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Gómez, Matías; Aránguiz, Rafael

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Impact of Submerged Breakwaters on Valparaiso Coast against Storm of August 8th, 2015, and Future Events under Scenario of Climate Change

M. Gómez
Department of Civil Engineering, Universidad Católica de la Santísima Concepción, Chile

R. Aránguiz
Department of Civil Engineering, Universidad Católica de la Santísima Concepción, Chile

National Research Center for Integrated Natural Disaster Management CONICYT/FONDAP/1511007 (CIGIDEN), Chile

Abstract: The Chilean coast is constantly affected by storm surges, causing damage to coastal infrastructure due to overflow and scour. In particular, the storm of August 8th 2015, which affected the coast of Valparaiso (33° S, 71.6° W), was characterized by the occurrence of wave heights of up to 8 meters. Moreover, due to meteorological components, the sea level raised significantly thus waves broke closer to the coastline generating a retreat of 10-20 m and subsequently, economical losses of more than USD $ 7.2 million. On that ground, the present paper study the morphodynamics in a beach of Valparaíso due to the August 8th storm and future possible events due to climate change. In addition, the use of submerged breakwaters is analyzed in order to assess mitigation effects in case of future storm surges. To do this, a numerical model was set up using the Delft3D software coupling the WAVE, FLOW and MOR modules. The results show that the model reproduced in a good manner the morphodynamics during the August 8th event. In addition, the use of submerged breakwaters on the model has a positive impact on the Valparaiso area under the attack of extreme events.

Keywords: storm, erosion, submerged breakwaters, Delft3D.

1 Introduction

The storm of August 8th, 2015 was characterized by the occurrence of several meteo-oceanographic effects that caused the destruction of the coastal infrastructure. Waves of 8 m and strong winds of up to 110 km/h were observed. In addition, an atmospheric pressure of 991 HPa increased the sea level, thus waves broke closer to the coastline (Winckler et al., 2015). The observed structural damage revealed the vulnerability of the coastal sites built on low ground due to the lack of understanding of the nature of this dynamic environment. This event generated a retreat of the coastline of 10-20 meters and erosion of 2.8-4.5 meters on the beaches along the Bay of Valparaíso. In addition, economic losses were estimated in more than USD $7.2 million. Particularly, Yolanda beach had a coastline retreat of 11.4 meters, a maximum erosion of 3.9 meters and a sediment loss of 35.000 m^3 (Winckler et al., 2017). Therefore, there is a need for mitigation measures such as the use of breakwaters.

Commonly, breakwaters are used as coastal protection elements on erodible coast. It aims to reduce the wave energy and retain sediment along the coast. Recently, the use of submerged breakwaters (SB) has been more frequently used compared to conventional structures, mainly due to their less negative aesthetic impact on the coast. Several researchers have studied the behavior of these structures by means of 2D and 3D models in wave flumes (Ranasinghe and Turner, 2006), getting an unclear tendency on the impact induced by the submerged breakwater (SB). While Lamberti and Mancinelli (1996) and Jacktson et al. (2002) concluded that SB reduce erosion on the beach, Groenewoud et al. (1996) and Stauble et al. (2000) indicated that the use of SB increase erosion in the lee side of the structure due to the strong offshore flow in the gaps. On the other hand, the occurrence of storm surge and mitigation measures have not been studied in the region (Carvajal et al., 2018), which is a motivation for the present study.

In the present study, we analyzed the morphodynamics process at Yolanda beach (see Fig. 1) due to the extreme historical event (HE) of August 8th, 2015. To do this, we used the Delft3D model coupled with the WAVE-FLOW-MOR modules. Furthermore, the use of submerged breakwaters was analyzed as a mitigation measure. For breakwaters design, the depth of closure is included to avoid the loss of sediment from the system. Recently, Martínez et al. (2018) have shown that the climate change has modified the frequency and intensity of storm surges on the Chilean coast, therefore the morphological evolution of Yolanda beach was also analyzed under an extreme future event (FE) including the mitigation effect of submerged breakwaters.

