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Risk Assessment of Coastal Infrastructure Considering Uncertainty in Coastal Forcing and Weather Pattern Impact

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16. Abstract

Sea level variability and intense storm surges present a critical challenge for coastal regions, increasing the risk of wave overtopping and subsequent flooding, with severe implications for public safety, infrastructure, and economic stability. This study develops a comprehensive data-driven stochastic modeling framework integrated with reliability analysis to enhance risk assessment for coastal infrastructure under variable weather-related scenarios. The framework addresses two key objectives: (1) accurately predicting variable sea water levels at critical coastal locations using a stochastic model informed by weather and condition data, enabling proactive planning and risk mitigation, and (2) conducting a quantitative risk assessment of wave overtopping through a reliability-based approach, offering a predictive warning system vital for strategic coastal defense. Additionally, the study incorporates factors such as land subsidence and seawall settlement into the analysis, assessing their impact on the long-term structural reliability of coastal defenses. The Galveston seawall in Texas serves as the test bed for model evaluation, demonstrating its applicability and robustness in real-world scenarios. The findings contribute valuable insights into the design and optimization of resilient coastal protection systems, providing practical tools to address the dual challenges of structural integrity and public safety in the face of weather and condition-induced uncertainties.

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RISK ASESSMENT OF COASTAL INFRASTRUCTURE CONSIDERING UNCERTAINTY IN COASTAL FORCING AND WEATHER PATTERN IMPACT

FINAL REPORT
SPTC Project Number: CY1-TAMU-02

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List of Abbreviations and Acronyms

PoF .... Probability of Failure
GPR .... Gaussian Process Regression
SWL .... Sea Water Level
MSL .... Mean Sea Level
USACE .... U.S. Army Corps of Engineers
NOAA .... National Oceanic and Atmospheric Administration
RBF .... Radial Basis Function
MLLW .... Mean Lower Low Water
NAVD88 .... North American Vertical Datum of 1988
MSE .... Mean Squared Error

Executive Summary

Coastal regions are vulnerable to the impacts of adverse weather patterns and conditions, including variable sea levels and intense storm surges. These phenomena pose significant threats to infrastructure, ecosystems, and communities, particularly through wave overtopping events that result in hazardous flooding. This project addresses these challenges by developing a novel, data-driven stochastic modeling framework to enhance risk assessment and support decision-making for coastal infrastructure resilience.

The framework integrates stochastic modeling techniques with reliability analysis to provide accurate predictions of variable sea levels and wave overtopping risks. By combining historical data, weather pattern and condition projections, and other factors, the model quantifies the probabilistic risks posed by variable sea levels and extreme weather events. Additionally, it incorporates critical deterioration factors, such as land subsidence and seawall settlement, which are often overlooked in traditional risk assessments.

A key contribution of this research is the development of a reliability-based forecasting and warning system that informs proactive coastal defense strategies. The system facilitates early interventions and enhances the design of resilient coastal protection structures, ensuring their structural integrity under various uncertainty scenarios. The Galveston seawall in Texas serves as a test case to validate the model and demonstrate its practical applicability.

This work provides actionable insights for policymakers, engineers, and researchers, enabling informed decision-making to safeguard coastal communities. The framework offers a scalable and adaptable solution that can be applied to other coastal regions worldwide, fostering resilient infrastructure planning.

Chapter 1. Introduction

1.1 Problem Statement

Coastal structures, such as seawalls and breakwaters, play a vital role in safeguarding densely populated coastal regions against storm surges, wave attacks, flooding, and erosion. However, these structures face challenges due to sea level variability and extreme weather events in these areas. The conditions exacerbate hydrodynamic forces, accelerate structural aging and deterioration, and compromise the reliability of coastal defenses. Consequently, ensuring the safety and functionality of coastal structures has become a critical priority (Wang et al., 2024).

Seawalls serve as crucial seashore defense structures, aiming to protect coastal communities from erosion and mitigate sea-induced flooding (Thomas & Hall, 2015). These barriers are strategically constructed to absorb and deflect the energy of incoming waves, thereby reducing the direct impact on inhabited and developed areas. Despite their robust design, weather patterns and conditions, along with sea level variability, challenge their capacity to shield effectively. Thus, evaluating and ensuring the reliability of these structures amid these forces is essential for maintaining coastal safety and resilience. Wave overtopping, a phenomenon where rising sea levels surpass the height of seawalls, undermines the seawalls' protective capabilities against coastal flooding. The inability to defend against wave overtopping can lead to disastrous outcomes, significantly impacting coastal communities and infrastructure through floods or other extreme disasters. The breach of seawalls compromises not only the safety of residents but also disrupts local economies and damages essential infrastructure. If the wave overtopping discharge is higher than the limit of the seawall, the coastal communities will face the risks of large quantities of water and potential flooding (Xie et al., 2019). Maintaining seawall reliability is thus vital for the resilience of coastal infrastructure when sea levels rise and all severe failures come from wave overtopping (Mase et al., 2015).

Current wave overtopping research, experimental or numerical, is valuable in seawall design aiming to reduce wave overtopping, especially under the target scenario. However, challenges arise when it comes to evaluating the performance of seawalls and quantification of the risk of overtopping amid the uncertainty in extreme weather conditions, or under other sea level scenarios. This information is critical for the planning and decision-making process. With great uncertainties, sea levels can be different from the targeted design scenario, and stakeholders and first responders face the challenge of predicting the potential risks and allocating resources. These conditions require the prediction of wave overtopping for the risk analysis of coastal seawalls.

The resilience of coastal infrastructure hinges on addressing both chronic stressors, such as aging and deterioration, and acute hazards, such as extreme storm events. Current approaches to designing and maintaining coastal defenses often rely on deterministic assumptions, focusing on most likely or worst-case scenarios, which fail to capture the inherent uncertainty and variability of coastal forces and structural responses. This limitation is further compounded by the lack of tools and guidelines that integrate chronic stressors with acute hazards into a unified framework for decision-making.

One of the most pressing challenges is wave overtopping, where rising sea levels and extreme wave heights exceed the protective capacity of seawalls, leading to coastal flooding and significant socio-economic disruptions. Although existing overtopping analyses aid in seawall design, they often:

1. Rely on static weather assumptions that do not account for the dynamic effects of weather pattern shifts.
2. Provide limited support for adaptive decision-making during disasters.

To address these challenges, there is a critical need for robust, probabilistic models that incorporate the combined effects of chronic and acute stressors, account for uncertainty in forces and structural capacities, and support risk-informed decision-making. Such models must enable the evaluation of alternative investment strategies, considering long-term performance, maintenance optimization, and economic trade-offs.

A stochastic framework that rigorously characterizes and propagates uncertainties in coastal forcing, structural deterioration, and resilience outcomes is essential. This framework must support the design, maintenance, and management of coastal structures to enhance their reliability and resilience under uncertain conditions. By addressing these gaps, we can better protect coastal communities and infrastructure from extreme weather events.

1.2 Objectives and Scopes of This Study

To assess the resilience of Texas and Louisiana port infrastructure, including seawalls, amid uncertainties tied to coastal forcing and sea-level rise (SLV), this study has three primary objectives:

- Gain insight into the current practices and policies of Texas and Louisiana coastal infrastructure for dealing with extreme weather events;
- Conduct case studies of risk-based lifecycle assessment of coastal infrastructure considering uncertainties in coastal forcing, SLV, and structural stability;
- Utilize research findings to devise strategies that reduce uncertainty, enhance risk assessment, and improve lifetime reliability.

Laying focus on the objectives just stated, the research has been conducted within the scope of the following tasks:

- Task 1: Assessment of Current Practices of Texas and Louisiana Coastal Infrastructure Concerning Shifting Weather Pattern Impacts.
- Task 2: Probabilistic lifecycle reliability assessment incorporating uncertainty in coastal forcing, extreme events, and SLV.

1.3 Organization of the Report

This report is organized into eight chapters, each addressing specific aspects of the study:

- Chapter 1 provides an overview of the report, including the problem statement, objectives, and scope of the study.
- Chapter 2 reviews existing research and methodologies related to wave overtopping discharge, prediction models, and mitigation strategies.

- Chapter 3 details the data-driven techniques employed to predict sea water levels at the seawall location and the reliability assessment of seawall overtopping. The chapter also includes a case study on the Galveston Seawall to demonstrate the effectiveness of the proposed model.
- Chapter 4 presents the results of the sea water level at the critical infrastructure prediction model under various scenarios, incorporating uncertainties, and evaluates the predicted risks of wave overtopping. The chapter also discusses implications for decision-making.
- Chapter 5 summarizes the study's key findings and provides recommendations for future research and development in the field.
- Chapter 6 emphasizes the practical applications and potential of the project outputs, focusing on the effective implementation of the results to address real-world challenges.
- Chapter 7 outlines activities related to technology transfer and community engagement, emphasizing participation and collaboration with stakeholders, such as highlighting the practical applications of the developed prediction tool, and showcasing its potential for real-world use.
- Chapter 8 includes details of publications and presentations.

Chapter 2. Literature Review

2.1 Wave Overtopping Discharge Mitigation Methods

Mitigating wave overtopping discharge has been a focus of extensive research, particularly in exploring various seawall designs and their effectiveness under different conditions (Dong et al., 2024). A range of seawall shapes has been analyzed to evaluate overtopping discharge, providing insights into optimizing design strategies.

For instance, Allsop et al. (Allsop et al., 2005) studied the performance of steep, battered, composite, and vertical seawalls, developing predictive methods for wave overtopping discharge. Similarly, Koosheh et al. (Koosheh et al., 2022) conducted 140 small-scale physical model tests to evaluate the mean overtopping rates for rubble mound seawalls, providing valuable experimental data. Schoonees (Schoonees, 2014) focused on impermeable recurve seawalls, demonstrating how their design can effectively reduce wave overtopping, thereby minimizing the required wall height for adequate protection.

In addition to experimental studies, numerical modeling has been employed to enhance the understanding and prediction of wave overtopping discharge for specific seawall types. Reeve et al. (Reeve et al., 2008) tested numerical methods to establish an empirical discharge formula for impermeable seawalls. Their approach involved solving Reynolds-averaged Navier–Stokes equations, simulating an irregular wave train, and modeling wave breaking and interaction with sloping impermeable walls. Similarly, Hieu and Vinh (Hieu & Vinh, 2012) proposed a numerical model for wave overtopping of seawalls supported by porous structures, highlighting the role of permeability in mitigating overtopping risks.

