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Joint distribution model for prediction of hurricane wind speed and size

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ABSTRACT

This paper suggests a methodology for characterizing the joint distribution of hurricane intensity (maximum wind speed) and size (radius of maximum winds). Such a model represents an extension of traditional wind hazard models by including joint information on the critical spatial dimension. Typically, the hurricane hazard is described in terms of maximum wind speed V_{max} (at the eye-wall), since damage descriptors associated with intensity scales (e.g., the Saffir–Simpson Hurricane Scale) and collateral hazards (e.g., hurricane surge) are related most often to maximum wind speed. However, recent studies have shed light on the importance of storm size (i.e., radius of maximum wind, R_{max}) in describing the hurricane wind field and thus the spatial extent of potential damage. The large losses from several recent hurricanes underscore the need for better understanding the impact of storm size on damage. To that end, we seek to develop event parameter combinations (e.g., V_{max} and R_{max}) that define "characteristic" risk-consistent hurricanes in one particular geographic region. A simulation framework is developed to generate 10,000 years of simulated hurricane events and a synthetic hurricane wind speed database for the state of Texas, using state-of-the-art hurricane modeling techniques and information extracted from historical hurricane data. The resulting 10,000 years database, which includes information developed for every zip-code in Texas, includes time of hurricane passage, maximum gradient wind speed and surface wind speed. Using this simulation framework, selected parameters (i.e., intensity and size parameters) are recorded for each hurricane at the time of landfall along the Texas coast. Using a hurricane decay model specifically calibrated for this location, parameters V_{max} and R_{max} at inland locations also are recorded. The critical values of V_{max} and R_{max} are then selected to jointly describe the intensity and spatial extent of hurricanes and the joint histogram is developed. Finally, these variables are statistically characterized and a suite of the characteristic V_{max} and R_{max} combinations corresponding to certain hazard levels are identified. The proposed methodology can be used to develop characteristic hurricane hazard definitions (and event parameter combinations corresponding to specific hazard levels) for use in performance-based engineering applications.

1. Introduction

Hurricanes (tropical storms) are among the most deadly hazards threatening the Gulf Coast of the United States and Mexico. Significant improvements have been made in hurricane forecasting, warning and evacuation. Recent studies (e.g., [9,5,13,20,26,7]) have focused on hurricane loss estimation and mitigation. Despite significant progress in hurricane hazard mitigation, the losses associated with recent events have been very large, demonstrating the vulnerability (both physical and economic) that exists in these coastal areas. More accurate hurricane models are needed to validate and define structural design criteria in load standards, better anticipate future events, and prepare for the storm's impact and for post-event recovery.

Typically, the hurricane hazard is described in terms of maximum wind speed V_{max} (at the eye-wall), since damage descriptors associated with intensity scales (e.g., the Saffir–Simpson Hurricane Scale) and collateral hazards (e.g., hurricane surge) are related most often to maximum wind speed. However, the hurricane storm size (i.e., radius of maximum winds, R_{max}) also plays an important role in describing the hurricane wind field intensity and thus the spatial extent of damage. Prior to hurricane Katrina in 2005, few studies addressed storm size when evaluating hurricane damage. Irish et al. [11] investigated the influence of storm size on hurricane surge for the coastal area around Corpus Christi, TX and showed that both maximum hurricane wind speed and storm size are important factors influencing hurricane surge and hence the damage impact on coastal infrastructure. For a given wind speed intensity, they found that storm surge (which caused

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the most damage in Katrina) varied by as much as 30% over a range of storm sizes. In order to more fully define future (predicted) events for purposes of design, assessment, disaster management, or loss estimation, joint distribution information on storm intensity (e.g., V_{max}) and storm size (e.g., R_{max}) is required.

Powell and Reinhold [18] proposed the using integrated kinetic energy (IKE) to define the intensity of a specific hurricane event by integrating the energy under the volume of the complete wind field, thereby explicitly considering storm size. However statistical (predictive) models cannot be developed based on the IKE concept that could result in design-basis event characterization for performance-based applications.

For performance-based engineering applications, it would further be useful to develop parameter combinations (e.g., V_{max} and R_{max}) that define (and therefore predict) "characteristic" risk-consistent hurricanes. Some recent studies have focused on risk-consistent hurricane hazard characterization and these are described below.

Legg et al. [15] suggested one way to identify a set of hurricanes to develop hazard-consistent probabilistic scenarios for the state of North Carolina. A set of hurricanes with different return periods was first selected by running HAZUS-MH [5] for each county in North Carolina and recording the maximum gust wind speed for each county. An optimization program was used to select a reduced set of hurricanes and determine the corresponding annual exceedance probabilities for a set of defined hazard levels. Once the data pairs of annual exceedance probability (or return period) and the maximum gust wind speed for each county were generated, the hazard curve (wind speed vs. annual exceedance probability or return period) for a given county was constructed. Although this approach successfully characterized the hurricane hazard in a consistent probabilistic manner, the maximum wind speed (i.e., a point-measure of intensity with no spatial descriptor included) was the only hazard metric considered.

