Large-Scale Modelling of Hydro- and Morphodynamics Associated with Reef Platform and Island Systems

Gerd Masselink[1](✉), Floortje Roelvink[1,2], Samuel T. Rose[3], Marion Tissier[4], Suzanna Zwanenburg[2], and Madelief Doeleman[2]

[1] University of Plymouth, Plymouth, UK
gmasselink@plymouth.ac.uk
[2] Deltares, Delft, The Netherlands
[3] University of Bath, Bath, UK
[4] Delft University of Technology, Delft, The Netherlands

Abstract. Hydro- and morphodynamic processes associated with reef platform and island systems are complex and challenging to measure under the energetic conditions that are commonly associated with significant island change. Numerical models of reef platform hydrodynamics are well developed and widely applied to predict the impact of sea-level rise (SLR) on future flood risk and island habitability. Morphodynamic modelling of atoll island response to SLR is much less well developed, partly due to a lack of suitable observational hydrodynamic and morphological data of island overwash required for developing a robust modelling capability. Hence, such modelling is largely based on uncalibrated models. Here, we describe a large-scale experiment in the Delta Flume where a 1:3 scale reef platform and island system was constructed out of concrete and sand, and subjected to a range of sea-level and wave conditions. It was found that the cross-platform changes in the hydrodynamics (wave energy dissipation, low-frequency wave energy, wave setup, wave runup) were represented very well by the 1D XBeach-NH model. During physical model simulations with SLR, the island was found to more or less keep pace with the rising sea level through overwash-induced deposition.

Keywords: Atoll Islands · Physical modelling · Overwash · Sea-Level Rise

1 Introduction

Atoll islands are considered amongst the world's most vulnerable environments to climate change as enhanced flooding due to sea-level rise (SLR) is expected to make most of them uninhabitable by 2050 [1]. However, island flooding can also result in overwash-induced deposition that increases island elevation and freeboard [2], and this may make the islands more resilient to SLR.

We presently do not have a robust modelling capability to investigate the future evolution of atoll islands due to SLR and this makes it difficult to design and evaluate

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climate adaptation strategies for these islands. The general approach is to ignore any morphological consequences of island flooding and only conduct hydrodynamic modelling. The challenge of long-term modelling of atoll island evolution due to SLR is that there is a paucity of data on overwash hydro- and sediment-dynamic processes to develop such models. To address this gap, a 1:3 scale model of an atoll island and reef platform was constructed in the Delta Flume, Netherlands, and subjected to a range of wave and water level conditions.

2 Experimental Set-Up

The large-scale validation tests were performed in Deltares' Delta Flume, which has a length of 300 m, a depth of 9.5 m and a width of 5 m. A 110-m wide 'reef platform' with a steep 'fore reef' was constructed out of sand capped with a 10-cm layer of concrete (Fig. 1). The fore reef was located 90 m from the wave board and had a slope of 1:4.5. The elevation of the platform' was 5 m above the flume floor. A 60-m wide 'atoll island' was created on top of the platform. The island consisted of a 1-m layer of fine sand ($D_{50} = 0.25$ mm) and its maximum elevation was 6 m above the flume floor. The island was placed on top of the platform with 45 m and 10 m of exposed platform at the front and the back of the island, respectively. At the back of the island was a 'lagoon' that drained in a reservoir by means of an adjustable weir. The weir was adjusted to the height corresponding to the 'ocean' water level in front of the island. Water draining landward into the lagoon during the testing, e.g., through overwash or groundwater seepage, thus flowed into the reservoir where the data collected by a pressure sensor was used to derive the associated discharge.

The main instrumentation deployed during the testing included: 24 pressure transducers (PTs) for measuring water levels, 12 electromagnetic current meters (EMCM) for recording mean and wave-driven currents, including overwash flows, 7 LiDAR scanners for measuring complete water surface elevation profiles across the reef/island systems, as well as the island morphology, 3 CCTV cameras for recording wave runup and overwash characteristics and 3 Optical Backscatter Sensors (OBS) for measuring suspended sediment concentrations.

The maximum significant wave height that can be generated at the Delta Flume is 2.0 m, but due to the limited water depth during the testing (5–6 m), the maximum significant wave height was 1.5 m. In all tests, the wave field was forced with a JONSWAP spectrum. The wave board is equipped with an Active Reflection Compensation (ARC) to ensure waves reflected from the reef platform/island model are not re-reflected towards the model. Second-order wave generation was used in all tests, meaning that in addition to the random incident waves, a bound long wave associated with wave groupiness is also generated at the wave board.