These studies collectively contribute to a better understanding of seawall performance and provide valuable frameworks for designing more resilient coastal defenses against wave overtopping.

2.2 High-fidelity Models on the Prediction of SLV and Wave Overtopping Discharge

Advancements in forecasting SLV and wave overtopping discharge increasingly rely on high-fidelity numerical models and specialized software. Stokes et al. (Stokes et al., 2021) developed a large-scale high-fidelity model to predict wave runup and overtopping volumes along a 1,000 km coastline in southwest England. This model, which utilized Delft3D with a 1 km resolution for wind and wave simulations, demonstrated strong predictive accuracy for up to three days in advance. However, it required approximately 2.5 hours for a three-day forecast and significant storage resources, highlighting its limitations for extended predictions or real-time applications.

To address these computational and storage challenges, Suh and Lee (Suh & Lee, 2023) proposed a grid-based numerical model tailored for predicting typhoon-induced storm surges and wave overtopping. While their model improved efficiency, it was limited to scenarios involving typhoons with a 100-year return period. Similar to other high-fidelity approaches, the model's reliance on significant computational resources and its narrow application scope restricted its effectiveness for broader, long-term predictions.

In addition to the limitations in generalizability and efficiency, these studies suffer from the drawback of deterministic results. Uncertainties are prevalent in complex coastal conditions, and disagreements persist under extreme conditions, such as unidirectional bimodal sea states (Orimoloye et al., 2021). This means certain conditions may not be considered or even recognized throughout the modeling process. To address this, the present study proposes dividing the complex process into two stages: (1) predicting the sea level at coastal communities, considering various factors affecting the transition from offshore to nearshore, and (2) using these predictions to assess seawall reliability, particularly focusing on wave overtopping discharge and the potential for overtopping failures.

Predicting sea levels is crucial for accurately assessing the risks associated with wave overtopping at seawalls. However, this task is challenging due to the inherent uncertainties in sea conditions, which are influenced by factors like swell and wind waves. These waves are themselves affected by complex coastal dynamics, including the local topography and weather patterns. Even small changes, such as slight seabed variations, can lead to significantly different wave patterns and, consequently, different wave heights at the seawall. While detailed numerical models exist for sea level prediction, they share common drawbacks: inefficiency and high costs (Merrifield et al., 2021). Furthermore, these models are limited to handling a narrow range of scenarios due to their deterministic nature, which restricts their ability to account for the full range of uncertainties. Offshore uncertainties can have a significant impact on sea levels at the seawall, leading to varying overtopping risks. Therefore, a stochastic model that incorporates wave and current process uncertainties is essential for more accurate and timely sea level predictions at the shoreline.

2.3 Existing Methods for Calculating Wave Overtopping Discharge

The EurOtop manual (van der Meer et al., 2018), developed for wave overtopping of sea defenses and related structures, provides numerous empirical equations for calculating wave overtopping discharge based on coastal water conditions. Recent studies have also attempted to propose new equations for wave overtopping discharge, considering assumed sea conditions (Mase et al., 2015) and additional influencing factors, such as wind (Di Leo et al., 2022). Moreover, large database models, such as the CLASH project (Steendam et al., 2005) (Crest Level Assessment of Coastal Structures by Full-scale Monitoring, Neural Network Prediction, and Hazard Analysis on Permissible Wave Overtopping), have been used to predict overtopping based on collected parameters like seawall shape and environmental conditions (De Rouck et al., 2009). For example, Geeraerts et al. (Geeraerts et al., 2007) employed neural networks within the CLASH project to identify relationships among various parameters and ultimately predict wave overtopping.

The EurOtop manual (van der Meer et al., 2018) offers a comprehensive set of equations tailored to the calculation of overtopping and post-overtopping processes for various types of seawalls. It provides detailed guidance for assessing these processes across different coastal structures. For instance, in the case of vertical and steep-fronted structures such as caissons, blockwork breakwaters, and vertical seawalls, the manual categorizes designs into several scenarios to simplify analysis. These scenarios include plain vertical walls, battered walls, composite vertical walls, and walls accounting for the effects of oblique waves, bullnoses or wave-return walls, and perforations. Additionally, it considers factors such as wind effects, scale and model effect corrections, providing a robust framework for accurate and adaptable design assessments.

For example, a definition sketch for plain vertical walls is shown in Figure 1. Based on the analysis of if there is an influence of foreshore, if there is a significant mound present, if there is a likelihood of impulsive overtopping conditions, there will be different equations to calculate the wave overtopping discharge based on the CLASH database formed experience equations.

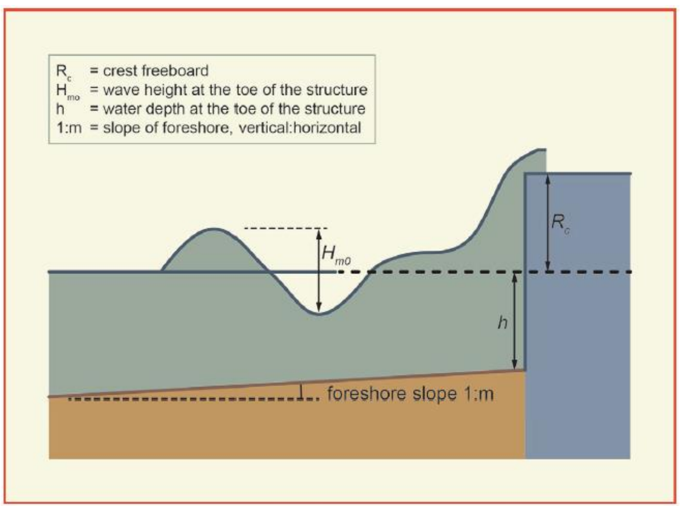

Figure 1. Definition sketch for assessment of overtopping at plain vertical walls (van der Meer et al., 2018)

If taking a mean value approach for no influencing foreshore, wave overtopping discharge will be:

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.047 \cdot \exp\left[-\left(2.35\frac{R_C}{H_{m0}}\right)^{1.3}\right]$$

Where:

q is wave overtopping discharge per linear meter of width

g is the acceleration of the gravity

H_{m0} is wave height at the toe of the structure

R_C is crest freeboard

Equation 1. Wave Overtopping Discharge Calculation for vertical seawall with no influencing foreshore (van der Meer et al., 2018).

For if there are impulsive conditions, the relative depth and wave steepness at the toe of the structure play a role, and this is reflected in the following where a recommended lower non-dimensional freeboard is applied $R_C / H_{m0} < 1.35$:

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.011 \cdot \left(\frac{H_{m0}}{hs_{m-1.0}} \right)^{0.5} \exp\left[-2.2 \frac{R_C}{H_{m0}} \right]$$

Where:

q is wave overtopping discharge per linear meter of width

g is the acceleration of the gravity

H_{m0} is wave height at the toe of the structure

R_C is crest freeboard

h is the local water depth in front of the structure

$s_{m-1.0}$ is wave steepness

Equation 2. Wave Overtopping Discharge Calculation for vertical seawall with impulsive conditions (van der Meer et al., 2018).

Chapter 3. Methodologies

3.1 Introduction

The methodology in this study is based on implementing a data-driven, uncertainty-informed methodology for time-dependent reliability analysis of coastal defense structures. Specifically, the research team conducted an improved time-dependent reliability analysis to more accurately quantify the Probability of Failure (PoF) resulting from wave overtopping discharge. To achieve this objective, the team developed a stochastic, data-driven model for onshore wave prediction, which serves as the basis for quantifying overtopping PoF. The findings from this approach can inform risk-warning systems and enhance coastal resilience.

A key feature of this methodology is the integration of Gaussian Process Regression (GPR) for accurately capturing and predicting the influence of wind waves and swell waves on the uncertain wave height. The approach includes predicting the probabilistic description of the Sea Water Level (SWL) at locations where coastal defense structures are sited, thereby enabling proactive risk mitigation. By incorporating forecasted weather data as an input to the model, the wave overtopping events can be forecasted well in advance. Ultimately, this enhanced predictive capability supports more informed decision-making and the implementation of proactive strategies aimed at safeguarding coastal infrastructure and communities.

3.2 SWL Prediction based on the Components of Water Level

The EurOtop manual provides the calculation of overtopping discharge in terms of the SWL and the wave conditions at the structures (van der Meer et al., 2018). The SWL, denoted as H in Figure 2, is composed of several key components: the Mean Sea Level (MSL) (h), the astronomical tide (H_T), and uncertain waves (H_U) associated with weather conditions, including the effects of wind waves and swell waves, that is $H = h + H_T + H_U$. The MSL reflects the water level when the ocean is calm. The astronomical tide, influenced by the gravitational pull of celestial bodies like the moon, is relatively predictable due to the known positions of these bodies. In contrast, the uncertain waves are more challenging to forecast as they are influenced by various factors including offshore and nearshore weather conditions, seabed topography, and local wind fields. Wind waves can interact with current waves, further complicating predictions. Figure 2 demonstrates how these components collectively determine the SWL at a coastal structure, underscoring the multifaceted factors that must be considered in the design and assessment of sea defense structures. Figure 3 details the formation process of SWL at the seawall, starting with offshore waves ($H_U{}'$). A portion of these waves, known as swell waves, moves toward the nearshore, where they interact with wind and tidal waves, ultimately forming the SWL at the seawall. Since tidal waves change slowly due to astronomical forces, it is assumed that these changes occur along with variations in MSL at a specific time point.

Among the three primary components of SWL, some elements, such as the MSL and tidal waves, can be predicted with relative ease. MSL predictions are based on historical trends over recent decades, and tools like the U.S. Army Corps of Engineers (USACE) Sea-Level Change Curve Calculator offer methodologies for such forecasts. Tidal waves, driven by astronomical forces, are readily available through the National Oceanic and Atmospheric Administration (NOAA) Tide and Currents database, providing official tidal predictions.

