Numerical modelling of tsunami scenarios for the island of Bonaire (Leeward Antilles)

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ABSTRACT: At coasts around the world where the impact of storm waves or tsunamis is known or assumed, large boulders and marine sands at coastlines are used as indicators for particular event characteristics and occurrence patterns over large time scales. Such deposits identified at the coast of Bonaire (Leeward Antilles) point to tsunami hazard which is not evident based on the instrumental and historical record. In this study, we compute historical and other potential tsunami events using Delft 3D and Delft Dashboard, in order to identify the most suitable event(s) for creating these sediment patterns as well as the source of possible future threats.

1 Introduction

At the eastern and northern coasts of the island of Bonaire (southern Caribbean, Leeward Antilles) large limestone boulders were transported from the cliff edge landward during high-energy wave events in the past. Whether these events were palaeo-tsunamis or severe hurricanes is controversial (e.g. Scheffers 2005; Spiske et al., 2008; Watt et al., 2010; Engel & May, 2012). Other potentially tsunami-laid shell-rich muds to coarse sands were found buried in Bonaire's circumlittoral bokas (Engel et al., 2012, 2013).

In an iterative approach, we simulate historical and other potential tsunami events in the Caribbean Sea, in order to identify the most suitable event(s) for creating these particular sediment patterns on Bonaire as well as the source of possible future threats. First results are presented. We perceive this work as an initial step towards a regional tsunami hazard assessment.

2 Bonaire

2.1 *Geological setting*

Bonaire originates from mid- to late Cretaceous submarine volcanism. The two volcanic cores of the island are connected and surrounded by Quaternary limestone terraces referring to former sea-level highstands (Engel & May, 2012).

The Lower Terrace (LT), which is the youngest carbonate platform, reaches up to 15 m a.s.l. (above mean sea level) in the northwest of Bonaire, in the central part of the island 3 to 6 m a.s.l., while it is near sea level in the southern part. The largest boulders for which tsunami transport is assumed are located on top of it in the central part (Figure 1a), mostly within 120 m from the coastline (Engel & May, 2012). Sandy candidate tsunami deposits are part of the sedimentary infill of inland embayments which are formed as drowned river valleys cut into the sequence of limestone terraces (Engel et al. 2012).

2.2 *Tectonic setting*

Bonaire is located on the Bonaire Microplate in the transpressional boundary zone between the Caribbean (CP) and South American (SAP) plates (e.g. Hippolyte & Mann, 2011). The predominant motion of the CP relative to the SAP is eastwards and includes right-oblique convergence in the boundary zone where interactions between the microplates include strike-slip motion, compression and extension (Audemard et al., 2005). The tectonic uplift and tilting are linked with active folding or faulting (Hippolyte & Mann, 2011).

2.3 *Potential triggers of tsunamis on Bonaire*

Most tsunamis in the Caribbean Sea have only local (<100 km) to regional (100-750 km) effects and are of regional seismic origin, including strike-slip, subduction or interplate events. In the southern Caribbean, faults along the Venezuelan coast generated tsunamis in historical times (Harbitz et al., 2012). Near field mass-wasting events cannot be excluded as well (cf. Hornbach et al., 2010). Larger regional tectonic tsunamis, such as the 1867 Virgin Islands tsunami, seem to have had only minor effects on Bonaire (Zahibo et al., 2003). Even though no historical account on the occurrence of a tsunami exists on the entire island (Harbitz et al., 2012), its 30-year probability for a run-up ≥0.5 m is c. 7% (Parsons & Geist, 2009).

3 Tsunami Model

3.1 The Model

Delft 3D (Deltares, 2014a) and DelftDashboard (Deltares, 2014b) of Deltares systems (NL) are used to compute different scenarios potentially threatening Bonaire. While DelftDashboard (DD) is used to generate the initial, earthquake-triggered tsunami wave, the bathymetric and topographic model of Bonaire, wave propagation throughout the Caribbean Sea, and corresponding wave heights at the coastline are simulated in Delft3D (D3D). DD allows the user to define boundary conditions for the assumed tsunami-triggering earthquake. Beside the basic inputs for the length, width and direction of the fault line, it is possible to define more precise parameters like strike, slip and slope.

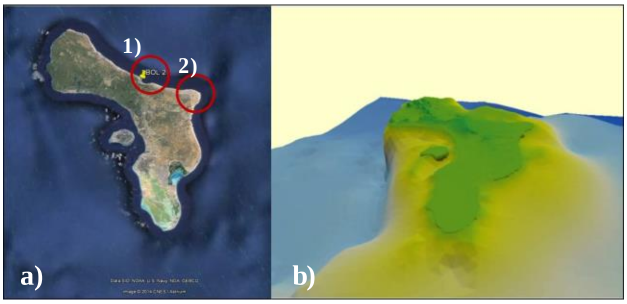

Figure 1: a): Island of Bonaire and Klein Bonaire (Google Earth). The red circles describe the study sites Boka Olivia (1) and Spelonk (2). Boulder BOL 2 is marked by the yellow pin at Boka Olivia. b): Numerical model of Bonaire.

It is possible to run the whole simulation in DD. However, for prudential reasons (e.g. combining different bathymetric data), we used D3D for realization. We implemented a bathymetry data set (spatial resolution of 500–600 m) provided by Gonzalez-Lopez & Westerink (University of Notre Dame) for the shallow bathymetry of the second nested model (Figure 1b). The overall and the first nested model consist of the coarser GEBCO08 data (GEBCO, 2014). The topography is generated with SRTM4.1 (Jarvis et al., 2008) for all models.