3 Test Conditions

The experimental test series consisted of 3 months of testing, divided into three phases:

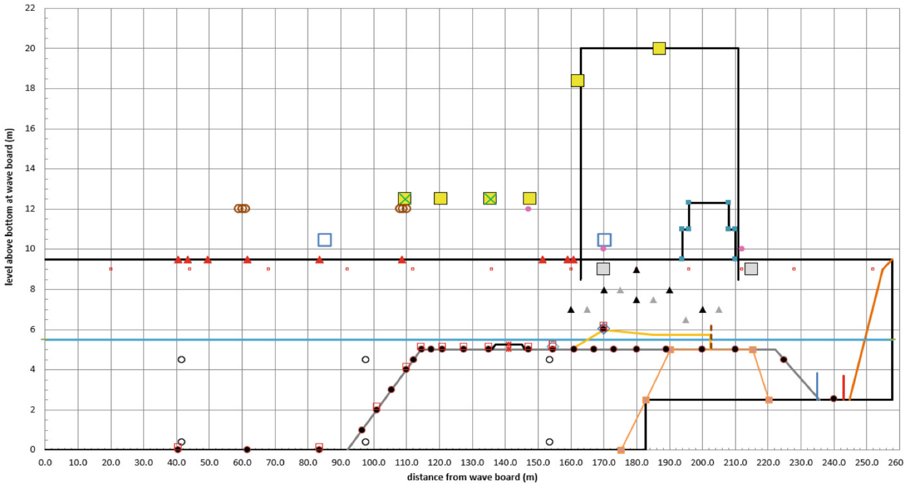

Fig. 1. Cross-section through the Delta Flume model: red triangles = wave gauges; yellow squares = LiDAR; grey squares = cameras; red squares = current meters; black dots = pressure sensors; black triangles = GCPs; blue horizontal line is default sea level; orange line = atoll island; black line = reef platform.

1. **TS1:** Hydrodynamic tests to measure wave transformation across the platform and runup on the island. Tests were conducted with and without artificial reef structures (Fig. 2) on the platform.
2. **TS2:** Morphodynamic calibration tests to identify different morphological response regimes (erosion, collision, overwash, inundation), also with and without artificial reef structures.
3. **TS3:** Sea-level rise morphodynamic tests to investigate the morphological response of the island to slowly increasing water levels

During **TS1** and **TS2**, the influence of artificial reef structures on wave transformation processes and island evolution was investigated. Two types of reef structures were deployed on the reef platform (Fig. 2 shows one type). During **TS1** an elevated berm (2.25 m above the platform) covered with geotextile cloth was added to the island to prevent overwash and morphological change, but during **TS2** and **TS3** the island is allowed to evolve and frequent reshaping will ensure that different forcing conditions start with the same island morphology.

Wave conditions used during the testing were based on an analysis of the modelled wave climates in the Maldives and the Pacific (and applying 1:3 Froude scaling). From the full wave climate at both sites, 11 representative wave conditions were extracted and these were used during the simulations. The most energetic wave condition modelled was $H_s = 1.5$ and $T_p = 5.77$ s.

During **TS1** and **TS2**, only a few sea level conditions were used, representing water depths across the reef platform of 0.17, 0.33, 0.50 and 0.67 m. During **TS3**, the sea level was increased from 0.33 m to 0.67 m in 1- or 2-cm steps per hour. These SLR simulations lasted a full week.

Fig. 2. Deployment of more than 100 artificial reef structures on the reef platform (see [3] for a description of the reef restoration runs).

4 Results

The measured cross-reef variation in mean sea level and significant wave height was compared with that modelled by a 1D XBeach-NH model during one of the **TS1** runs with a still water level of 0.33 m and offshore waves characterized by $H_s = 1$ m and $T_p = 7.51$ s (Fig. 3). The numerical model was run for two different bed roughness values ($C_f = 0.01$ and $C_f = 0.001$), both representative for smooth surfaces. The dissipation of incident wave energy across the reef platform, the wave setup profile and the increase in very-low frequency energy is reproduced very well by the numerical model in both cases, but the landward increase in infragravity energy is best modelled with the lower value of C_f.

