Impact of Sea Level Rise on Overtopping, Wave Load, and Erosional Power: The Case of The Glass Window Bridge, Eleuthera, The Bahamas

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Abstract

The Glass Window Bridge Located in Eleuthera, The Bahamas, is the only bridge connecting Eleuthera's northern and southern mainland, facing the Atlantic Ocean to the east and the Great Bahama Bank to the west. This bridge is under constant threat from hurricanes and large swells in the Atlantic Ocean. The existing bridge has been subject to severe damage arising from wave impact forces since its construction. In addition, severe overtopping of the cliffs near the Glass Window Bridge causes damage to the roads and severe erosion, that over the years has created unique geologic features. As the global climate warms and sea level rises (SLR), coastal areas will be subject to more extreme flooding and intense hurricanes. Therefore, assessing the impact of potential SLR on the GW bridge and guiding bridge wave mitigation measures are of crucial need. A 3D Digital Terrain Model (DTM) of the bridge site and adjacent ocean bathymetry is constructed from satellite data. This study develops a multiphase computational fluid dynamics (CFD) model based on the DTM to study the impact of wave-breaking for three major historical storm events, and for three different estimates of SLR for the year 2100. Our results suggest that, due to SLR, the islands are subjected to increased overtopping, which occurs even during normal wave conditions. Notably, nonlinear increases in wave splash extent and wave-induced bridge loads are observed as SLR increases. Our results indicate that SLR additionally magnifies the erosional energy, accelerating further changes in the geological features of the island.

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Introduction

The Glass Window Bridge Located in Eleuthera, The Bahamas, is the only bridge connecting Eleuthera's northern and southern mainland, facing the Atlantic Ocean to the east and the Great Bahama Bank to the west. This bridge is under constant threat from hurricanes and large swells in the Atlantic Ocean. Previous research at this site has shown that due to these strong swells and overtopping processes throughout history, unique geologic features can be observed today[1]. These strong swells have been shown to displace large boulders at this site.

Figure 1 : A) shows the aerial view of Eleuthera, with the Great Bahama Bank to the left and Atlantic Ocean to the right. B) shows an aerial close-up of the Glass Window Bridge. C) shows the overtopping and spray generation during normal wave conditions.