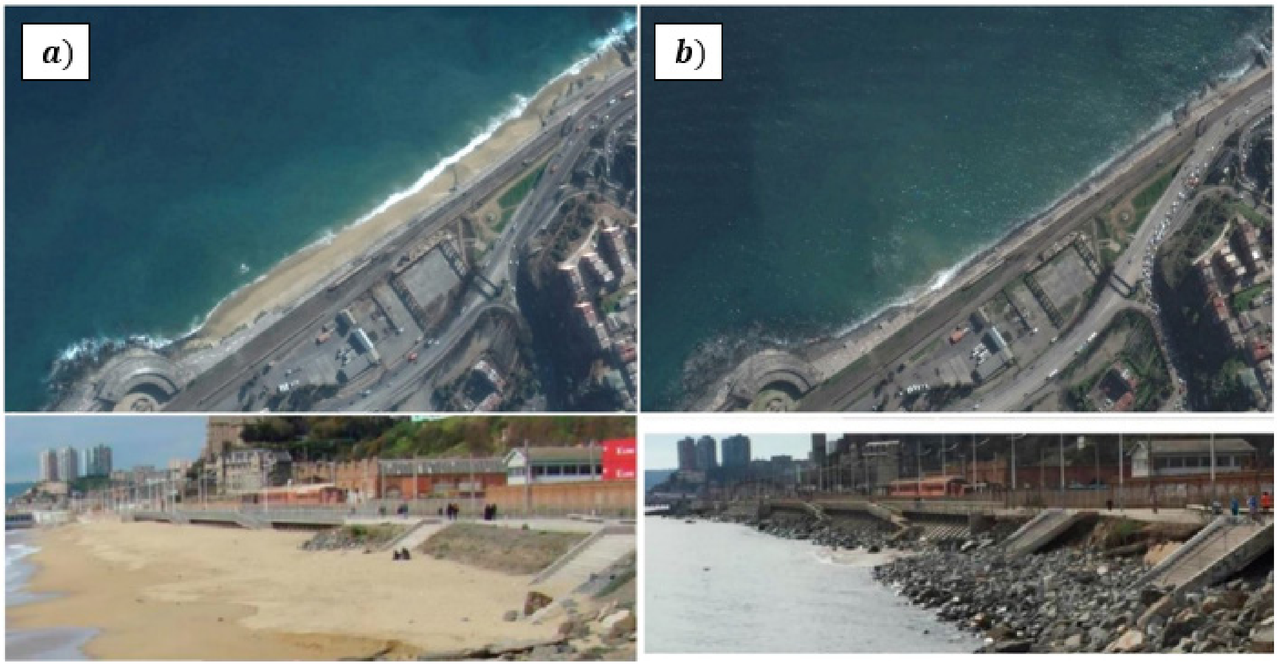

Fig. 1. Yolanda beach, a) before and b) after storm of august 8th, 2015. Source Winckler et al (2017).

2 Methods

2.1 Numerical Simulations

2.1.1 Model setup

For the development of the present study, the WAVE-FLOW-MOR modules of the Delft3D software were coupled (Lesser et al., 2004). The event at Yolanda beach was simulated from 6 pm on August 6th until 3 am on August 10th, with the first 6 hours used as warm up. The WAVE model consists of 3 nested grids and the input data are waves and wind every hour obtained from the WaveWatchIII model at the node 33°S 73°W. The currents and bottom changes were given by the FLOW module. WAVE-FLOW modules communicate every 60 minutes. The FLOW model is 3D with 10 sigma layers and its domain ranges from -17 m on the seaside to +6 m on the landside. In addition, the roller model is activated to characterize the wave breaking (Morris, 2001). In order to model sediment transport, the Soulsby/Van Rijn equation (Delft3D-FLOW, 2013) was used, considering a D_{50}=0.320 mm and D_{90}/D_{50}=1.3.

2.1.2 Calibration

The calibration was done by setting the parameters of transport due the presence of currents. We considered three variables to define the general morphological variations of Yolanda beach, namely coastline retreat (ΔL), erosion (ΔS) and sediment loss (ΔV). All data used in the calibration are given in Winckler et al. (2015).

2.1.3 Future scenario

The future event considered changes of tides, meteorological and wave components at the end of the century. The mean variation of sea level used in this study corresponds to the projected level given by Hamlington et al. (2014). This projection considers inter-decadal internal climate variability in the region. Furthermore, the variation of peak direction (D_p), peak period (T_p) and extreme wave height (H_{95}) suggested by Camus et al. (2017) was used. Finally, the projection of wind speed belonging to the 95th percentile determined by Mori et al. (2013) was considered.

