

Effect of tsunami breakwater as a mitigation measure at the Bay of Concepción

Efecto de rompeolas para tsunamis como una medida de mitigación en la bahía de Concepción

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This article presents the results of the 2010 tsunami simulation in the Bay of Concepcion. It is also studied the effect of breakwaters at the bay's mouth on inundation area and run-up. A modeling of static and non-uniform deformation of the 2010 tsunami is used, and the propagation and run-up is simulated by means of the software Delft3D-FLOW. The first case considers a breakwater between the northern part of Quiriquina island and the north of Tomé with a maximum water depth of 40 m. While the second alternative considers a breakwater between the southern end of the Quiriquina island and the south of Tomé, with a maximum water depth of 20 m. In addition, the effect of a third breakwater, which acts in combination with the above alternatives, between the island and Tumbes was studied. The results show that the use of a tsunami breakwater significantly reduces both the flooding area and inundation height, however, it does not completely eliminate flooding in the area between the cities of Penco and Talcahuano. Finally, the best alternative, from a technical point of view, seems to be the use of a breakwater between the Quiriquina island and the southern side of Tomé and without considering other breakwater between the island and Tumbes.

Keywords: numerical simulation, static and non-uniform initial condition, tsunami breakwater, inundation area

El artículo presenta los resultados de la simulación del tsunami del 2010 al interior de la bahía de Concepción. Se estudia el efecto que tendría en el área de inundación y run-up la utilización de rompeolas en la entrada de la bahía. Para ello se utiliza una modelación de la deformación estática no uniforme del tsunami de febrero del 2010 y la propagación hacia el interior de la bahía se simula mediante el programa computacional Delft3D-FLOW. El primer caso considera un rompeolas entre la isla Quiriquina y el sector norte de Tomé con una profundidad máxima de 40 m, mientras que la segunda alternativa contempla una estructura entre el extremo sur de la isla y el sector sur de Tomé, con una profundidad máxima de 20 m. Adicionalmente se estudió el efecto de construir un tercer rompeolas entre la isla y la caleta Tumbes, tal que actúe en combinación con las alternativas anteriores. Los resultados muestran que la utilización de este tipo de estructuras disminuye considerablemente tanto el área de inundación como la altura de flujo y run-up, sin embargo, no elimina por completo la inundación en el sector comprendido entre las ciudades de Penco y Talcahuano. La alternativa más conveniente desde un punto de vista técnico, demuestra ser la utilización de un rompeolas entre la isla Quiriquina y el sector sur de Tomé y sin considerar otro rompeolas entre la isla y Tumbes.

Palabras clave: modelación numérica, condición inicial estática no uniforme, rompeola para tsunamis, área de inundación

Introduction

On 27 February 2010 at 03.34 local time (06:34 UTC) a big earthquake, with a moment magnitude of 8.8 and epicentre off the coast close to the border between the Bío Bío Region and the Maule Region,

took place and generated a destructive tsunami.

The destruction caused by the earthquake was important, however, the tsunami caused a much significant devastation. Many people were killed and the total economic loss in Chile was estimated to be

20 billion US dollar. Repeated tsunami waves hit the Bay of Concepcion, measurements showed water levels up to 6 m in Penco, Talcahuano and Tumbes.

Once again this event shows the importance of mitigation measures. In this article the effect of a breakwater in the Bay of Concepcion is investigated. This kind of structures could help to decrease the wave height and the wave energy, and subsequently the inundation area.



Figure 1: Location of the Bío Bío Region and the Bay of Concepcion

The Bay of Concepcion is located in the Bío Bío Region as shown in Figure 1. The bay is largely formed by the peninsula of Tumbes and is open to the north. Many port facilities and a Navy base are located here. The bay includes the cities of Penco, Tomé, Tumbes and Talcahuano. Quiriquina island is located more to the west and divides the entrance of the bay. The west opening is shallower and smaller compared to the wider and deeper water at the east.

Numerical simulations help to understand in a general way the tsunami hazards. They are useful to calculate tsunami height, travel times, *run-up* height, inundation area, etc. Since wave lengths of tsunamis are typically a lot longer than the average depth, shallow water theory is used in numerical models. To obtain proper and accurate model results, good quality information for the model input is necessary. The topographic and bathymetric data has to be reliable. The initial water level conditions have to be good estimations and models should be compared with measured data, such as inundation and water levels.