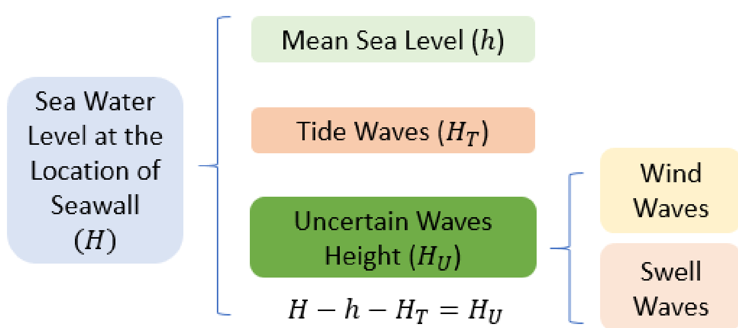

Figure 2. Components of the SWL at the seawall at the seashore structures

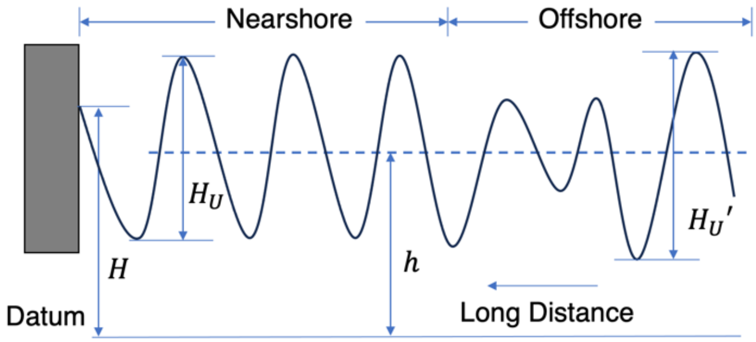

Figure 3. Process of SWL formation at the seawall, from offshore to nearshore.

The challenge in predicting SWL largely lies in accounting for wind waves and swell waves, which introduce uncertainty. Wind waves are influenced by local wind speeds, while swell waves are related to offshore wind and wave conditions. Additionally, wind can either amplify or diminish the wave height. Several uncertainties complicate this analysis: (1) the alignment between offshore wave and wind directions significantly impacts swell wave height at the shore; (2) the wind field can be intricate, and data from a single sensor may not accurately capture nearshore wind conditions, especially the sensors are typically located near the surface of water or land, where wind speeds can vary significantly from those in the broader filed; (3) changes in topography and weather conditions from offshore to nearshore introduce additional unpredictability; and (4) the phase difference between swell waves and local waves at the shore further complicates predictions. The inherent unpredictability of wind waves and swell waves, influenced by alignment, topographies, and phase differences, presents a substantial challenge in accurately predicting SWL.

To tackle this challenge, a GPR model is developed to leverage nearshore and offshore wind speeds, and offshore wave height and periods, learning from these variables to offer a more precise prediction of SWL at coastal infrastructures. GPR is a non-parametric Bayesian approach towards regression problems, which is widely used in machine learning due to its inherent capability to quantify uncertainty over predictions (Wang, 2023). The GPR model is specifically designed to navigate the uncertainties introduced by wind and swell waves, as depicted in Figure 4.

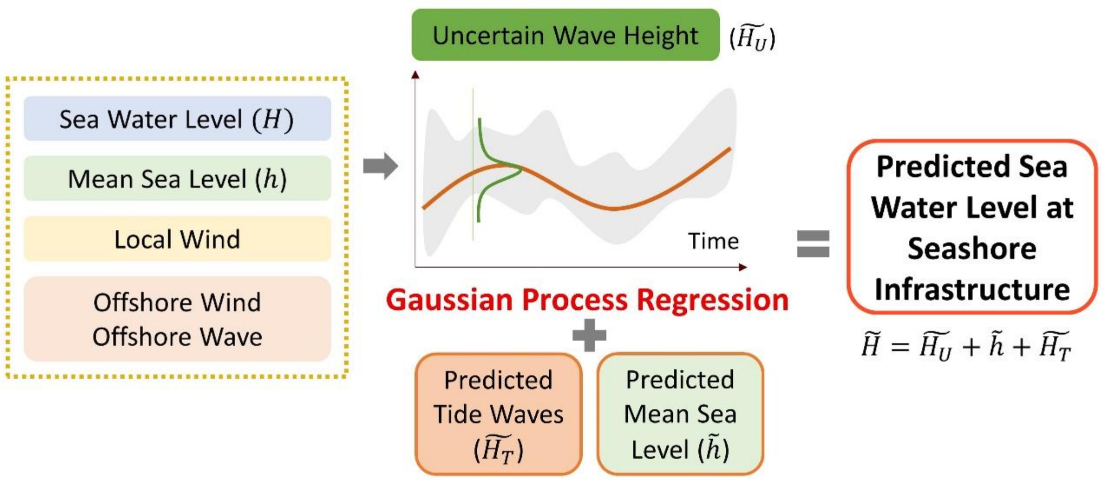

Figure 4. Proposed framework for stochastic prediction of Sea Water Level: Gaussian Process Regression for Uncertain Wave Height prediction combined with Tide Waves and Mean Sea Level for coastal infrastructure assessment

In training, the uncertain wave height (H_U) is determined by subtracting the MSL (h) and tidal wave (H_T) influences from the SWL. The model also accounts for periodic patterns by including the time of the month, day, and hour, helping to understand the underlying uncertainties with specific times and seasons. However, representing the month as a numerical value could imply an ordinal relationship that is not intended. To address this, the month variable is transformed into a set of dummy variables ensuring that it is treated as a distinct categorical variable without implying any inherent order. This is often referred to as one-hot encoding in the context of machine learning applications. Given that uncertain waves often exhibit periodic behavior, a custom mean function inspired by sinusoidal patterns is introduced in the GPR model. The mean function (μ_x) is sinusoidal mean, defined by three key parameters: amplitude (A), frequency (f), and phase ($\emptyset$). The mean function is expressed as follows:

$$\mu(x) = A \cdot sin(f \cdot x + \emptyset)$$

Where:

x is the input data.

Equation 3. Mean Function used for sinusoidal patterns in GPR model training

This sinusoidal mean function enhances the GPR framework's ability to capture underlying periodic trends in the data.

For the prediction phase, inputs such as local wind speed, offshore wave height, offshore wave period, offshore wind speed from weather forecasts, and their corresponding time are used to estimate the uncertain wave components ($\widetilde{H}_U$) by GPR,

$$H_U\left(X^*\right)\Big|X, H_U, X^* \sim GP\left(\mu\left(X^*\right), \sigma^2\left(X^*\right)\right)$$

Where:

X is a vector of all input parameters in training

X^* denotes a vector of input parameters used for prediction

$\sigma^2\left(X^*\right)$ is the variance, which is determined by the kernel function, which, by default, is assumed to be the Radial Basis Function (RBF) kernel.

Equation 4. The estimation of uncertain wave components.

All symbols with a tilde (e.g., $\widetilde{H}$, $\tilde{h}$, $\widetilde{H}_T$, $\widetilde{H}_U$) represent the same quantities as those without a tilde, but specifically in the prediction phase, as opposed to actual, collected sensor data.

By integrating the estimates of uncertain waves with predictions of MSL ($\tilde{h}$) and tidal waves ($\widetilde{H}_T$) from existing models, the final predicted SWL ($\widetilde{H}$) at coastal infrastructures is computed, offering a comprehensive approach to forecasting sea-level impacts on coastal defenses.

3.3 Reliability Assessment of Seawall Overtopping based on the SWL prediction

Given the prediction of SWL at coastal infrastructure using the GPR model, the subsequent step involves estimating the overtopping discharge based on this predicted SWL distribution. The overtopping discharge is influenced solely by the seawater conditions near the shore. Current empirical equations for calculating overtopping discharge are based on these nearshore conditions, which further supports the validity of the proposed two-step framework.

The EurOtop manual provides several formulas for calculating the overtopping discharge, taking into account the weather conditions and seawall configurations (van der Meer et al., 2018). Furthermore, it provides guidelines on acceptable overtopping levels for structures, pedestrians, and vehicles. Therefore, combining the discharge result and tolerable value forms into a limit state function,

$$g = q_{lim} - q\left(H_U, H_T, h\right)$$

Where:

q_{lim} is the tolerable wave overtopping discharge

q is the wave overtopping based on the current scenario

Equation 5. The limit state function used for the wave overtopping.

By applying Equation 5 in the reliability assessment, the PoF related to wave overtopping can be calculated under various weather conditions. When weather forecasts are available, the predicted PoF enables proactive planning for activities, informs designers to account for potential extreme weather conditions, and helps the first responders prepare for possible hazards.

3.4 The Potential Effect of Seawall Height Deterioration

Over time, a seawall's effective height may diminish due to various factors, including land subsidence, structural settlement, material degradation, and changes in the surrounding environment. Land subsidence, often caused by natural processes or human activities such as groundwater extraction, can lower the ground level relative to the seawall, effectively reducing its height. Similarly, physical settlement resulting from the long-term compaction of foundation soils or the gradual downward movement of the seawall structure itself can also contribute to a reduced protective height.

This height reduction poses a significant threat to the seawall's ability to prevent flooding and mitigate coastal erosion, particularly when sea levels rise and extreme weather events happen. A lower seawall height increases the likelihood of wave overtopping, which can lead to hazardous flooding, damage to adjacent infrastructure, and risks to public safety.

Moreover, seawall height deterioration interacts with other factors, such as storm surge intensity, tidal variations, and wave dynamics, amplifying the risk to coastal defense systems. Assessing the potential effects of height reduction is critical for understanding long-term reliability and resilience. Predictive models and regular monitoring are essential to quantify these impacts and inform timely maintenance or retrofitting measures.

3.5 Case Study on Galveston Seawall

The case study examines the seawall at Galveston, TX, intending to quantify the impact of a rise in sea level on the structures along the Gulf of Mexico. The Galveston seawall (Davis Jr, 1951), a critical piece of infrastructure built in the early 20th century, was designed to protect the local community from extreme waves. Its construction was a direct response to the catastrophic hurricane of 1900, which devastated Galveston Island, resulting in over 6,000 fatalities and extensive property damage. The seawall features a concrete gravity design with a base width of 16 feet at an elevation of 1 foot above mean low water, tapering to a top width of 5 feet at an elevation of 17 feet above mean low water. It is founded on piles and protected from undermining by sheet piling, along with a layer of riprap that extends 27 feet outward from the toe of the wall and is 3 feet thick. Since its completion in 1904, the seawall has undergone continuous reinforcement and extensions over the years to address damage from major hurricanes and to enhance its protective capabilities. Following the storms of 1909 and 1915, which revealed foundational weaknesses, the embankment was elevated, and riprap was added to enhance its stability. In the 1930s, groins were constructed along the shoreline to mitigate erosion, and a significant 3-mile extension to the southwest was completed in 1957 to protect newly developed urban areas. Regular maintenance efforts have tackled issues such as subsidence and sand erosion, ensuring that the seawall remains an effective barrier against storm surges and coastal erosion. These continued efforts underscore the necessity of long-term care and preparedness to address future risks.