2.2 Design of submerged breakwater

Six different configuration of submerged breakwaters were analyzed; (I) continuous, (II) three blocks and two gaps, (III) two blocks and one gap, (IV) three blocks and two gaps no erodible, (V) and (VI) same as II and III, but with blocks along gaps. First, the wave height at Yolanda beach for mean wave condition $(\overline{H_{s,i}})$ was estimated. Then, the depth at which the predominant wave break $(\overline{h_b})$ through the Battjes (1974) criterion was calculated. In order to not affect the propagation of the average wave, the depth of the crest of the breakwater Rc was determined from the minimum low tide (LT) and the breaking depth $\overline{h_b}$. On the other hand, the extreme wave height at which the breakwater will induce wave breaking, $H_{s,I}$ was calculated through the maximum water depth on the breakwater $h_{b,h}$ (considering highest astronomical tide and meteorological tide).

In order to avoid the eroded sediment from the beach leaves the system, the location of the submerged breakwater considered the depth of closure, D_c, proposed by Capobianco et al. (1997) with a deep change criteria of 10 cm (k=2.8). The transmission coefficient (K_t) was determined from Delft Hydraulics (2002). Finally, the design of the length (L_r) and gaps (G) considered the criterion of Ming and Chiew (2000) for case I and Pilarczyk and Zeidler (1996) for cases II y III.

3 Results

The storm of August 8th, 2015 increased the sea level in 0.2 m and wind speed reached up to 25 m/s. Large waves of up to 8 m with a predominant NW direction (see Fig. 2) and the exposure of the bay of Valparaíso to that direction were the main cause of the damage along the coastline (Winkler et al. 2017).

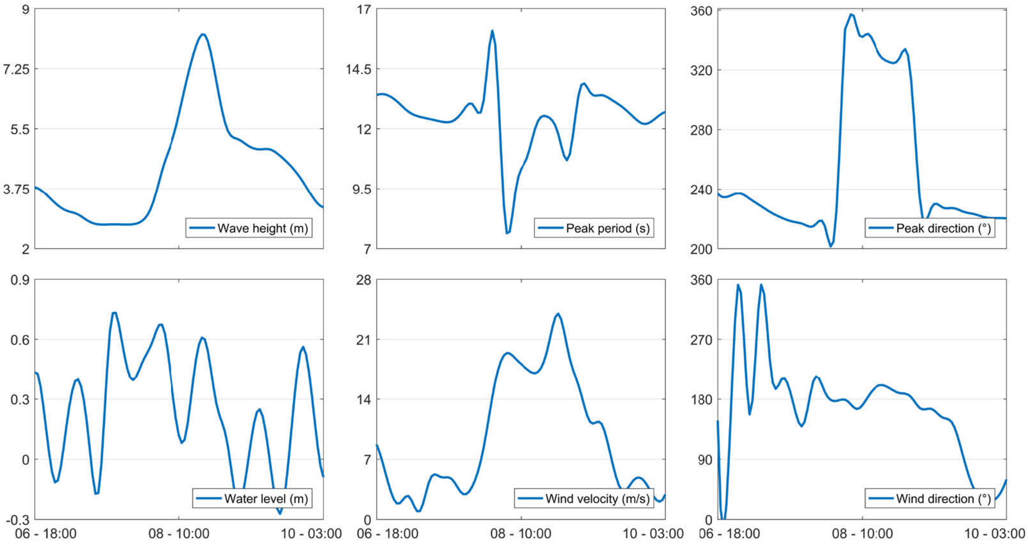

Fig. 2. Time series of wave, tide and wind during storm of August 8th 2015.

Using as calibration parameters (coastline retreat, erosion, and the volume of sediment loss) the model reproduced in good a manner the morphological variation of Yolanda beach due to the storm of August 2015 (see Tab. 1). The model indicated an average coastline retreat of 11.37 meters, an erosion of 3.42 meters and an eroded sediment volume of 37 thousand m^3 (see Fig. 3). Comparing these results with those measured after the storm, there are errors of less than 10% (see Tab. 1).