The present paper uses the Delft3D-FLOW software for numerical simulation of tsunamis. Delft3D is a 3D software modelling package developed by Deltares, (Deltares, 2009). This software is especially useful for computations of rivers and coastal areas. Different modules can be used to simulate multidimensional hydrodynamic flow and transport phenomena.

Delft3D-FLOW is the hydrodynamic module, and it solves the Navier Stokes equations for an incompressible fluid, under shallow waters and Boussinesq assumptions. In the vertical momentum equation, the vertical accelerations are neglected, which leads to the hydrostatic pressure equation (Deltares, 2009). Therefore, this module is used to determine the tsunami propagation and flooding for the Chilean coast model. To do this, a curvilinear grid is used to model the flow.

Delft3D-RGFGRID is used to build the curvilinear grid in the Chilean coast model for the Delft3D-FLOW module. The resolution of the grid is 130 m at the bay mouth and 80 m near Talcahuano.

Delft3D-QUICKIN is used to build the bathymetry files for the Delft3D-FLOW model according to the grid made by Delft3D-RGFGRID. To obtain bathymetry and topography information GEBCO, SRTM, topographic maps and nautical charts were used (IOC 2009).

The use of tsunami breakwaters

Studies of the effectiveness of breakwaters against tsunamis started in Japan after the 1960 Chile earthquake. Ofunato Port on the Sanriku Coast was the first to build a bay mouth breakwater and it was constructed from 1963 to 1968 (Murata *et al.* 2010). Figure 2 shows the 1960 m long breakwater in Kamaishi, which was also built to protect the bay from tsunamis. At 63 m it is the world's deepest breakwater and took 31 years to be constructed. The work was finally completed in March 2009 (Tanimoto and Goda 1992).

Other examples are in Suzaki and Kuji ports. These are composite type structures, because they had to be built fast. Different possible structures are rubble mound, caisson and new specially designed tsunami breakwater (Murata *et al.* 2010). After the big tsunami of 2004 a lot of funds have been allocated to tsunami breakwater research. Besides

scale model experiments, there is no other experience yet with these new designs.



Figure 2: Kamaishi port breakwater, taken from <http://www.city.kamaishi.iwate.jp>

As the tsunami breakwater, or bay mouth breakwater, is designed to close part of the bay mouth, it will decrease the inflow rate of tsunami into the bay, in addition, the structure could alter the resonance period of the bay (Murata *et al.* 2010). Moreover, the long wave character of the tsunami and the line shape of a breakwater will cause high reflection and thus even higher water levels in front of the breakwater or even overtopping. Therefore, the breakwater must be designed to withstand high velocity gradients over the crest.

A further effect that must be investigated is the scour at the base of the breakwater and toe protection. There is also the possible change of the bay's environment. Because of the limited opening with the classic permanent breakwaters, water quality due to decrease in water circulation may change.

Numerical simulation of tsunami breakwaters

In the Delft3D software, breakwaters are represented by 2D weirs. Because the width of the breakwater would be much smaller than the grid size, only the influence on the flow is considered. In the software, weirs are fixed non-movable constructions generating energy losses due to constriction of the flow. They are commonly used to model sudden changes in depth (roads, summer dikes) and groynes in simulation models of rivers (Deltares, 2009). The mathematical concept was developed by Wijbenga (1990). For a 2D weir the crest height is taken into account

only in the drying and flooding algorithm. The energy loss generated by the weir is not computed directly by the convective terms in the momentum equations, it is parameterised and added in the momentum equation instead. The 2D weirs block the flow in the U or the V direction in the grid. If the water level, or the tsunami wave, exceeds the breakwater height, the breakwaters act as a weir.

The breakwater in the present case has a height of 5 m above the still water level and it will prevent water to overtop until the tsunami wave reaches a higher value.

Two different breakwater locations are considered. A breakwater north and a breakwater south of Tomé to Quiriquina island, see Figure 3. The northern breakwaters will block tsunami waves from entering the entire bay. The southern breakwaters are in much shallower water but leave Tomé exposed. The northern breakwater is located at 40 m water depth and the southern breakwater is located at 25 m water depth. Because of the typical shape of breakwaters, the depth is a very important characteristic.

