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INFLUENCE OF SEA LEVEL RISE ON A COASTAL BARRIER SYSTEM AND ITS RELIABILITY AGAINST FUTURE STORM SURGES IN THE HOUSTON-GALVESTON AREA, TEXAS

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ABSTRACT

The Ike Dike is a concept of coastal barrier system designed to protect the Houston-Galveston area (HGA), which is highly susceptible to flood risks from storm surges. The barrier system has been proposed with different alignments and configurations: movable, permanent, and extended permanent barrier systems. We have evaluated and compared the feasibility of three barrier types as a function of sea level rise (SLR), taking into account the reliability of the movable barrier. We employ the Delft3D Flexible Mesh suite to simulate storm surges in a hydrodynamic model, incorporating pressure and wind velocity fields spatialized by the Holland's model from synthetic storm tracks. Simulations are driven by a range of SLR projections and synthetic storm tracks, with different barrier types. Probabilistic flood depths are predicted for specific return periods by fitting the 30-year maxima flood depths from the simulations to a probability distribution function. Using the CoreLogic database of residential properties in the HGA and building damage functions, we calculate probabilistic flood damages for each predicted flood depth. This allowed us to quantify flood risk as the expected annual damage, integrated over a range of return periods. Our results indicate that the permanent and extended permanent barrier systems are more effective at mitigating storm surge risk than the movable barrier system. Moreover, the necessity of the extended permanent barrier system becomes more significant as SLR increases.

Keywords: *"Coastal Barrier System", "Sea Level Rise", "Reliability of Barrier", "Storm Surge Simulation", "Synthetic Storm Tracks"*

1. Introduction

Since Hurricane Ike struck the Houston-Galveston area (HGA) in 2008 and caused damages to this region, an Ike Dike concept has been proposed as a coastal barrier system to protect the HGA from future storm surges. This barrier system was planned to construct seawalls along the coastlines from the west end of Galveston Island to High Island, as well as the floodgates at the mouth of Galveston Bay (Merrell et al., 2011). Jackson State University (JSU) examined the effects of several alignments of the Ike Dike, with varying span of the coastal barrier (Ebersole et al., 2018; USACE, 2021).

2. Coastal Barrier System

2.1. Movable Barrier System

A configuration of a movable barrier system is based on the USACE's Galveston Bay Storm Surge System. The system consists of a gate system, beach and dune systems, a ring barrier system, and Galveston seawall improvements. The Bolivar Roads Gate System, the main component of this system, features navigable sector gates, vertical lift gates, and shallow water environmental gates across Bolivar Roads. Under normal conditions, the gates remain open to allow vessel navigation and continuous tidal flow and drainage. However, when a storm surge is forecasted to exceed a specific trigger water level at the entrance of Galveston Bay, the gates are closed. The beach and dune systems are comprised of dual dunes extending along the western coast of Galveston Island and the Bolivar Peninsula. The ring barrier system encircles the eastern portion of Galveston Island with a seawall, and the existing Galveston seawall will be raised up. The schematic illustration of the Galveston Bay Storm Surge System and the conceptual design of the Bolivar Roads Gate System are shown in **Fig. 1** (USACE, 2021).
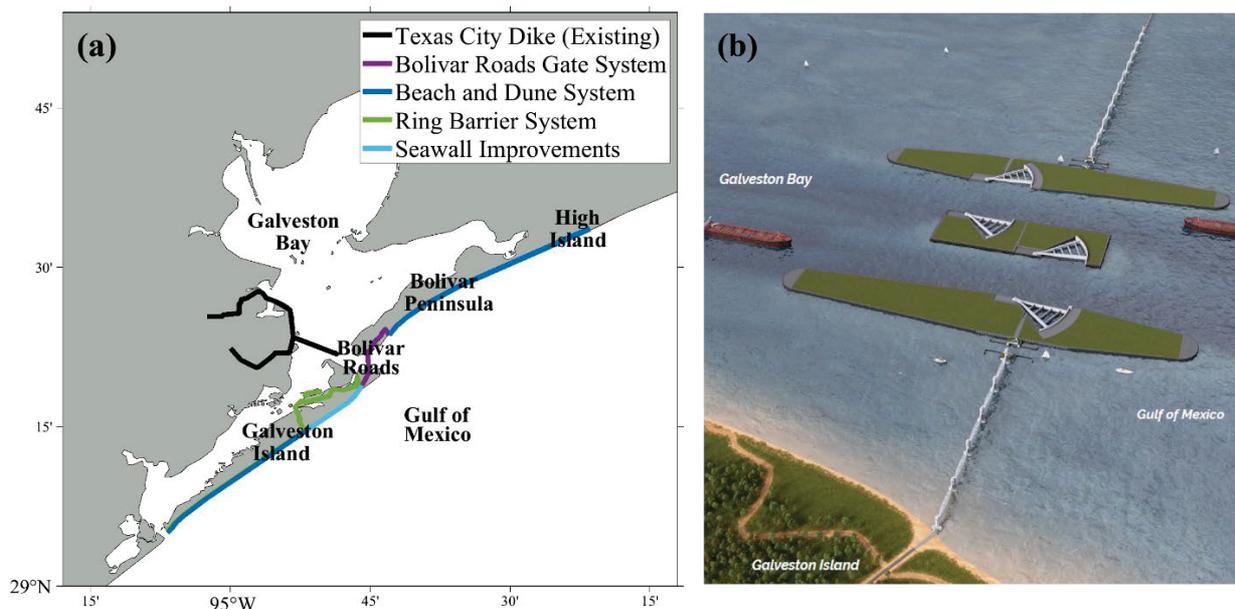