Research Objective

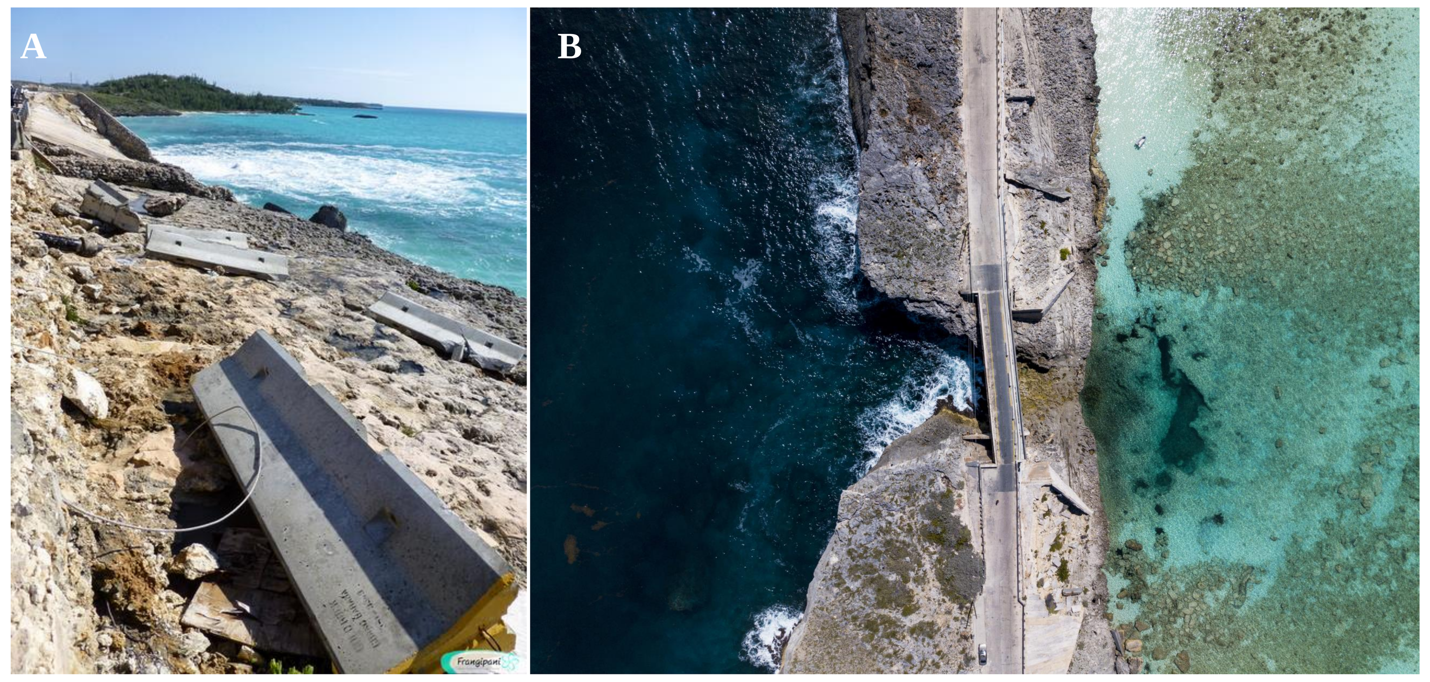


Figure 2 : A) depicts the damage caused by the Perfect Storm of 1991, wherein the roads were toppled into the Great Bahama. B) depicts the aerial image of the 12 feet westward displaced bridge

Storm	Historical Storms	Wave Height (m)	Time Period (s)	Sea-Level Rise (mm/yr)
Storm 1	Hurricane Sandy 2012	9.5	11	0 2.5
Storm 2	Hurricane Andrew 1992	7.5	12	5 7.5
Storm 3	Perfect Storm 1991	4.7	17	10

- The existing bridge has been subject to severe damage arising from wave impact forces since its construction. In addition, severe overtopping of the cliffs near the Glass Window Bridge cause damage to the roads and pose a threat to vehicles traversing the site. The Perfect Storm of 1991 displaced the GWB by twelve feet westward toppling a lane of traffic.
- Although the damaged section of the bridge has been fixed, its **complete reconstruction** is being currently planned.
- Our main objective is to quantify the **overtopping volume and the wave loads** hitting the islands that contribute to long term geomorphological changes.
- Three historical storms that affected these Islands will be studied.
- The effect of **Sea-Level Rise** is considered to understand the future trends in overtopping volumes and wave loads.

Methodology

- A 3D model of the bridge site is constructed with a Digital Terrain Model (DTM) obtained from satellite-derived data, along with satellite-derived bathymetry. The model is dissected into four regions of interest to save computational time: a) Section 1 b) Section 2 c) Section 3 d) Section 4.
- For this application we use a multiphase solver, due to the importance of both air and water in wave breaking phenomenon.
- The current problem statement is multi scale:
  1. Large flow structures within fluid flow (system scale)
  2. breakup and coalescence processes (meso scales)
  3. Motion and interaction of particles (micro scales)
- We use an OpenFOAM solver → interIsoFoam (Volume of Fluid Method (VOF); viz. Eulerian-Eulerian approach) coupled with an open-source wave generator tool → waves2Foam[2]
- To accurately predict the wave breaking and spray generation processes, the *k-ω* SST turbulence model was used. Since the standard OpenFOAM turbulence model does not use variable-density incompressible turbulence models, I coupled a variable density turbulence model[3] to interIsoFoam to accurately compute the above processes.
- Grid size of 3 cm (1 liter) for 2D simulations and 40 cm (64 liter) for 3D simulations.