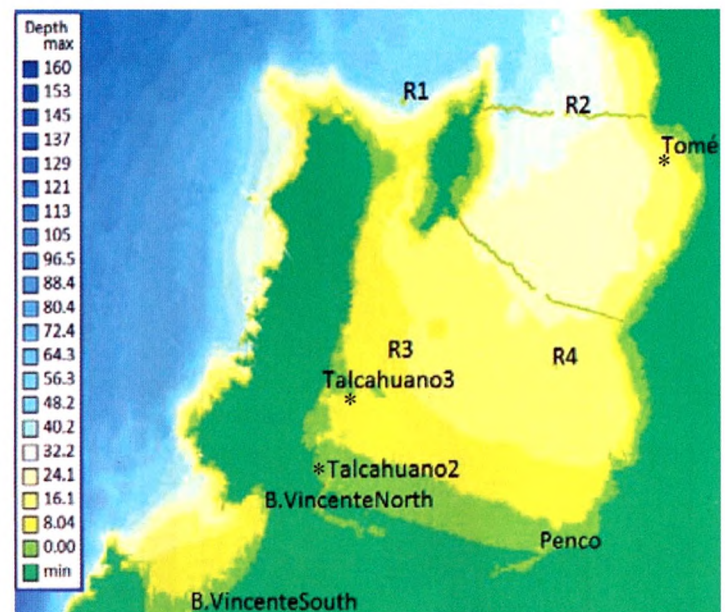


Figure 3: Location of the breakwaters, bathymetry and observation points

Four protection scenarios were considered. The northern and the southern breakwater close the bay in two different locations on the right side of Quiriquina island. They have a gap in the middle for ships to pass. Two additional model scenarios were run with the breakwaters and an extra closure of the gap on the left of the island. The northern breakwaters have a total length of 5.2 km and the deepest point is 41 m. The opening for ships is approximately 600 m.

The southern breakwaters have a total length of 6.3 km and the deepest point is 26 m. The opening is approximately 500 m. The closure on the left side of Quiriquina island is in the shallowest water. The water depth is only 13 m.

Initial condition

The initial condition is built from a static deformation, which is generated by means of the Okada formulation (Okada 1985). This formulation is based on an elastic earth crust. A complex rupture pattern can be simulated by dividing the fault plane into a series of smaller segments. The vertical displacement of the seabed induces a corresponding displacement of the water surface, which is applied as the initial condition of the model.

The initial condition for the 2010 event is generated from the interplate displacement proposed by Delouis *et al.* (2010). To do this, the strike, dip and slip angles are as follows: $\theta = 15^\circ$, $\lambda = 18^\circ$ and $\delta = 110^\circ$. Figure 4 shows the result for the static initial condition used in the numerical simulation. The figure shows that the initial condition has two wave height peaks.

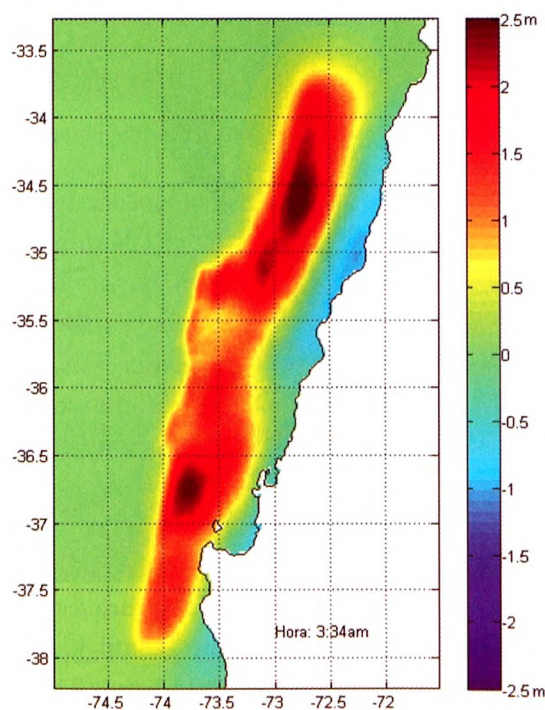


Figure 4: Initial sea surface deformation for the 2010 event

Calibration of the model

The model is calibrated with the wave gauge that was located in Talcahuano port. Unfortunately the device broke after the second wave so there is only a short recording

of the water levels in the bay during the 2010 tsunami. Figure 5 shows the comparison between the recorded water level by the West Coast Alaska Tsunami Warning Centre and the modelled water levels.