To account for local tidal conditions, the nearest datum data were collected from Pier 21, TX, provided by NOAA Tide and Currents. As of the data in 2024, the Mean Lower Low Water (MLLW) is -0.31 meters relative to the datum of the North American Vertical Datum of 1988 (NAVD 88) (National & Atmospheric, 2024). In this study, the prediction location is assumed to be at -0.6 meters. The seawall, with a height of 4.87 meters, is configured as illustrated in Figure 5, where R_C is the crest freeboard (Davis Jr, 1981).

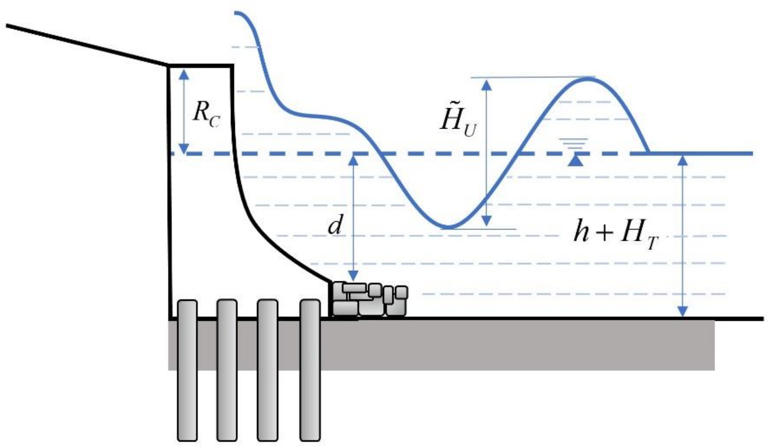

Figure 5. A simple schematic of the Galveston seawall configurations.

3.5.1 Data Sources

As the extreme weather in the Gulf of Mexico often follows the routes from the center to the coast (Kalourazi et al., 2020), it is reasonable to assume the route follows from a sensor near the center (N42001) to a nearshore site, N42035, eventually reaching the seashore at Galveston seawall (Pier 21). N42001 (25°55'32"N 89°39'43"W), as well as N42035 (29°14'12"N 94°24'13"W), is a 3-meter foam buoy station owned and maintained by the National Data Buoy Center. Thus, the offshore data is collected from N42001, while nearshore wind data comes from N42035, the nearest station with long-range data. Additional nearshore data for the Galveston seawall is collected from Pier 21, TX.

Various components of the SWL must be collected to accurately predict uncertain wave heights, including MSL, tide waves, wind, and wave data. Ground truth SWL data is also essential for training and validating predictive models. The approach to data collection varies for historical and future scenarios. For past data, SWL and tide wave records are obtained from Pier 21 in Texas, while local wind data is sourced from NOAA's N42035 station and offshore wind and wave data from the N42001 station, provided by the USGS Coastal and Marine Geology Program. For future data, MSL projections are acquired through the USACE Sea-Level Change Curve Calculator, which offers low, mean, and high projections beginning in 2024. Offshore wind and wave projections will continue to be drawn from the USGS Coastal and Marine Geology Program, using the GFDL-ESM2M model under the RCP 4.5 scenario from the Geophysical Fluid Dynamics Laboratory to simulate future conditions. Local wind forecasts for future scenarios are not available in this study and are assumed to align with the data from 1995 to 2005.

3.5.2 GPR Model for Uncertain Waves

Data spanning from 1995 to 1999 (Training and validation), 2000 to 2005 (Testing), and from 2026 to 2037 (Prediction) was collected for analysis. With the prediction of the uncertain wave from the GPR model, the PoF for wave overtopping reliability can be predicted for the years 2026 to 2037 based on SWL prediction.

Given the periodic nature of waves, a sinusoidal mean with $A = 5$, $f = 8$, and $\emptyset = 0$ is used for the prior distribution in the GPR model to achieve the best evaluation metrics after several trials, and an RBF Kernel with a lower bound of 1e-05 on the length scale is incorporated as a prior assumption.

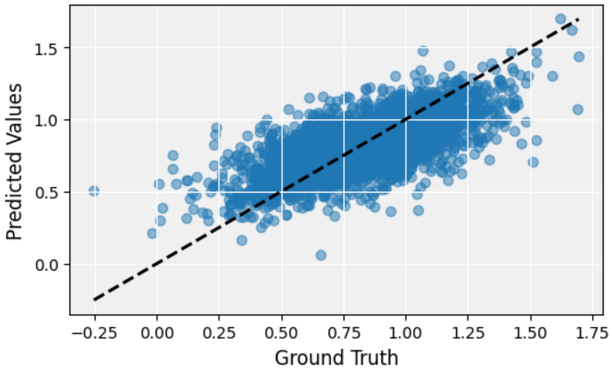

Figure 6. The predicted uncertain waves versus ground truth.

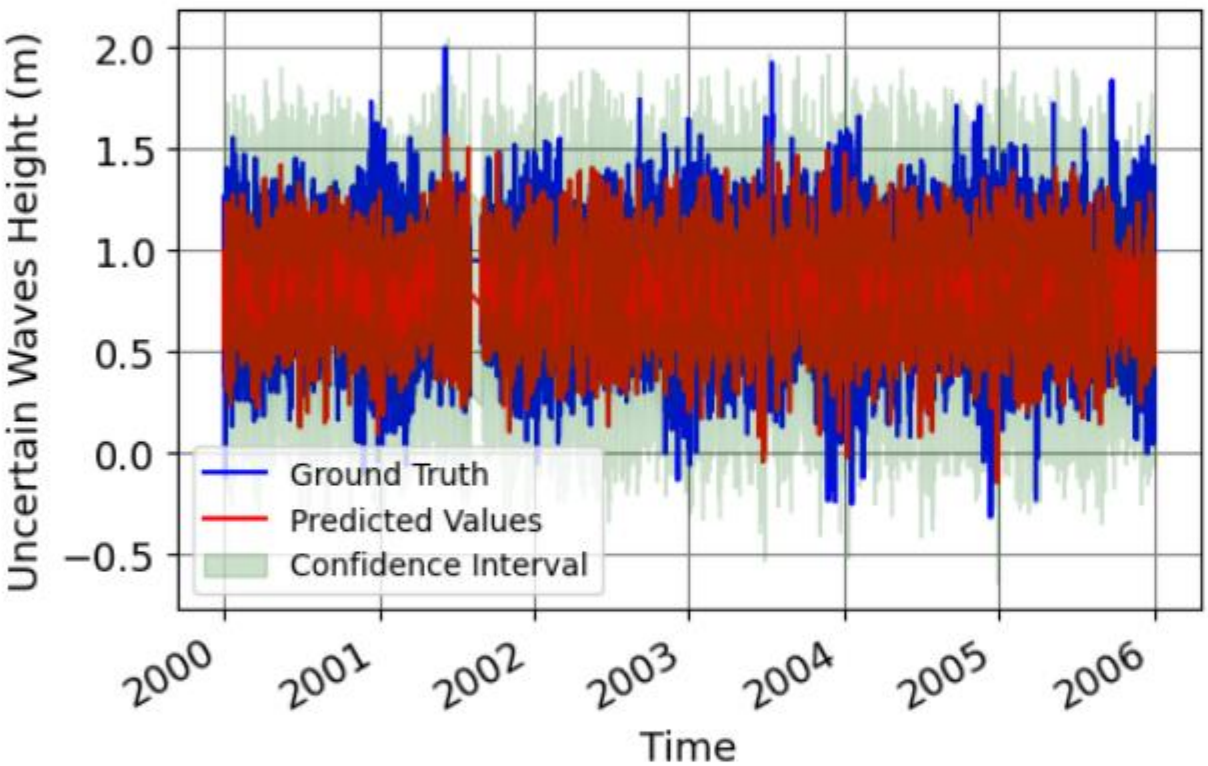

Figure 7. Comparison of uncertain wave height prediction on ground truth and the predicted uncertain waves including mean and variance.

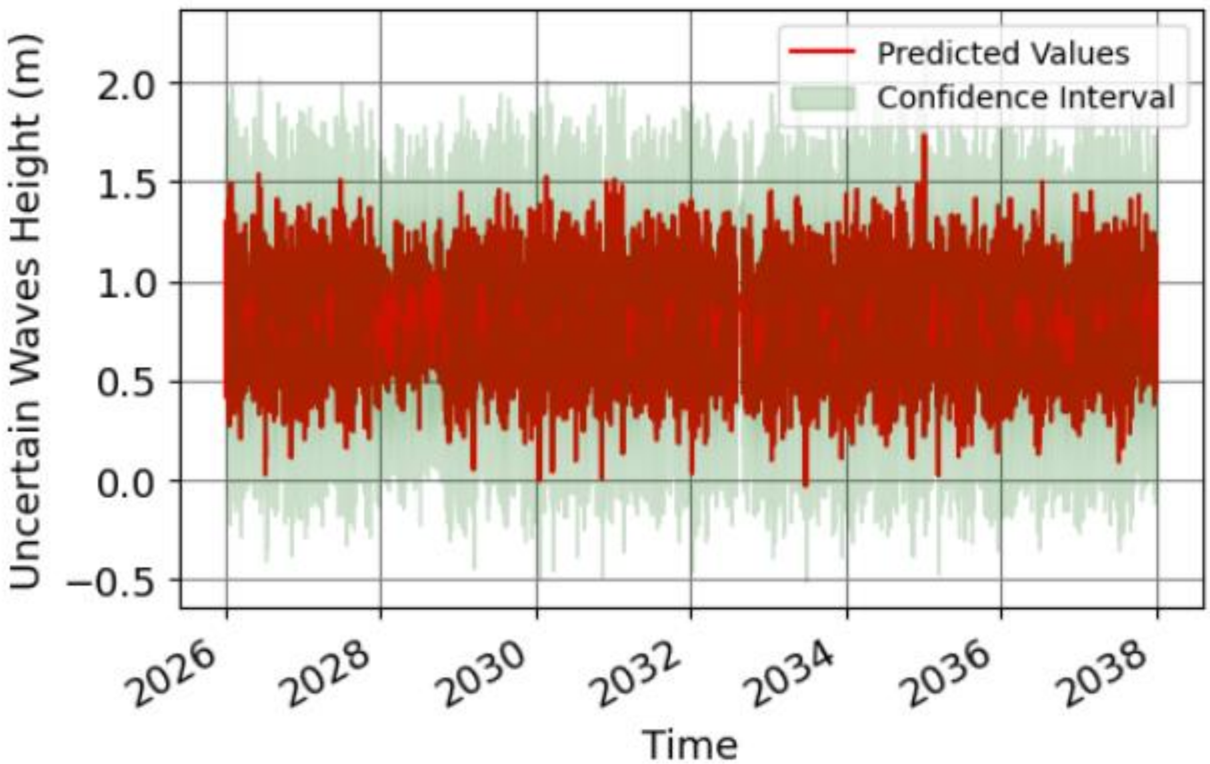

Figure 8. Future wave prediction of uncertain wave height prediction showing mean and variance.