Fig. 1. (a) Schematic illustration of the Galveston Bay Storm Surge System; (b) conceptual design of the Bolivar Roads Gate System (USACE, 2021)

As the mean sea level rises in the future, the storm surge gates of the barrier system will need to close more frequently, leading to an increase in chance of failure of closure due to structural, mechanical, technical, or human errors (Chen et al., 2020; Mooyaart et al., 2017). By analyzing the probability of closure failure, we quantify the reliability of the movable barrier in relation to sea level rise (SLR) and trigger water level. The annual probability of closure failure is determined based on the gate closure frequency, defined as the number of storm events per year in which the surge exceeds the trigger water level at the entrance of Galveston Bay.

2.2. Permanent Barrier and Extended Permanent Barrier Systems

A permanent barrier system is a dam, akin to a coastal barrier system with storm surge gates that are permanently closed, ensuring perfect reliability. This type of barrier becomes necessary if the movable gates need to be closed too frequently due to significant SLR, resulting in high operational and maintenance costs. However, permanently closing the gates at the entrance of Galveston Bay would require expensive and slow-to-operate shipping locks to facilitate navigation, in addition to drainage pumps, especially if the bay is to be maintained at a lower water level than the mean sea level outside the dam, and incur significant environmental effects by removing tidal exchange of salt water.

Given significant SLR, of the coastal barrier system proposed by the USACE may not be sufficient to protect the HGA, as the low-lying coastal areas would be submerged and more susceptible to inundation from future storm surges. A concept of an extended permanent barrier system was proposed by JSU, extending the western section of the barrier inland to Freeport and the eastern section inland to High Island (Ebersole et al., 2018). This configuration also includes closing a passage of water to the west of Galveston Island, thereby preventing storm surges from entering the bay. Despite its effectiveness in mitigating storm surges, the extended permanent barrier system would demand significantly higher construction and maintenance costs compared to the movable and USACE permanent barrier concepts.

We compare the feasibility of movable, permanent, and extended permanent barrier systems by compensating the benefits of coastal flood risk mitigation against the construction, operation, and maintenance costs with SLR scenarios. **Fig. 2** illustrates the alignments of the three proposed coastal barrier systems for the HGA.
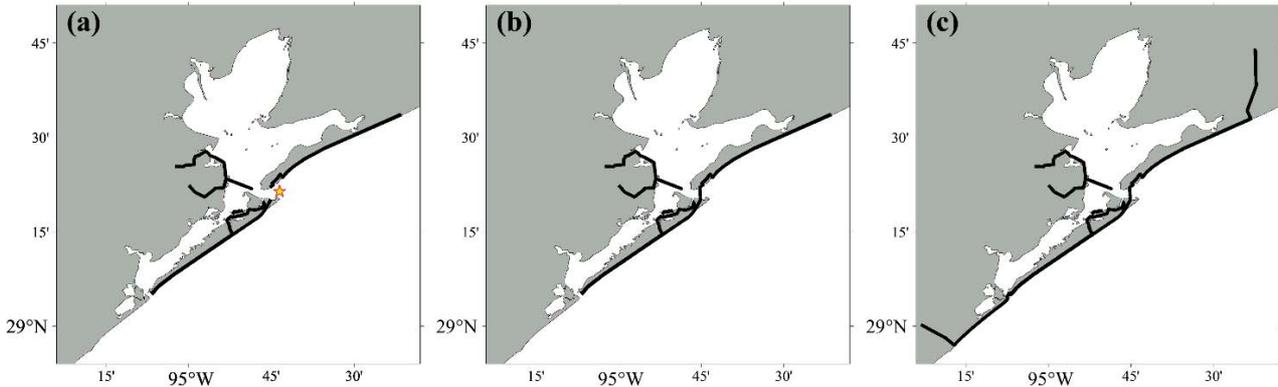