Tab. 1. Measured and simulated morphological evolutions due storm of August 8th 2015

	Coastline retreat (m)	erosion (m)	Sediment loss (m^3)
Measured	12.5	3.9	35,000
Simulated	11.37	3.42	37,211
Error (%)	9	7.5	6.3

To represent the effect of a future event in Yolanda beach, sea level, wave and wind projections at the end of the century were analyzed. An increase in sea level of 1 mm/year is assumed (Hamlington et al., 2014), getting an increase in sea level of 8.5 cm at the end of the century. Based on Camus et al. (2017) a decrease of H_{95}, T_p and D_p of 5 cm, 0.01 s and 1.75°, respectively, is obtained. Finally, a variation of 7% in wind speed belonging to the 95th percentile is considered.

In the design of the breakwater, an average wave height of 0.6 meters is considered in Yolanda beach and a breaking depth of 0.85 meters based on Battjes (1974). The lowest tide is found to be 0.86 m, therefore, the depth of breakwater crest is defined to be at 1.71 m below mean sea level in order to not affect the predominant wave propagation. Furthermore, an increase of 0.2 m in sea level is considered due to the meteorological conditions during extreme waves. In addition, considering high tide during the extreme event a water depth of 2.76 meters above the breakwater crest ($h_{b,h}$) is obtained. The depth of closure is found to be 6.24 m, thus the breakwater is located 160 m from the coast line. Finally, considering a width of 50 m at the bottom of the breakwater, the transmission coefficient is found to be 0.4. All parameters are shown in Tab. 2.

Tab. 2. Design criteria of submerged breakwater for Yolanda beach

$H_{s,i}$	h_t	LT	Rc	HT	MT	$h_{b,h}$	$H_{s,i}$	Dc	X	Lt	B	B/ Lt	Rc/ $H_{s,i}$	Kt
0.6	0.85	-0.86	1.71	0.86	0.2	2.76	3.31	6.24	160	49.1	50	1.01	0.51	0.4

The lay out of the 6 breakwaters are presented in Tab. 3. Case I considered a single breakwater of 520 meters long, cases II, IV and V consist of three breakwaters and two gaps, and cases II and VI consider two breakwaters. Case IV assumes that a geotextile is installed in the gap, avoiding erosion. The cases V and VI have two rows of breakwaters, in order to reduce the strong flow in the gaps.

Tab. 3. Proposed layout of breakwaters

Case	Scheme	L_r	G	Erosion between breakwaters	Two rows of breakwaters
I	L_r	520	0	-	-
II	L_r/G/ L_r/G/ L_r	130	65	Yes	No
III	L_r/G/ L_r	210	100	Yes	No
IV	L_r/G/ L_r/G/ L_r	130	65	No	No
V	L_r/G/ L_r/G/ L_r	130	65	Yes	Yes
VI	L_r/G/ L_r	210	100	Yes	Yes

*Lr is the length of breakwaters and G is the length of gaps

The model indicated that the event of August 8th generated an erosion on the beach in the order of 1.5 to 3.5 m. This sediment was transported to depths greater than 8 meters in a southwest direction. In case I, there is a considerable decrease in the erosion along the beach and the sediment is transported to a depth of 5 meters (see Fig. 3b). In addition, a large amount of sediment is deposited on the lee side of the breakwater. Cases II and III (Fig. 3c and Fig. 3d) manage to reduce erosion along the beach, but erosion in the gaps is generated due to the strong flows. Case IV (see Fig. 3e) does not present changes with respect case II (Fig. 3c). Finally, it is observed in cases V and VI (Fig. 3f and Fig. 3g) that the strong flow decrease, so the sediment is deposited between breakwaters. Even though the simulations showed an increase of erosion in the southwestern area, it is important to mention that this area consist of rocks, and subsequently no erosion would occur.

The future event (Fig. 3h) showed similar behavior as the historical event, although a slightly smaller erosion is generated on the beach. On the other hand, the future event with SB type VI showed less erosion (Fig. 3i) than the historic event with the same breakwater (Fig. 3g). Therefore, the use of these kind of structures would be more effective on Yolanda beach in the future.