The model's effectiveness is demonstrated by comparing the GPR-predicted mean values against the recorded ground truth of uncertain waves, yielding a Mean Squared Error (MSE) of 0.049 for validation data from 1995 to 1999, and 0.073 for testing from 2000 to 2005, illustrating the model's precision in capturing wave behavior and contributing factors. Figure 6 shows the predicted mean value of uncertain waves versus the ground truth during the training phase. Since the GPR model is designed for uncertain predictions, traditional metrics might not fully capture its performance. However, the low MSE indicates that even deterministic metrics demonstrate the method's effectiveness. Figure 7 illustrates that the ground truth and the predicted values for uncertain wave heights are in close agreement. Consequently, the model is deemed suitable for future predictions, as shown in Figure 8.

3.5.3 Wave Overtopping Reliability Prediction

The GPR wave model can be utilized to forecast future uncertain wave patterns by leveraging weather prediction data, both from coastal and offshore sources. The outcome of this prediction, when integrated with forecasts of tidal waves and sea level variability, yields an estimated SWL at coastal infrastructures.

The design of the Galveston seawall, which includes rock mounds at the front, allows for a simplification of composite vertical walls as described in EurOtop for analysis. In scenarios where the water level regularly falls below the base (toe) of the structure, the seawall can be approximated as a vertical wall to calculate wave overtopping. Accordingly, EurOtop provides specific equations to estimate wave overtopping based on varying weather conditions,

$$\frac{q}{\sqrt{g \cdot H_{m0}^{3}}} = 0.054 \cdot exp\left[-\left(2.12\frac{R_C}{H_{m0}}\right)^{1.3}\right]$$

Where:

g is the gravity

R_C is the crest freeboard

H_{m0} is the wave height at the toe of the structure

Equation 6. Wave Overtopping calculation for the simplifications of Galveston seawall.

According to the USACE Coastal Engineering Manual (USACE, 2012) as shown in Figure 9, various criteria for the tolerable rate of wave overtopping (in liters/second per meter, L/s per m) have been established based on the specific needs and safety concerns of different targets. In this study, three distinct scenarios are considered:

- A tolerable rate of 0.001 L/s per m, which is associated with minor building damage to fittings, signposts, and unsafe driving at high speeds.

- A tolerable rate of 0.03 L/s per m, which presents danger on grass sea dikes and horizontal composite breakwaters and poses risks to pedestrians on the seawall.
- A tolerable rate of 1 L/s per m, which leads to major structural damage, makes conditions highly dangerous for pedestrians and renders it unsafe for vehicles at any speed.

These criteria are essential in evaluating the potential impacts of wave overtopping on infrastructure and public safety, providing guidance for the design and assessment of coastal defense systems.

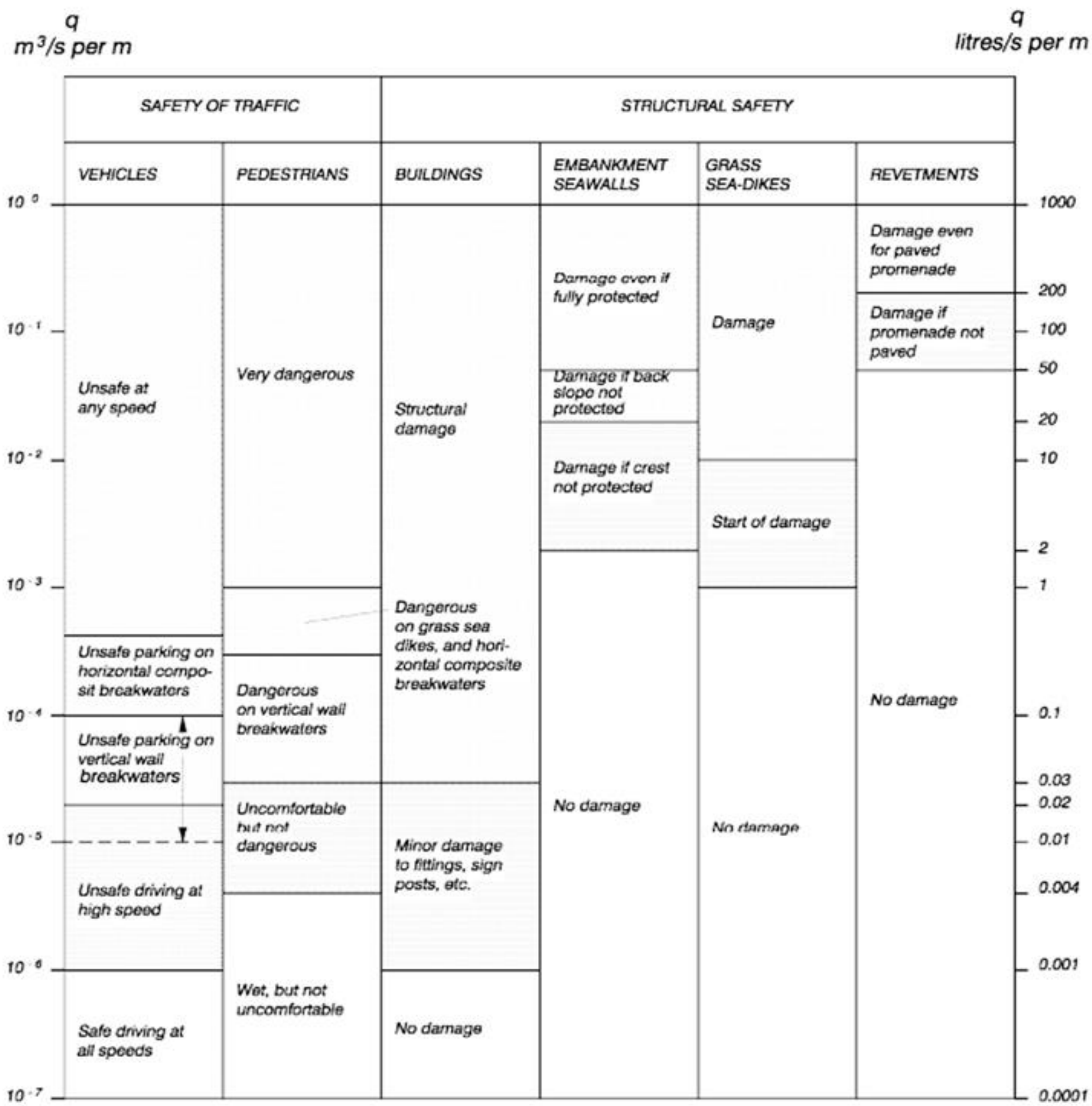

Figure 9. Safe overtopping guidelines provided in USACE,2012

3.5.4 The Potential Effect of Seawall Height Deterioration

This section examines the potential effects of such height deterioration on the Galveston seawall. Two factors contribute to the deterioration of the seawall height: global subsidence in Galveston and settlement of the seawall itself. Liu et al. (Liu et al., 2020) studied how land subsidence affects relative sea level variability at the Galveston Pier 21 tide gauge in Texas, estimating a subsidence rate of 3.51 mm/year.

Seawall settlement in Galveston has varied from 1.45 ft at the eastern end to 0.1 ft near the central portion around 27th Street, between the seawall's construction (1902-1904) and 1951 (Davis Jr, 1951). Assuming these conditions persist and the settlement rate remains linear and consistent, the settlement rate ranges from 9 mm/year to 0.6 mm/year. Uneven settlement would cause cracking along the seawall, leading to serious structural concerns, which could be explored in future research. For this analysis, a uniform settlement rate of 4 mm/year across the entire seawall is assumed.

The total relative change to the NAVD 88 datum is estimated at 7.51 mm/year. Deterioration is assumed to begin in 2024, based on the relative sea level data accessed from NOAA Tide & Currents for that year.

Chapter 4. Results and Discussions

4.1 Introduction

This chapter presents the validation of the SWL prediction model and the risk predictions for the Galveston seawall under different scenarios. The findings of this study highlight varying levels of risk for different population segments, suggesting the potential for a tiered warning system. Ensuring the long-term structural integrity and functionality of coastal defense structures such as the Galveston seawall requires a detailed understanding of how weather and other conditions impact its risk and reliability. This understanding is crucial for informed decision-making during the design and ongoing maintenance of the structure. The results can inform decision-makers to better prepare for and mitigate the effects of potential events. Such forecasts are vital for supporting proactive, long-term strategies in coastal management and infrastructure safety planning. To ensure the safety of pedestrians and vehicles, it is essential to issue timely warnings to prevent access to dangerous areas near or behind the seawall. Similar to weather forecasts, these warnings should aim for maximum accuracy to minimize risks while causing minimal disruption to daily activities.