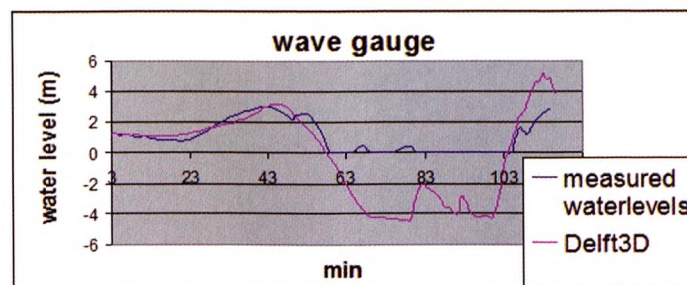


Figure 5: Coordinate location of wave gauge: -36.7083, -73.1097

The tide effect was not included in the model. The first waves ran in the bay at low tide so the modelled tsunami heights and inundation are slightly overestimated. Also, the change in the elevation of the land after the earthquake is not considered. From Figure 5 it is possible to see that there is a good agreement between the recorded and the modelled water level, at least where the comparison is possible.

Results

Figure 6 shows the time series in observation point Talcahuano3, which is located near the Naval Base. It is seen from Figure 6 that both breakwaters decrease the maximum wave height. In addition, the fluctuation inside the bay is also decreased, due to the fact that longer wave periods are observed. Similar situation were found in other locations in the bay.

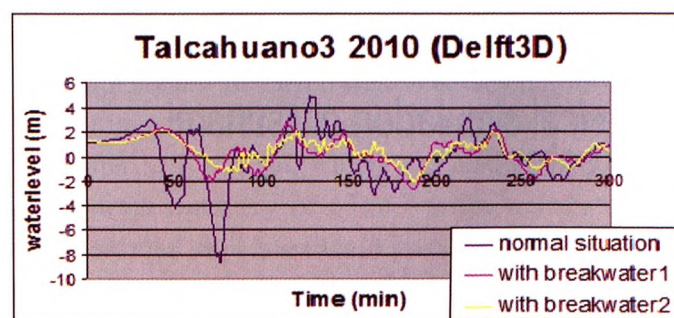


Figure 6: Water level observations at point Talcahuano3

In Tomé, however, the largest effect of shifting the northern breakwaters to the location more to the south is that it leaves Tomé largely exposed, as seen in Figure 7. While the northern breakwater decreases the wave height, the southern one enhances the minimum water level and maintains the maximum wave height, but the latter

happens earlier than the normal situation. This effect could be due to reflection in the breakwater.

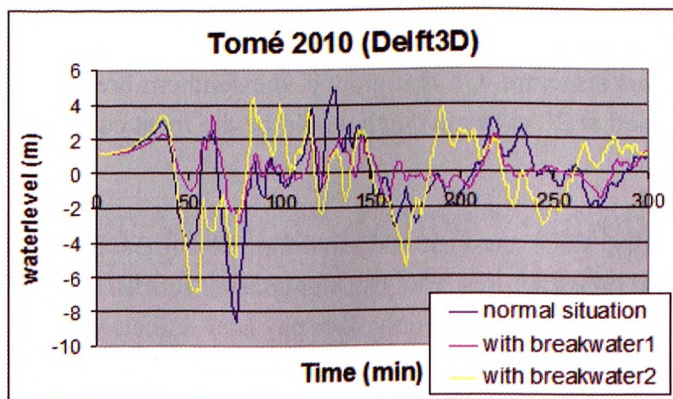


Figure 7. Water level observations at Tome.

Figure 8 shows the inundation area around Concepcion bay after the 2010 tsunami according to the Delft3D model and the static initial condition generated. During the tsunami it was low tide and also on average the land rose 30 cm. It shows clearly that large flat areas in Talcahuano, Penco and Tomé are flooded. Based on this result we conclude that the area between Penco and Talcahuano is exposed to high risk (unsafe) for building and habitation.