Figure 4 shows the results of a SLR simulation conducted during **TS3**. During this run, sea level increased by 2 cm per hour and a total SLR of 0.34 m was achieved over 18 × 1-h runs. Whole-island accretion of c. 0.2 m occurred as a result of overwash. In addition, the front of the island retreated by c. 10 m and the lower part of the beachface became flatter. The crest of the island (the highest point) only accreted by a few cm. It could thus be inferred that despite the overwash-induced accretion, the island was losing freeboard and could not keep up with rising sea level. This is only partly confirmed by the time series of island overwash, where it can be seen that for the same wave forcing (same colored symbols in the right panel), overwash discharge only moderately increased during the SLR simulation.

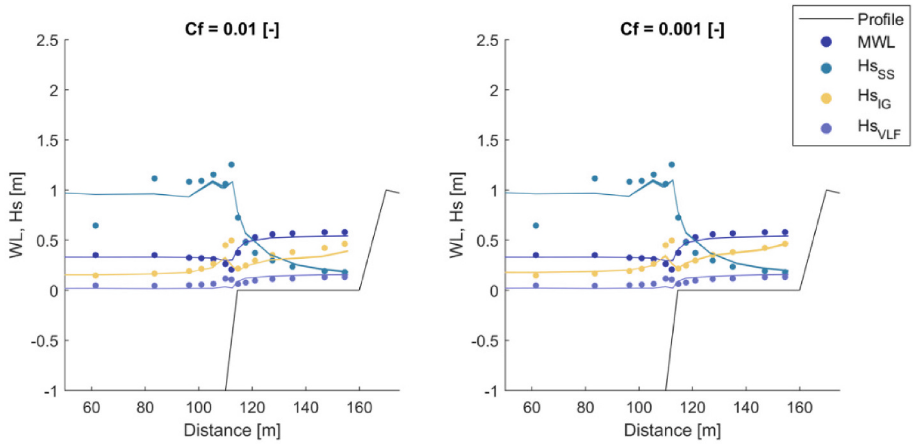

Fig. 3. Cross-reef variation in measured and XBeach-modelled mean sea level (WL) and significant wave height (H_s). Left and right panel show numerical model results for Colebrook-White roughness $C_f = 0.01$ and 0.001, respectively. Symbols and lines represent measurements and model results, respectively. Different colors represent (from top to bottom): grey blue = incident wave height; dark blue = mean water level; orange = infragravity wave height; and light blue = very-low- frequency wave height.

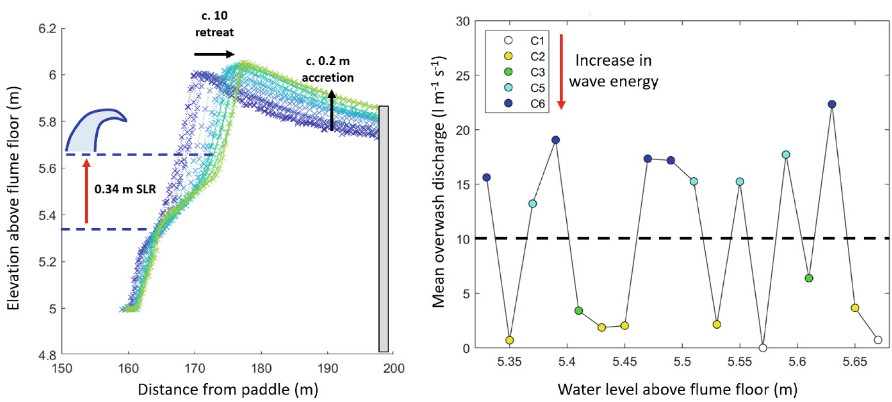

Fig. 4. Island development (left panel) and mean overwash discharge at the island crest (right panel) for one of the SLR simulations during **TS3** with the rate of sea-level rise set to 2 cm per hour. The colors in the left panel represent a progression in time from blue to green. In the right panel, the overwash discharge represents hourly averages and the different colored symbols represent different wave conditions, with wave energy increasing from C1 to C6.

5 Conclusions

A unique data set on reef platform wave transformation and atoll island dynamics was collected at the almost proto-type scale (1:3) in the Delta Flume. So far, the wave transformation across the reef platform is produced very well with a 1D XBeach-NH model using a smooth bed. The next steps are to extend the comparison to the measurements of runup and overwash discharge. The real challenge will be to reproduce the observed island development with a morphodynamic model. Such model can then be used to investigate long-term atoll island development in response to sea-level rise.

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