4.2 The SWL Prediction and Model Prediction

Compared with the current state of the art summarized in Chapter 2, the proposed methodology offers advantages in both accuracy and computational efficiency. As discussed in Section 2.1, existing wave overtopping mitigation studies primarily focus on evaluating various seawall geometries through experimental and numerical investigations. While these approaches provide valuable design insights, they are limited to fixed physical configurations and do not fully address predictive capabilities under variable or uncertain sea conditions. Similarly, the high-fidelity models described in Section 2.2 achieve detailed simulations of wave overtopping and storm surges but require substantial computational resources and produce deterministic results, which restrict their applicability for real-time or long-term predictions. The empirical and database-driven methods outlined in Section 2.3 offer useful generalized equations but lack adaptability to site-specific or time-varying conditions. In contrast, the methodology developed in this study integrates data-driven learning with physics-informed modeling to accurately predict SWL and associated overtopping risks under uncertainty. This hybrid approach captures the stochastic nature of coastal processes. The model dynamically adapts to local site characteristics and evolving inputs, enabling both short-term forecasting and long-term risk assessment.

This study illustrates the model's projections for SWL under three scenarios, reflecting different potential contributions from the various components of SWL: low water levels, intermediate levels, and high water levels.

The SWL predictions serve dual purposes:

(1) Design and Hazard Preparation: Forecasted water levels at critical infrastructure sites can inform structural design, ensuring resilience against future water-related hazards. This helps optimize planning and design strategies for long-term infrastructure performance.

(2) Risk Assessment for Key Infrastructure: Predicted water levels provide essential input for assessing risks to critical infrastructure, such as seawalls. By incorporating these predictions, risk models can evaluate potential damage scenarios and inform maintenance or mitigation strategies.

4.3 The Risk Prediction of Galveston Seawall

The predictions show distinct stakeholders based on their specific tolerable rates of wave overtopping and require varying degrees of time precision in their alerts. The following subsections outline the risk predictions for three different scenarios:

4.3.1 Risk Prediction at Scenario (1)

Scenario (1) – Tolerable Wave Overtopping Rate of 0.001 L/s per m: The forecast period spans from 2026 to 2037, with the monthly average PoF for minor building damage, shown in Figure 10 and Figure 11. Over time, the divergence among these scenarios becomes increasingly pronounced. Certain year experience unusual weather conditions, notably 2028 and 2029. PoF_INT, PoF_HIGH, and PoF_LOW in Figure 10 and Figure 11 correspond to different projections of MSL, which do not imply a ranking of low, intermediate, and high in PoF. Figure 10 shows the highest PoF values without considering deterioration are 0.4181, 0.4251, and 0.4359 for PoF_LOW, PoF_INT, and PoF_HIGH, respectively, on 2034-10-02 at 18:00:00. With deterioration in Figure 11, these values increase to 0.4244, 0.4298, and 0.4458, representing increases of 1.51%, 1.11%, and 2.27%, respectively.

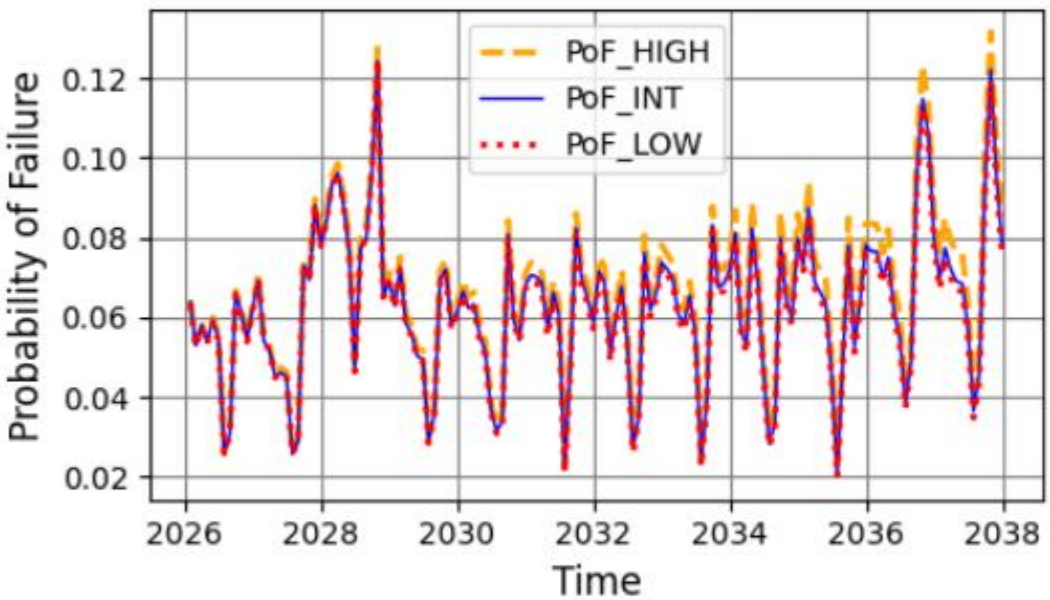

Figure 10. Monthly average PoF without considering the deterioration effect of area subsidence and seawall settlement for risk scenario (1): Tolerable Wave Overtopping Rate of 0.001 L/s per m.

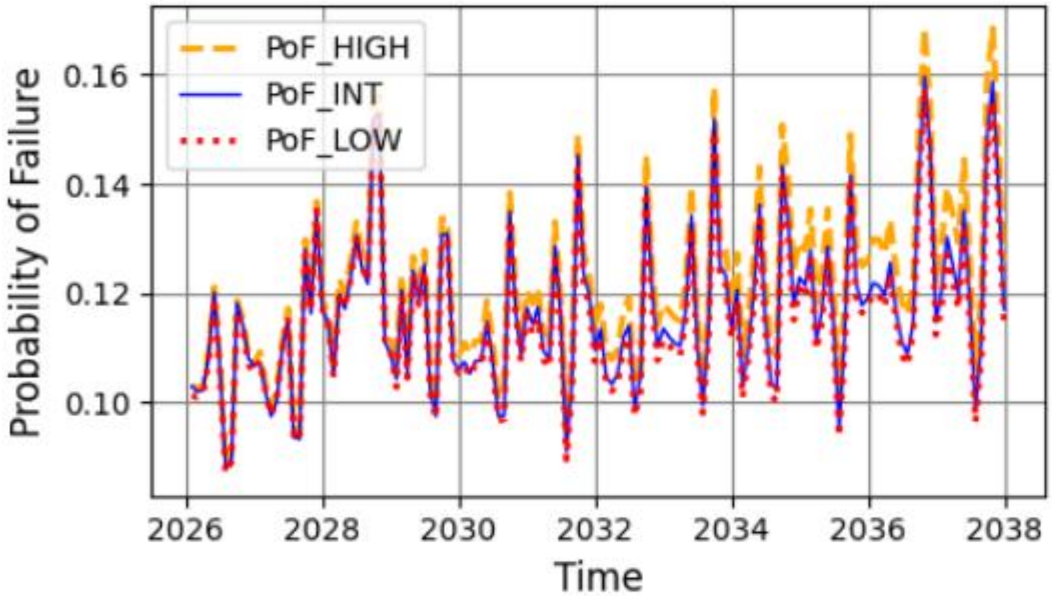

Figure 11. Monthly average PoF considering the deterioration effect of area subsidence and seawall settlement for risk scenario (1): Tolerable Wave Overtopping Rate of 0.001 L/s per m.

4.3.2 Risk Prediction at Scenario (2)

Scenario (2) - Tolerable Wave Overtopping Rate of 0.03 L/s per m: The PoF for a smaller span, January 1-2, 2037, is illustrated for the warning of pedestrians in Figure 12 and Figure 13. It suggests setting thresholds later to alert residents about potential emergencies, factoring in specific local conditions such as the condition of the infrastructure, weather scenarios, and evacuation strategies. Figure 12 shows the highest PoF values are 0.088, 0.09, and 0.0986 on 2034-10-02 at 18:00:00. With deterioration in Figure 13, these values rise to 0.0962, 0.098, and 0.1052, corresponding to increases of 9.32%, 8.89%, and 6.70%, respectively.

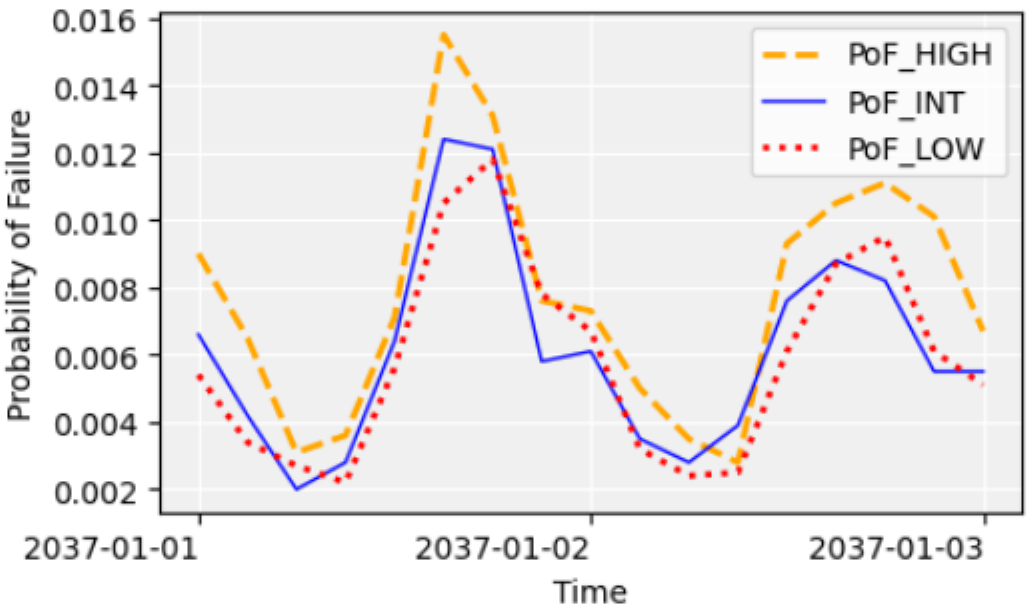

Figure 12. PoF in three-hour intervals without the effects of deterioration due to area subsidence and seawall settlement for risk scenario (2): Tolerable Wave Overtopping Rate of 0.03 L/s per m.