The time effort for the computation depends highly on the refining rate and therefore on the number of grid cells which are included in the model. In order to keep the computational effort as low as possible and the accuracy as high as necessary, three nesting steps were realized. The overall model (48.123 cells) spans from Barbados in the east to approximately the western coast of Haiti in the west. The northern boundary lies on the latitude of Puerto Rico and the southern on the latitude of Valencia (Venezuela). The second model covers the ABC Islands Aruba, Bonaire and Curaçao and spans to the Isla los Roques in the east (51.000 cells). The third one finally covers Bonaire and its satellite island Klein Bonaire off the western shore (300.000 cells).

Because of the relative coarse grids which are used in the overall and secondary model, the computational time is comparatively short with less than 20 minutes. Due to the increased refining rate for the third model, the computation time increases. For the Bonaire model (second nesting step) the simulations finally run approximately 30 minutes on a common four core PC.

3.2 The 1900 Macuto Scenario

One of the first modelled scenarios is a tsunami triggered by an earthquake which occurred on 10/29/1900 off the coast of Venezuela at Macuto. The earthquake occurred in a depth of 25 km with an estimated magnitude of 8.4. At Puerto Tuy (located 121 km from the epicenter) run-ups up to 10 m occurred in consequence (NOAA, 2014).

The distance between the epicenter of the earthquake and the coast of Bonaire is approx. 170 km. Figure 2 displays the time step at which the highest water level at Bonaire is modelled. Approximately 35 min after the initial earthquake the tsunami reaches Boka Olivia in northeastern Bonaire with localized wave heights between 1.5 and 2.2 m, exactly where boulders of up to 150 t were documented on top of the elevated carbonate platform. However, it is to be noted that wave heights of this historical scenario are assumed not to be sufficient to transport these clasts (Engel & May, 2012). Furthermore, at other potentially tsunami-affected sites, such as Spelonk, Boka Bartol, or Saliña Tam, no significant run-up could be obtained.

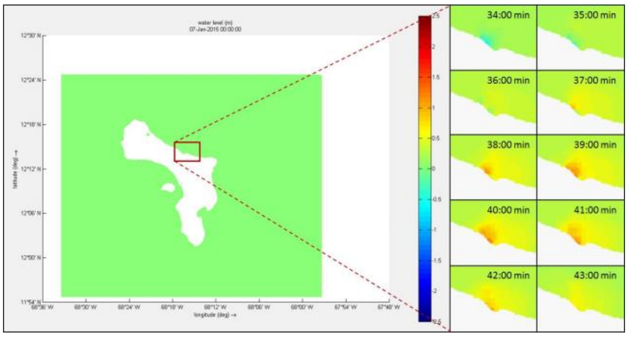

Figure 2: Highest simulated wave impact on Bonaire for the 1900 Macuto Scenario. The maximum occurs at 40:00 minutes.

4 Outlook

In the next working steps we want to include tsunami-induced boulder transport into a unified numerical two-phase model (e.g. Pudasaini, 2012; 2014). The advantage of such a model will be the adequate replication of the boulder transport in a two-phase flow, which occurs during a tsunami, mainly as the tsunami and water waves approach the coastline and their subsequent inland wave run-up. To achieve this and as demanded by Sugawara et al. (2014), the model will account for sediment entrainment in variable grain sizes during the run-up and the inherent variability of flow densities and associated forces. This will include the dynamically evolving drag and impact forces. Additionally, we enhance the existing boulder dataset of Engel & May (2012) by applying the 'Structure from Motion' (SFM) (e.g. Westoby et al., 2012) technology for the development of 3D boulder models from common photographs. According to first results, the volume of the largest boulder documented at Boka Olivia (BOL 2) amounts to c. 77 m³ (Figure 3) and, thus, was underestimated by Engel & May (2012).

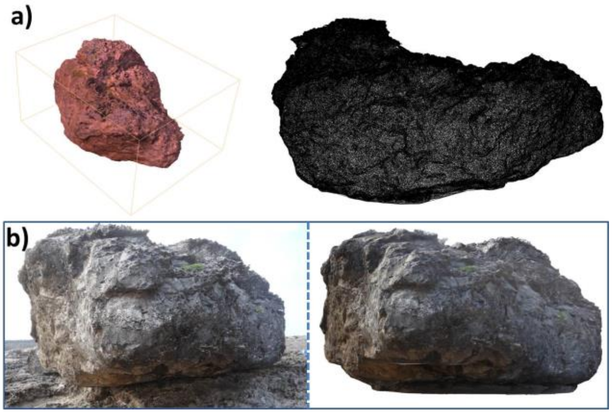

Figure 3: Perspective view and wireframe model of the numerical 3D Boulder BOL 2 (a). Comparison between an original boulder photography and the corresponding numerical model (b).

As Nandasena & Tanaka (2013) stated, experimental validations of numerical boulder transport models were often neglected in previous studies. We will validate the enhanced two-phase model by performing suitable experiments in a wave and current flume at the Institute of Hydraulic Engineering and Water Resources Management (RWTH Aachen University). Therefore, we will create scaled plastic models of the numerical 3D boulder in order to reproduce natural conditions more accurate than in previous flume experiments (e.g. Nandasena & Tanaka, 2013). Furthermore, the validation will be performed with variable relevant boundary conditions and other important fluid dynamical and frictional numbers including different Froude numbers, bottom friction or degree of submergence (cf. Weiss & Zainali, 2014).

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