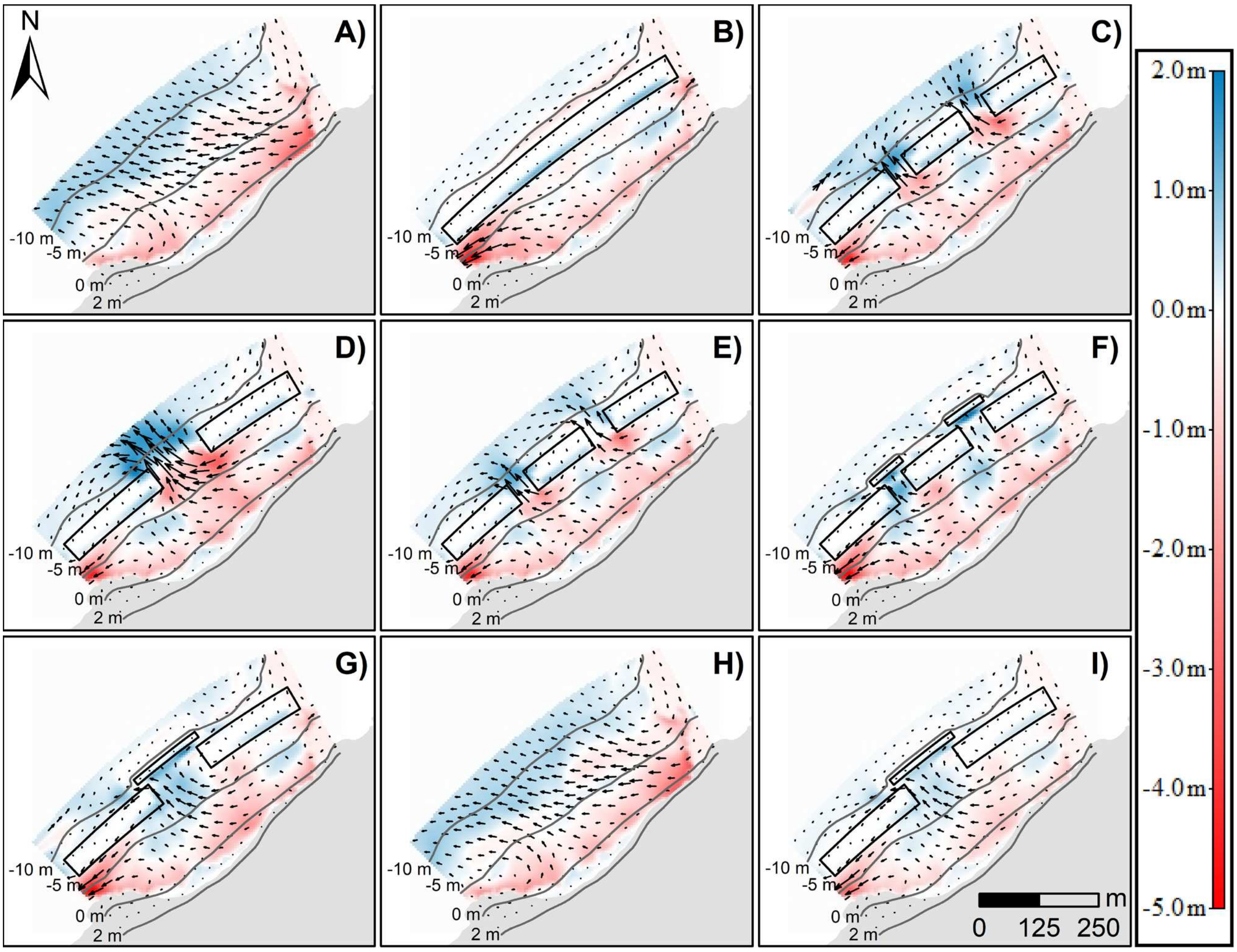

Fig. 3. Morphodynamic of Yolanda beach due to storm. a) HE without SB, b) HE with SB I, c) HE with SB II, d) HE with SB III, e) HE with SB IV, f) HE with SB V, g) HE with SB VI, h) future event without SB, y f) FE with SB VI. Vectors indicate the mean sediment transport during the storm, red represent erosion and blue accretion.

It is observed that the use of breakwater reduces the coastline retreat between 7 to 41%, the maximum erosion in 43% and the volume of sediment eroded by approximately 30% (see Fig. 4). With regards to coastline retreat, the case VI generates greatest reduction. Furthermore, the maximum erosion and volume of eroded sediment on the beach does not show significant differences among the proposed layouts. Finally, cases V and VI provide better protection to the beach against extreme events.