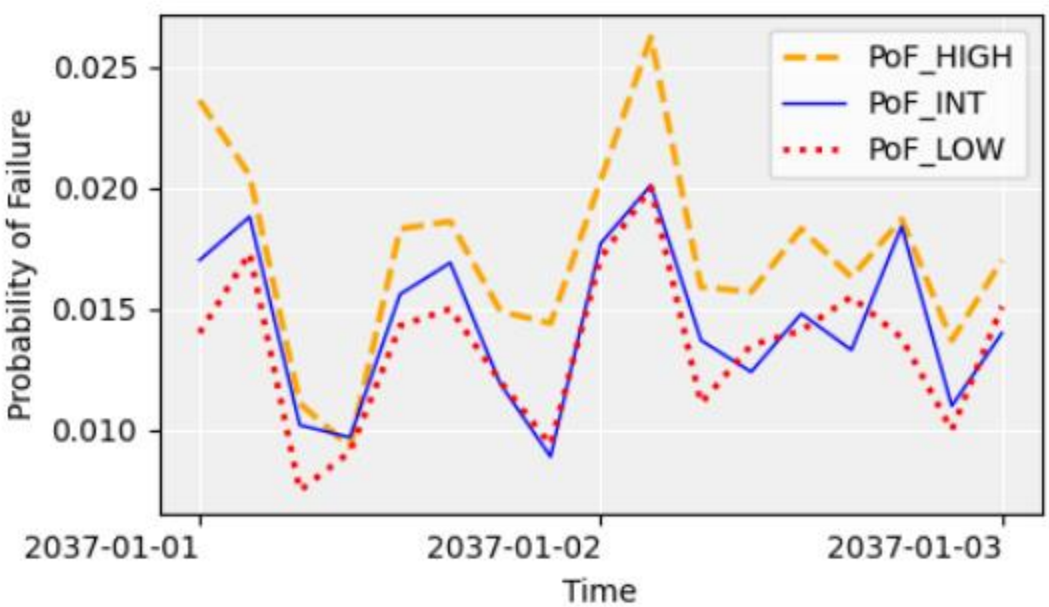

Figure 13. PoF in three-hour intervals with the inclusion of deterioration effect due to area subsidence and seawall settlement for risk scenario (2): Tolerable Wave Overtopping Rate of 0.03 L/s per m.

4.3.3 Risk Prediction at Scenario (3)

Scenario (3) - Tolerable Wave Overtopping Rate of 1 L/s per m: The PoF is zero during the period from 2026 to 2037 because no extreme weather conditions are anticipated that would exceed the scenario's high tolerance threshold.

The PoF changes highlight the significant impact of deterioration over 10 years. This underscores the importance of accounting for seawall deterioration in design and maintenance. Additionally, the results indicate that deterioration has a greater impact when the overtopping discharge limit is higher.

4.4 Limitations and Potential Future Research

The current study has some limitations. Firstly, sensors used for local data collection are not precisely located at the Galveston Seawall, and the nearshore wind data are not exactly on the ideal route. This can lead to approximation bias, as wind conditions can vary over distances. Additionally, even if sensors are positioned along the preferred route, single-point data collection may still pose issues because the complex wind field might show variations between closely spaced locations. For future studies, it would be beneficial to deploy close multiple sensors to thoroughly analyze the conditions in general. This study has demonstrated the effectiveness of uncovering relationships between sensor data in predicting sea levels, which is particularly useful for monitoring seashore activities and infrastructure. With more data, predictions will become more accurate and effective.

Furthermore, the current predicted PoF of overtopping discharge relies on assumed nearshore wind predictions, which may affect the accuracy of future results. Future predictions could be enhanced by incorporating weather prediction models.

Some sensors along the Gulf of Mexico were recently installed, resulting in a lack of data for periods prior to their installation. This limitation affects the overall availability of data for analysis. However, as more data becomes available from these newly installed sensors, the dataset will expand over time with additional sensors being deployed in the future. This will allow future research to benefit from a more comprehensive dataset, ultimately leading to more accurate predictions. Furthermore, the findings of this study could be integrated with digital twin technology, where the accumulation of big data would enhance the digital twin's ability to autonomously process information. This integration could lead to the development of advanced, minimally intrusive disaster warning systems and optimized resource allocation.

Chapter 5. Conclusions and Recommendations

In this study, a data-driven risk-informed framework is presented for improved quantification of probability failure for wave overtopping discharge taking into account uncertainties in wave and sea water level scenarios. The Galveston Seawall in Texas was used as a case study. By decomposing sea water levels into components such as mean sea level, tidal variations, and variable wave actions, and integrating sensor data from the Gulf of Mexico, the framework enables probabilistic forecasting of seawater levels. These forecasts are then applied in time-dependent reliability analysis to quantify future probabilities of failure associated with wave overtopping under various sea level scenarios.

The research demonstrated the utility of this framework by presenting risk assessments in the form of a tiered warning system tailored to stakeholders, including pedestrians, drivers, and infrastructure designers. This system provides actionable insights for decision-making, enabling proactive measures to address risks at different tolerance levels. The study also highlighted the critical role of structural deterioration factors, such as subsidence and seawall settlement, which could increase overtopping risks by up to 10% over the next decade. These findings underscore the importance of predictive analytics in infrastructure planning, particularly in the context of challenges.

The impact of this research is multifaceted. It advances the application of predictive analytics in coastal resilience, demonstrating the power of integrating sensor data and probabilistic modeling to forecast risks and inform decision-making. By quantifying future probabilities of failure, the study shifts the focus from reactive responses to proactive planning, enabling better safety measures and resource allocation.

The tiered warning system provides a systematic approach to risk communication, supporting timely and effective actions for users. For pedestrians, the framework offers early warnings during high-risk periods, while for infrastructure designers, it provides data-driven insights to guide the planning and maintenance of coastal defenses. This comprehensive approach ensures that the findings are not only scientifically robust but also practically applicable.

The study also brings attention to the impact of deterioration factors on risk projections. The inclusion of subsidence and seawall settlement in the modeling underscores the necessity of regular monitoring and maintenance of aging infrastructure. This emphasis is particularly relevant for the risks faced by coastal communities.

The framework developed in this research can be adapted to other coastal regions for predicting variations in sea water levels and quantifying wave overtopping risks. The integration of predictive analytics with real-time sensor data lays the foundation for incorporating digital twin technology into coastal resilience strategies. Digital twins could enable autonomous simulations and optimizations of infrastructure performance under shifting conditions, representing a significant step forward in disaster mitigation and resource management.

Future research should aim to refine the predictive models through expanded data collection and the inclusion of additional factors. Deploying more sensors across broader regions, incorporating advanced weather prediction models, and leveraging historical data could significantly enhance the accuracy and reliability of forecasts. Expanding the framework's application to other coastal regions would also test its robustness and provide insights for addressing infrastructural challenges.

In conclusion, this research contributes to building more resilient coastal communities by advancing predictive analytics and risk assessment methods that evaluate the future performance of seawalls in protecting coastal infrastructure against wave impacts and flooding. The tiered warning system and detailed risk assessments provided empower stakeholders—from local authorities to residents—with actionable insights for strategic planning and immediate response. Ultimately, this research paves the way for more informed, effective, and timely decision-making, ensuring safer and more coastal communities.

Chapter 6. Implementation of Project Outputs

The primary outcomes of this project include a robust framework for probabilistic sea water level prediction, a time-dependent reliability model for wave overtopping risk assessment, and an analysis of seawall deterioration effects due to area subsidence and settlement for various scenarios. Here are the key impacts and benefits of implementing these outputs:

- **Infrastructure Design and Management**: The probabilistic framework aids in predicting sea-level variations and assessing overtopping risks, which can be incorporated into design codes and standards. This integration helps engineers and planners enhance the resilience of crucial structures such as seawalls, ports, and coastal transportation systems.
- **Decision-Making and Resource Allocation**: The tiered risk prediction system developed through this project enables effective resource allocation and prioritization of interventions. Decision-makers can utilize detailed risk assessments to guide their strategies, ensuring that interventions are both timely and cost-effective.
- **Maintenance Strategies**: Insights into seawall deterioration—particularly the roles of subsidence and settlement—emphasize the need for regular monitoring and proactive repairs. These insights support the implementation of predictive maintenance schedules that ensure the sustained functionality of coastal defenses.
- **Community Preparedness and Safety**: The tiered warning system can be seamlessly integrated into local emergency management protocols, providing timely and specific alerts to stakeholders, including residents and infrastructure operators. This system enables communities to respond swiftly and effectively to emerging hazards, reducing the risk of loss and disruption.
- **Scalability and Adaptation**: The methodologies devised can be extended beyond the Galveston Seawall to other coastal areas and infrastructure types. By adapting to region-specific conditions and integrating local sensor data, the

framework can adapt to various challenges. This adaptability enhances its applicability across various geographic and condition contexts.

These benefits highlight the practical applications and potential of the project's outputs in building more resilient coastal communities.

Chapter 7. Technology Transfer and Community Engagement and Participation (CEP) Activities

The research findings and developed predictive model have been implemented into a spreadsheet decision-support tool that predicts SWL at coastal infrastructures and assesses the risk of wave overtopping for coastal defense structures like seawalls. This tool can be used to quantify the future risk of overtopping discharge and inform hazard preparedness, providing timely information that enhances the responsiveness for disaster management and recovery.

The development of a specialized tool for predicting SWL at coastal infrastructures and assessing the risks of seawall wave overtopping, with considerations for seawall deterioration of area subsidence and seawall settlement, marks an advancement in coastal infrastructure management under various scenarios. This tool enables stakeholders to evaluate the risk and reliability of coastal infrastructure, particularly in scenarios such as wave overtopping, while accounting for challenges such as those imposed by aging infrastructure. By offering these insights, the tool facilitates the adoption of proactive measures to mitigate risks and strengthen resilience. The tool's core functionality revolves around a data-driven probabilistic model tailored specifically for the Galveston Seawall. This model seamlessly integrates critical condition data, including offshore wind and wave heights as well as nearshore wind and tidal conditions. By leveraging these inputs, the tool accurately forecasts SWL at the seawall location while quantifying the PoF due to wave overtopping. The overtopping discharge limit, a crucial factor for PoF predictions, is customizable, though it is strongly recommended to use values established by the USACE to ensure consistency and reliability.