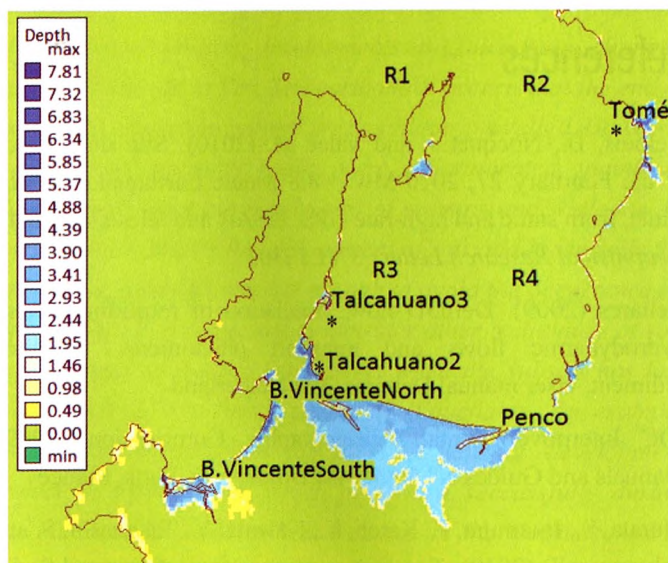


Figure 8: 2010 tsunami modelled inundation, no mitigation measures (MSL)

Although, the flooded area has been slightly overestimated by the model when compared to the real inundation (probably due to incomplete DEM data and no consideration of low tide and land uplift), it serves as a good reference for the scenarios with breakwaters.

Figure 9 and Figure 10 show the inundation in case the gap between Quiriquina island and Tumbes is still open.

The inundation around Talcahuano and Penco is similar in both scenarios. The inundation in the build up areas is largely reduced. The lowland area in between also is better protected. The model was not yet ready to consider also greenbelts and levees in the simulation. These could maybe protect the area even further so it is safe to use it as a building ground.

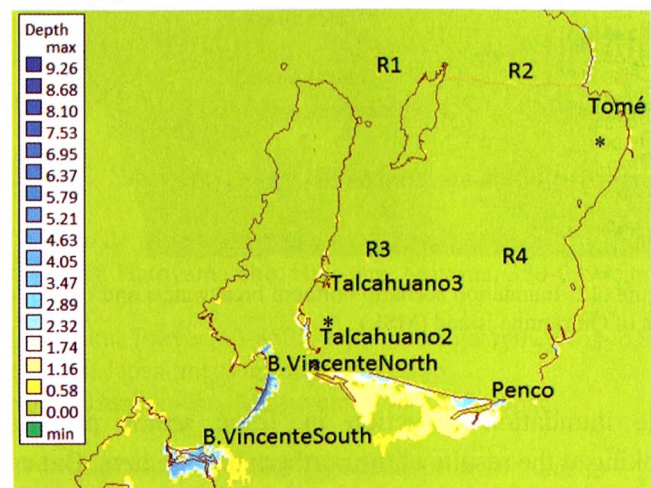


Figure 9: Inundation scenario northern breakwaters (MSL)

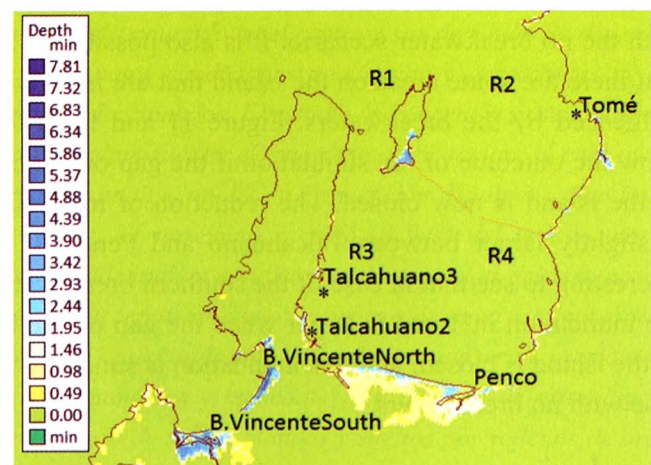


Figure 10: Inundation scenario southern breakwaters (MSL)