Fig. 2. Alignments of the coastal barrier system on the Houston-Galveston area: (a) movable barrier system when the gates are open with a marker of a water level observing point; (b) permanent barrier system; (c) extended permanent barrier system

3. Model Setup and Validation

3.1. Hydrodynamic, Wave, and Hurricane Models

We utilize the Delft3D Flexible Mesh (D-Flow FM) suite as a hydrodynamic model to simulate storm surges and integrate it with the Simulating Waves Nearshore (SWAN) spectral wave model to capture wave dynamics interacting with current flows. The model domain covers the northwest Gulf of Mexico with a grid of varying resolutions – finer resolution in the HGA and coarser further offshore. We use 15-arcsecond bathymetry data for global bathymetry and 1-arcsecond topography data for high-resolution topography (GEBCO, 2023; NOAA, 2023). The Manning's n coefficients of Dewitz (2003) are applied to represent roughness variations based on land cover classifications, and air-sea drag coefficients of Zweers (2010) are used to simulate storm surge effects from wind speed. We also use the Holland (1980) model to convert hurricane track data into spatial pressure and wind velocity fields, which are applied as meteorological boundary conditions in D-Flow FM.

The models are validated against water levels, wind speeds, pressures, significant wave heights, and peak periods observed at NOAA tide stations or a wave buoy around Galveston Bay during Hurricane Ike. Relative root-mean-square error and R-squared values evaluate the models' performance, demonstrating strong agreement between the simulated and observed data.

3.2. Synthetic Storm Tracks

To simulate present and future storm surges, we use sets of synthetic storm tracks that are statistically downscaled from the Hadley Centre Global Environmental Model (HadGEM), a CMIP6 general circulation model provided by WindRiskTech (Emanuel et al., 2008). HadGEM generated 150 storm tracks for each year from 1981 to 2010 under 20th century climate conditions, and 150 tracks for each year from 2071 to 2100 under the very high greenhouse gas (GHG) emission scenario outlined by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2023).

3.3. Relative Sea Level Rise

Relative SLR is estimated as the cumulative effect of global SLR and regional SLR, projected by the IPCC (2023) and Sweet et al. (2022), respectively. As a result, the relative SLR scenarios for the year 2100 are constructed as 0.99 m (scenario 1), 1.08m (scenario 2), and 1.17 m (scenario 3). In addition, to represent the mean sea level around the mid-21st century, a scenario of 0.5 m (scenario 0.5) is also constructed. These SLR projections serve as initial and boundary conditions for mean sea level in the D-Flow FM. Simulations without sea level rise or with scenario 0.5 m are conducted using synthetic tracks under present climate conditions, whereas synthetic tracks are simulated with SLR scenarios 1, 2, and 3 for future climate conditions.

4. Flood Risk Estimation

4.1. Probabilistic Flood Depth Predictions

Using 30-year annual maximum flood depths produced from storm surge simulations for each scenario, we generate probabilistic flood maps for specific return periods through extreme value analysis. The generalized extreme value (GEV) distribution is employed as the probability distribution function to fit the flood depths at each grid cell using the maximum likelihood estimation method, to predict the probabilistic flood depths for specific annual exceedance probabilities.

4.2. Property Damages and Flood Risk

To analyze the total flood damage to residential properties in the HGA, we utilized data on the locations and assessed values of residential properties from the 2021 CoreLogic, Inc. database. The dataset includes approximately 1,380,000 properties in Harris and Galveston Counties, Texas. Each property is matched to its corresponding probabilistic flood depth, and a damage ratio is computed using several residential building damage functions (Xu, 2023). By multiplying the property values by the damage ratio, we calculate the flood damage for each property, which allows us to estimate the total flood damage in the study area. Finally, flood risk is quantified as the expected annual damage, which is the hazard-weighted damages over a range of return periods from simulated storm scenarios (Arnell, 1989).

Flood risk is estimated for each SLR scenario with different types of barrier systems. The simulation results indicate that permanent and extended permanent barrier systems are much more effective at mitigating flood risk from storm surges compared to the movable barrier system. Furthermore, as SLR becomes more pronounced, the extended permanent barrier system demonstrates better performance relative to the permanent barrier system, emphasizing its importance in the future.

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