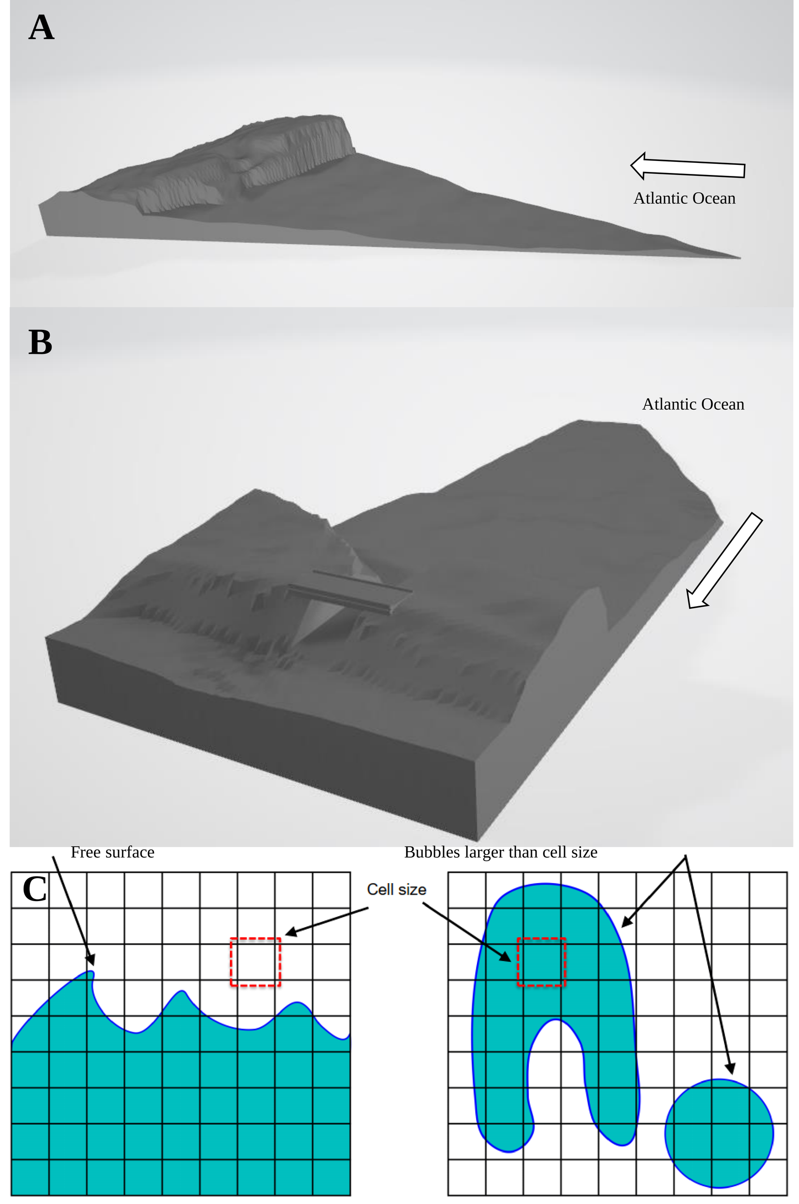
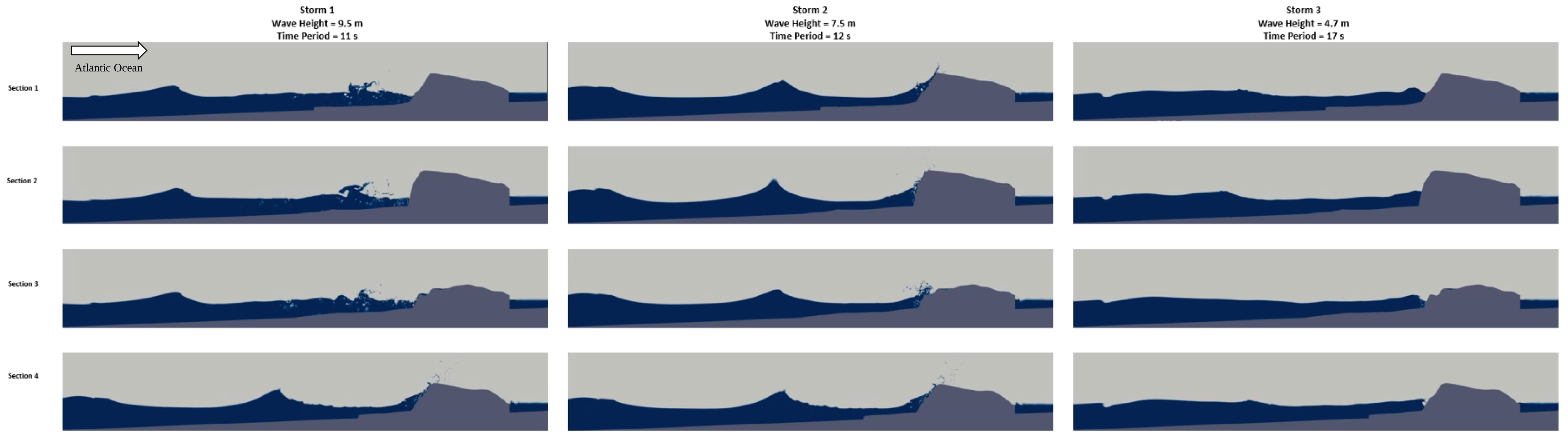
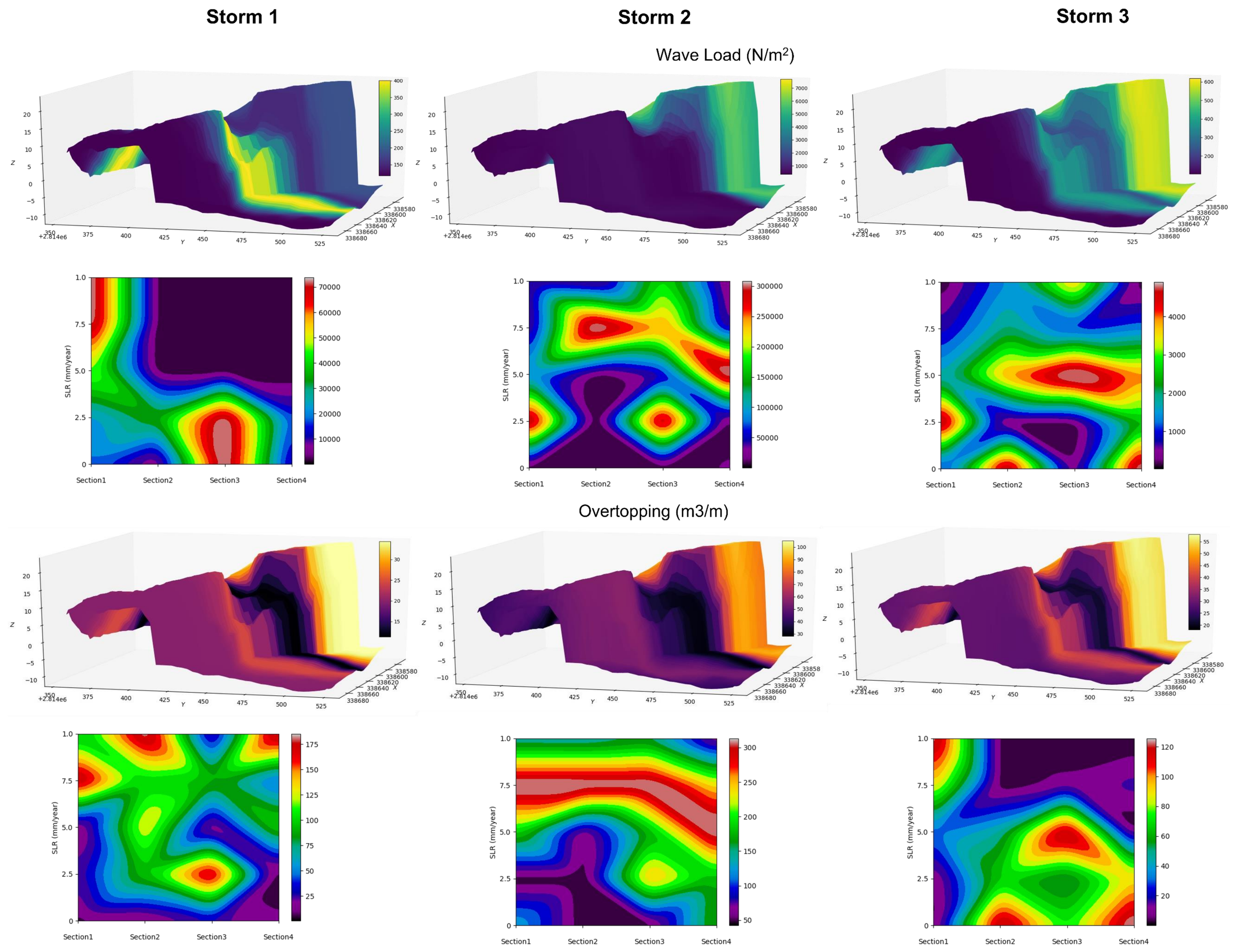


Figure 3 : A) shows the DTM of the Landform site with the Atlantic Ocean depicted. B) shows the DTM of the Bridge site. C) shows the Volume of Fluid (VOF) approach used to solve the multi-scale and multiphase problem.

Results and Conclusions





- From our study, we see that, at current sea levels the Storm 1 causes considerable **wave loading** on Section 3 due to intense wave breaking phenomenon at the location.
- Storm1, 2 and 3 are seen to cause significant overtopping at Section 1 and 2. This can be observed as the huge amount of spray being generated to the wall-like cliffs (at Section 1 and 2).
- The SLR study shows that different storms react to the increase in mean sea level in different ways.
- All storms cause increased overtopping on the all the four cross-sections as SLR increases.
- The wave loading characteristic for the different storms also show a sharp increase as SLR increase.
- The above changes are attributed to the increase in water level, which causes the waves to break closer to the island (than further offshore), thus causing a sharp increase.
- This study gives overtopping rate estimates for drainage system design considerations for the new roads.

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