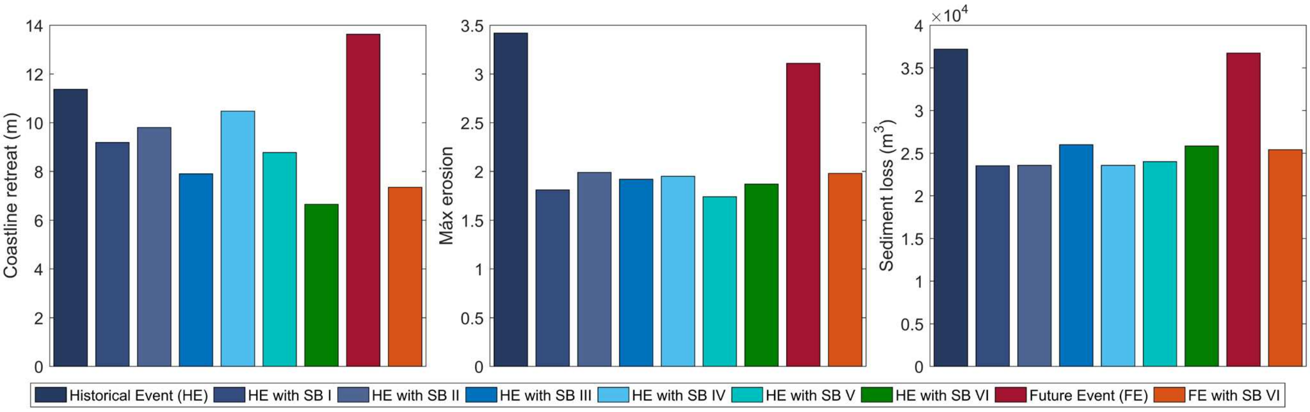

Fig. 4. Parameters morphological evolution on Yolanda beach due storm.

4 Discussion

The numerical model represent in a good manner the morphodynamics process at Yolanda beach due to extreme event of August 8th, 2015, but it still requires a more complete calibration. To do this, it is necessary to incorporate a more detailed bathymetry of the beach before and after the event.

Recently, local researchers discussed about the use of definitive solutions against extreme events (Martínez et al., 2018) due to the fact that change in sea level are more affected by seismic cycle rather than climate change in this region (Contreras-López et al., 2017; Montecino et al., 2017). In a similar manner, global debate is focused on the real impact of submerged breakwaters (Ranasinghe & Turner, 2006; Johnson et al., 2005). Lamberti and Mancinelli (1996) y Jacktson et al. (2002) indicate that these structures have a positive impact on the coast, reducing the erosion, while Groenewoud et al. (1996) y Stauble et al. (2000) argue that the incorporations of submerged breakwaters generates erosion due to strong flow that occurs in the gaps. However, in the present study, the depth of closure criterion proposed by Capobianco et al. (1997) was incorporated into the design of the studied breakwaters with the aim of preserving the sediment into the system during the storm. With this, a positive impact was obtained on the coast against extreme event in all cases, coinciding with Lamberti and Mancinelli (1996) and Jacktson et al. (2002). Furthermore, the result could be improved by increasing the breakwater width, decreasing the depth of breakwater crest (this implies analyzing emerging breakwaters) and the selection of more robust closure depth such those proposed by Hellermeier (1981) or Capobianco et al. (1997) with k=3.1 thus decrease the strong flow in the gaps. However, this implies an increase in the construction costs, but the development of alternative systems and material (e.g. sand-filled geotubes as a core) can reduce the cost (Pilarczyk, 1999).

5 Conclusions

The storm of August 8th, 2015 was characterized by the occurrence of several meteo-oceanographic effects without historical precedent. This event, reached wave heights of 8 m, eroding a volume of 35.000 m3 in Yolanda beach, revealing the vulnerability of the coast against storm surge.

The incorporation of submerged breakwaters proved to be a good alternative to mitigate the impact of extreme waves in Yolanda beach. In general, the breakwaters reduced sediment loss by 30% in Yolanda beach, although it is still necessary to continue the study with different breakwater dimensions and the dynamic processes under normal wave condition. In addition, it would be necessary to analyze the effect of submerged breakwaters in the other beaches of Valparaíso Bay.

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