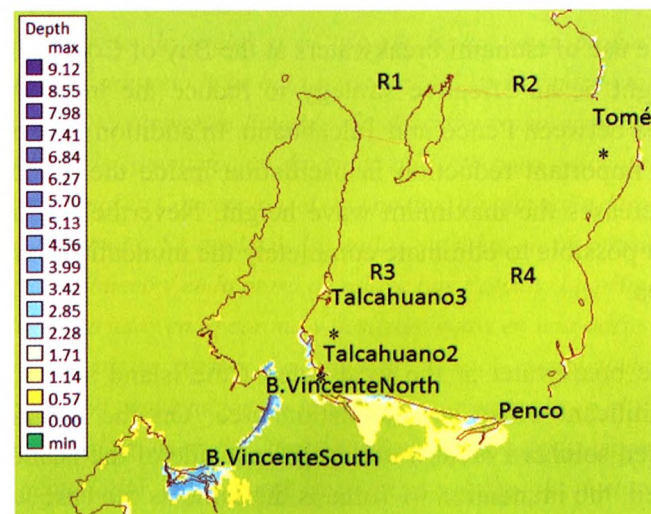


Figure 11: Inundation scenario northern breakwaters and closed left side of Quiriquina island (MSL)

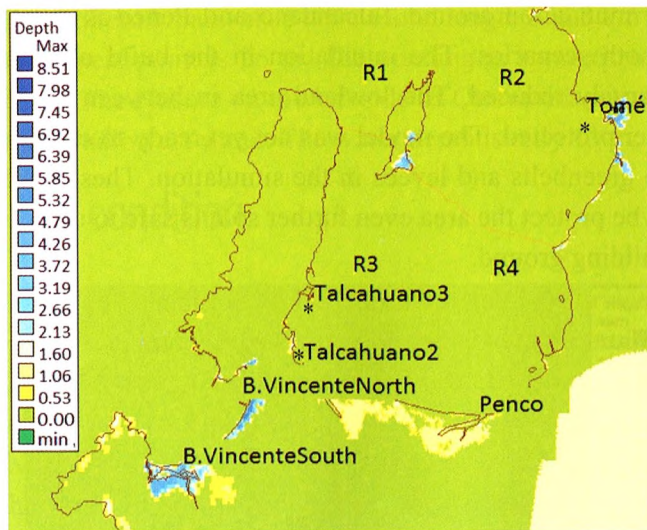


Figure 12. Inundation scenario northern breakwaters and closed left side of Quiriquina island (MSL)

The inundation reduction in Tomé seems promising looking at the results of the northern breakwaters. But even the southern breakwaters seem to have a positive effect on the inundation in Tomé if the results are compared with the no breakwater scenario. It is also possible to see that there are some areas on the island that are negatively influenced by the breakwaters. Figure 11 and Figure 12 show the outcome of the simulation if the gap on the east of the island is now closed. The reduction of inundation is slightly larger between Talcahuano and Penco. It is interesting to see that in case of the southern breakwaters the inundation in Tomé is larger when the gap on the left of the island is closed, and this inundation is similar to the case with no breakwaters.

Conclusions

The use of tsunami breakwaters at the Bay of Concepcion might be an effective strategy to reduce the inundation area between Penco and Talcahuano. In addition, it shows an important reduction in oscillation inside the bay and decreases the maximum wave height. Nevertheless, it is not possible to eliminate completely the inundation at this area.

The breakwater at the west side of the island shows no significant effect on inundation area. On the contrary, when southern breakwater at the east side of the island is used, the inundation in Tomé is the same as the case with no breakwaters in the bay.

The northern breakwater at the east side of the bay shows to be the most convenient alternative if only the inundation and wave height are considered, however, the deepest water depth is 40 m which would considerably increase the cost of this structure. On that ground, the southern breakwater, located at 20 m water depth would be the most convenient choice.

Finally, since the cost and environmental impacts of this kind of structures can be significant, further research should consider not only the physical effect, but also the social, economic and environmental impact, due to the fact that the effects on the bay's ecosystem could be significant. On that ground, the way in which climate, currents and sediment transport should be investigated.

Acknowledgments

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