Phan and Simiu [16] proposed a multi-hazard risk assessment approach to develop design criteria for structures subjected to hurricane wind and storm surge. The joint distribution of (correlated) wind speed/storm surge height was developed for the area around Tampa Bay, FL. This general approach to fitting the joint distribution of two hazard (intensity) variables (i.e., wind speed and surge height) could also be used to determine the joint distribution of two hurricane (event) variables (e.g., V_{max} and R_{max}). However, the maximum storm surge was generated by the SLOSH model [12] and often did not occur at the same time as maximum hurricane wind speed occurred. In the approach suggested by Phan and Simiu, the maximum storm surge and the maximum hurricane wind speed for one event were assumed to occur simultaneously and therefore any design criteria developed using their approach would be conservative, which is generally favorable from an engineering design viewpoint. An alternative method for estimating the joint exceedance probability, in load effects space, was proposed by Phan et al. [17]. This approach did not result in overestimation of the joint wind speed and storm surge effects.

State-of-the-art hurricane prediction models are introduced to simulate hurricane events in this paper. Using the models developed by Vickery et al. [23], Vickery et al. [24], Lee and Rosowsky [14] developed a framework for the simulation of hurricane events. The availability of historical hurricane records [10] has enabled such event-based simulation procedures to be developed in the public sector. Previously, such models were largely proprietary. This paper uses the simulation framework developed by Lee and Rosowsky to develop a hurricane wind speed database for the state of Texas. Key components for the framework are the gradient wind-field model [6] and the tracking and central pressure models [23,24]. Decay model parameters specifically for Texas were developed as part of this study. These models and their various parameters are described in the following sections. Using the Texas coastline as an example, all of the information (intensity, size and direction) needed to describe 10,000 years of hurricane events is completely developed in the synthetic wind speed database. Using this information, the dominant variables (e.g., V_{max}, R_{max}) can be jointly characterized statistically and the characteristic hurricane hazard (considering both wind speed and size) can be defined.

2. Proposed methodology

The approach developed in this study to generating a synthetic hurricane wind speed database and defining risk-consistent characteristic hurricanes (through the development of the joint distribution of hurricane wind speed and size) is described in the following four steps. First, a 10,000 year synthetic hurricane wind speed database for the state of Texas is developed using state -of-the-art hurricane wind field and tracking models [6,23,24], event-based simulation techniques and information extracted from historical hurricane data [10]. In the analysis, after a simulated hurricane makes landfall, the hurricane intensity decays as a function of distance travelled inland using a decay model developed specifically for Texas. The resulting 10,000-year database, which includes information developed for every zip-code in Texas, includes time of hurricane passage, maximum gradient wind speed and surface wind speed (developed using appropriate gradient -to-surface wind speed conversion factors described in a later section).

Second, once the synthetic hurricane wind speed database is developed, the critical event parameters are extracted. State-of-the-art parametric hurricane wind field models such as the one used to create the 10,000 year synthetic hurricane wind speed database include multiple parameters (e.g., maximum wind speed V_{max}, radius of maximum winds R_{max}, Holland pressure profile parameter B, etc.) describing the vortex shape of the gradient wind-field. Among these, two critical parameters, the maximum wind speed V_{max} (i.e., at the eye-wall) and the radius of maximum winds, R_{max}, are selected in the present study to describe the wind speed intensity and the size of the hurricane, respectively. These parameters will be further discussed in a later section.

The focus in the present study is on characterizing (probabilistically) the hurricane at the time of landfall. Therefore, the key parameters (i.e., V_{max} and R_{max}) for each hurricane at the time of landfall along the Texas coast is extracted from the 10,000 year simulated hurricane wind speed time histories. Hurricane information (descriptors) from the closest time (data are generated/stored at 6-h intervals) prior to landfall are used. In addition to statistically characterizing hurricane events at the time of landfall, the parameters for attenuated inland hurricane events also were extracted.

Third, the joint histogram of selected variables is constructed. Specifically, the histogram of V_{max} and R_{max} is generated for hurricane events which were simulated to make landfall along the Texas coast. Note that each data pair of V_{max} and R_{max} is presumed simultaneous herein. Once the joint histogram is generated, the joint exceedance probability "surface" of V_{max} and R_{max} at the time of landfall can be developed. The joint annual exceedance probability of V_{max} and R_{max} at the time of landfall can then be determined knowing the mean annual occurrence rate. Using the hurricane decay model developed for Texas and the translational hurricane wind speed at the time of landfall, V_{max} and R_{max} data pairs at inland locations (i.e., at certain distance inland or time since landfall) can be determined.

Fourth and finally, characteristic hurricane parameter combinations corresponding to specific hazard levels (e.g., annual exceedance probabilities or mean recurrence intervals) are selected/identified. Once the joint annual exceedance probability of V_{max}