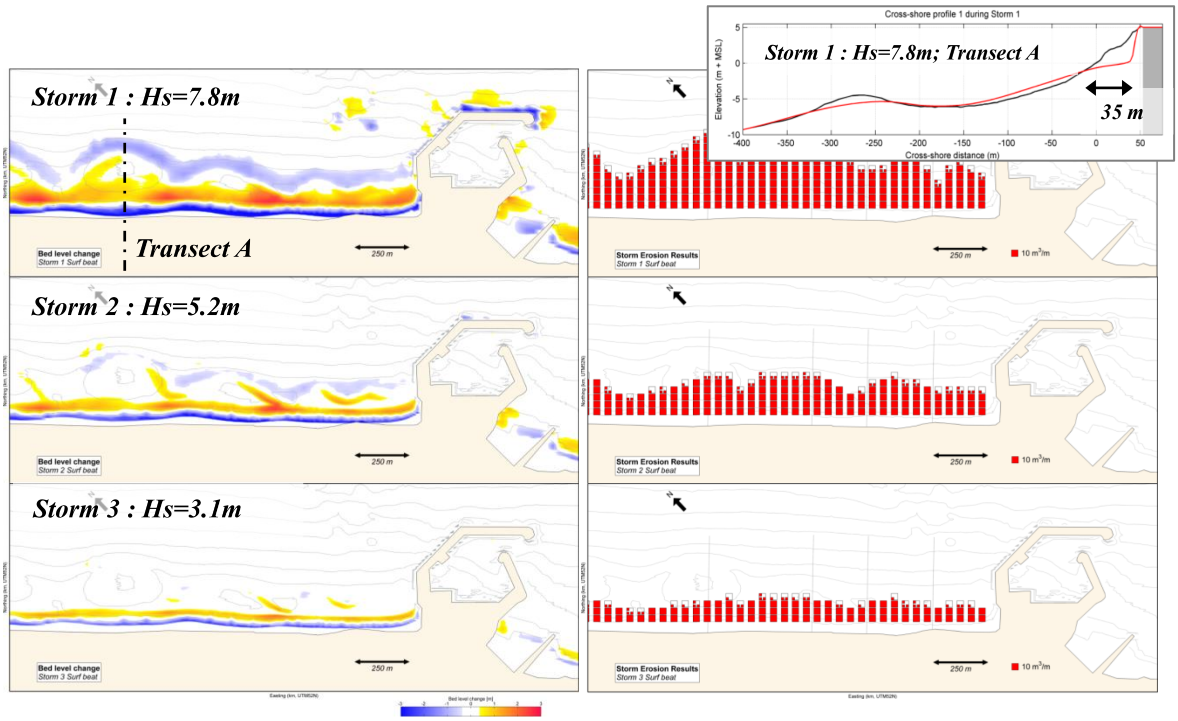

Figure 12. Computed erosion during the extreme October 2006 storm (Hs=7.8 m, Tp=12s), the 1/2 year storm (Hs=5.2m, Tp=12s) and 1/1 year storm event (Hs=3.1m, Tp=9s).

4.5 *Impact of storm erosion*

The potential impact of storm erosion (of the dry beach) is investigated with the XBeach model for three representative storm events (e.g. October 2006, 1/2 year and 1/1 year recurrence). The model results show that erosion of 15 to 35 m can take place for the most extreme event (e.g. October 2006) that is considered (see Figure 12, transect A). For this event the erosion extending up to the sea wall at transects near Gangneung port. The 1/1 year storm resulted in coastline retreat rates of 5 to 15m, while a retreat of 8 to 25 m was modelled for the 1/2 year storm. The considerable (temporal) retreat of the coastline during a 1/2 year storm indicates that storm retreat should be accounted for in the design of any coastal infrastructure (e.g. sea walls, boulevards, beach buildings), even for structures with a relatively small lifetime.

5. Conclusions & Discussion

The Korean East coast experiences coastal erosion causing damage to the coastal infrastructure. So far the processes driving the coastal erosion were not well understood. This study investigated the relevance of four (potential) coastal erosion processes at the beaches of Anmok and Namhangjin: (1) large-scale coastal reorientations, (2) the construction of Gangneung port, (3) beach state dynamics in the foreshore and (4) storm erosion. As the investigated erosion processes act on different temporal scales ranging from hours to decades, a framework was setup consisting of dedicated numerical models and data analysis techniques to study the relevance of each of the processes individually.

The results show that the effects of the large-scale coastline evolution on the coastal erosion are limited, but the construction of Gangneung port resulted in severe erosion at Namhangjin beach (up to 60m). The implementation of several protection measures at Namhangjin beach has mitigated the erosion to a large extent. Nevertheless, the presence of crescentic bars in the foreshore and occasional storms can still cause (temporary) coastline retreat in the order of 20-30m each, which should be accounted for in the planning of coastal infrastructure and/or mitigated by protection measures.

The study results provide useful insights into the individual contributions of the investigated processes to coastal erosion. These insights can help in the design of effective mitigation or adaptation strategies. Nevertheless, the inter-relations between the processes at the different time scales (e.g. between hard structures, beach state dynamics and storm impacts) are still not well understood. Future work should focus on gaining a better understanding of these interactions in order to design effective (protection) strategies to mitigate or adapt to the coastal erosion.

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