The tool is developed in Excel, and is currently publicly available for download on GitHub: https://github.com/Xukaizh/SWL_Tool.git. Figure 14 shows a snapshot of the main interface. The tool's design emphasizes ease of use and accessibility for a wide range of stakeholders, from coastal engineers to policymakers. Users input relevant condition data into the predefined 'InputSheet,' specifying timeframes and overtopping discharge limits. Upon running the tool, it generates detailed outputs, including 3-hourly and monthly average sea-level predictions under varying uncertainty levels, as well as PoF values for the Galveston Seawall. These outputs are systematically organized in the 'OutputSheet,' offering users both high-level summaries and detailed datasets for in-depth analysis.

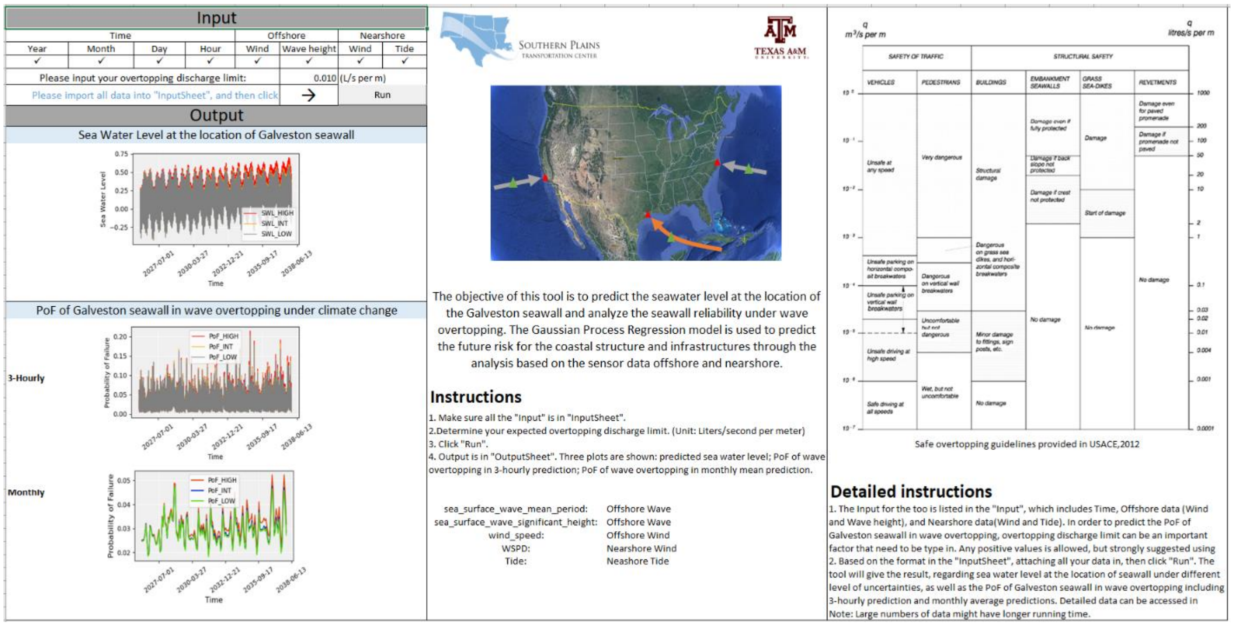

Figure 14. The developed Excel tool for the SWL prediction and seawall overtopping risk assessment.

Chapter 8. Invention Disclosures and Patents, Publications, Presentations, Reports, Project Website, and Social Media Listings

Conference Presentations:

Zhang, X., and Noshadravan, A. “A Data-Driven Stochastic Modeling Framework for Improved Risk Characterization of Wave Overtopping on Coastal Defense Structures.” Presented at the EMI/PMC 2024 Conference, 2024 & EMI/PMC 2024 student paper competition of Probabilistic Method Committee (PMC).

Journal paper submission:

Zhang, X., & Noshadravan, A. (2025). Data-Driven Stochastic Approach for Assessing Future Risk of Wave Overtopping in Coastal Defense Structures. Journal of Engineering Mechanics, 151(8), 04025031.

A short description of the innovation:

The research project introduces an innovative, data-driven stochastic framework that seamlessly integrates condition data with probabilistic modeling to predict the probability of failure associated with the wave overtopping in seawalls. This framework uniquely accounts for sea-level variability and nearshore wave heights, thereby enhancing the accuracy and timeliness of reliability assessments for these critical coastal defenses under various scenarios.

Applied to the Galveston Seawall, this pioneering approach has proven its capability to forecast overtopping probabilities across a range of scenarios, including variable sea-levels and structural subsidence. This bridges the often wide gap between theoretical research and practical application, offering a robust pathway toward designing more resilient coastal infrastructure. Furthermore, it facilitates targeted maintenance strategies and bolsters community preparedness for coastal hazards.

The findings and the newly developed predictive model have been encapsulated into a user-friendly, spreadsheet-based decision-support tool. This tool enables stakeholders to project future sea-level variability and assess wave overtopping risks with a new level of precision, thereby transforming how coastal defense structures like seawalls are designed and maintained. Through this innovative approach, the project not only advances the scientific understanding of coastal resilience but also equips planners and engineers with the tools needed for proactive, informed decision-making in coastal hazard management.

References

Allsop, W., Bruce, T., Pearson, J., & Besley, P. (2005). Wave overtopping at vertical and steep seawalls. *Proceedings of the Institution of Civil Engineers-Maritime Engineering*, *158*, 103-114.

Davis Jr, A. B. (1951). History of the Galveston sea wall. *Coastal Engineering Proceedings*, *2*, 24-24.

Davis Jr, A. B. (1981). *Galveston's Bulwark Against the Sea: History of the Galveston Seawall*. Galveston District, U.S. Army Corps of Engineers.

De Rouck, J., Verhaeghe, H., & Geeraerts, J. (2009). Crest level assessment of coastal structures—general overview. *Coastal Engineering*, *56*(2), 99-107.

Di Leo, A., Dentale, F., Buccino, M., Tuozzo, S., & Pugliese Carratelli, E. (2022). Numerical analysis of wind effect on wave overtopping on a vertical seawall. *Water*, *14*(23), 3891.

Dong, S., Salauddin, M., Abolfathi, S., & Pearson, J. M. (2024). Improved prediction of wave overtopping rates at vertical seawalls with recurve retrofitting. *Ocean Engineering*, *302*, 117647.

Geeraerts, J., Troch, P., De Rouck, J., Verhaeghe, H., & Bouma, J. J. (2007). Wave overtopping at coastal structures: prediction tools and related hazard analysis. *Journal of Cleaner Production*, *15*(16), 1514-1521.

Hieu, P. D., & Vinh, P. N. (2012). Numerical study of wave overtopping of a seawall supported by porous structures. *Applied Mathematical Modelling*, *36*(6), 2803-2813.

Kalourazi, M. Y., Siadatmousavi, S. M., Yeganeh-Bakhtiary, A., & Jose, F. (2020). Simulating tropical storms in the Gulf of Mexico using analytical models. *Oceanologia*, *62*(2), 173-189.

Koosheh, A., Etemad-Shahidi, A., Cartwright, N., Tomlinson, R., & van Gent, M. R. (2022). Experimental study of wave overtopping at rubble mound seawalls. *Coastal Engineering*, *172*, 104062.

Liu, Y., Li, J., Fasullo, J., & Galloway, D. L. (2020). Land subsidence contributions to relative sea level rise at tide gauge Galveston Pier 21, Texas. *Scientific reports*, *10*(1), 17905.

Mase, H., Tamada, T., Yasuda, T., Karunarathna, H., & Reeve, D. E. (2015). Analysis of climate change effects on seawall reliability. *Coastal Engineering Journal*, *57*(03), 1550010.

Merrifield, M. A., Johnson, M., Guza, R., Fiedler, J. W., Young, A. P., Henderson, C. S., Lange, A. M., O'Reilly, W. C., Ludka, B. C., & Okihiro, M. (2021). An early warning system for wave-driven coastal flooding at Imperial Beach, CA. *Natural Hazards*, *108*, 2591-2612.

National, O., & Atmospheric, A. (2024). *Datums for Pier 21, TX (station id: 8771450). Accessed: September 18, 2024*.

Orimoloye, S., Horrillo-Caraballo, J., Karunarathna, H., & Reeve, D. E. (2021). Wave overtopping of smooth impermeable seawalls under unidirectional bimodal sea conditions. *Coastal Engineering*, *165*, 103792.

Reeve, D., Soliman, A., & Lin, P. (2008). Numerical study of combined overflow and wave overtopping over a smooth impermeable seawall. *Coastal Engineering*, *55*(2), 155-166.

Schoonees, T. (2014). *Impermeable recurve seawalls to reduce wave overtopping* Stellenbosch: Stellenbosch University].

Steendam, G. J., Van Der Meer, J. W., Verhaeghe, H., Besley, P., Franco, L., & Van Gent, M. R. (2005). The international database on wave overtopping. In *Coastal Engineering 2004: (In 4 Volumes)* (pp. 4301-4313). World Scientific.

Stokes, K., Poate, T., Masselink, G., King, E., Saulter, A., & Ely, N. (2021). Forecasting coastal overtopping at engineered and naturally defended coastlines. *Coastal Engineering*, *164*, 103827.

Suh, S. W., & Lee, M. H. (2023). Analysis of typhoon-induced wave overtopping vulnerability due to sea level rise using a coastal–seawall–terrestrial seamless grid system. *Journal of Marine Science and Engineering*, *11*(11), 2114.
Thomas, R. S., & Hall, B. (2015). *Seawall Design*. Butterworth-Heinemann.
USACE. (2012). *Coastal Engineering Manual Part VI: Design of Coastal Project Elements*. U. S. A. C. o. E. (USACE).
van der Meer, J., Allsop, W., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P., & Zanuttigh, B. (2018). *Manual on Wave Overtopping of Sea Defences and Related Structures*. EurOtop. www.overtopping-manual.com
Wang, B., Hua, L., Mei, H., Wu, X., Kang, Y., & Zhao, N. (2024). Impact of climate change on the dynamic processes of marine environment and feedback mechanisms: an overview. *Archives of Computational Methods in Engineering*, 1-32.
Wang, J. (2023). An intuitive tutorial to Gaussian processes regression. *Computing in Science & Engineering*.
Xie, D., Zou, Q.-P., Mignone, A., & MacRae, J. D. (2019). Coastal flooding from wave overtopping and sea level rise adaptation in the northeastern USA. *Coastal Engineering*, *150*, 39-58.

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