WIND HAZARD ANALYSIS IN HURRICANE-PRONE REGIONS

by
Hon Chuen Joe Lai
and
Anne S. Kiremidjian

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ABSTRACT

Typhoons are one of the most catastrophic natural phenomena on earth. Thus, communities that are located within the hurricane striking zone are at risk. To reduce the risk and mitigate the related hazards, engineers need to: (1) estimate the parameters such as pressure gradient and rainfall intensity within a hurricane; and (2) assess the hurricane-induced hazards, which include extreme winds, storm surges, river floods, and landslides, that a coastal structure will experience during its lifetime. In this thesis, the methodology used in hurricane risk analysis is reviewed and computer algorithms are developed to quantify the hurricane-induced wind hazard. The discussion will emphasize on the recognition of hurricane striking zone, identification of hurricane-induced hazards, and assessment of wind risk for hurricanes.

The multiple pathway model is an ideal model to conduct a complete hurricane risk analysis. In this thesis, the need for applying the multi-pathway model to assess the potential human and property exposure to hurricane hazards such as extreme winds are addressed. In addition to the multiple pathway model, a wind hazard model used to study the wind hazard caused by hurricanes at the site of interest is reviewed. The wind hazard model includes two sub-models. They are: (1) a recurrence model; and (2) an extreme wind model. The recurrence model can be either a homogeneous Poisson process or a non-homogeneous Poisson process. The mean rate of hurricane occurrences for the homogeneous Poisson process is estimated by a constant mean model; on the other hand, the mean rate of hurricane occurrences for the non-homogeneous Poisson process is estimated by a globally constant seasonal model. The extreme wind model can be described by either a Gumbel or a Weibull distribution. Before the extreme wind model can be applied, the extreme gradient winds induced by hurricanes have to be evaluated. The extreme gradient winds can be assessed by the wind field model of a hurricane.

Furthermore, a simulation model, which is used to assess the hurricane-induced wind hazard at the site of interest, is reviewed. The simulation model is employed because of insufficient data. In simulation,
the random variates for each of the following five random variables are generated from the selected theoretical distribution with a random number generator. The required random variables are: (1) the latitude of a hurricane center; (2) the longitude of a hurricane center; (3) the minimum pressure within a hurricane; (4) the translation speed of a hurricane; and (5) the moving direction of a hurricane. Random numbers are generated by the linear congruential generator. Lognormal distribution is the chosen theoretical distribution for each of the five random variables in the case of Hong Kong.

Finally, the wind hazard model with the observed data and the simulation model with the simulated data are applied to calculate the wind hazard curves at Hong Kong. The purpose of applying the wind hazard model is to validate the simulation model. Validation is to find out whether the actual system can be closely resembled by the simulation model. The validation procedure has to be performed because existing data are insufficient. Two Pascal programs called "WindHazard" and "Simulation" are developed. "WindHazard" is written based on the wind hazard model. The input data for this program is the observed data supplied by the Royal Observatory of Hong Kong.

"Simulation" is written based on the simulation model. This program used the internally generated data as the input data. Since the terminating criterion of a simulation is usually governed by the duration of the available data, a 30-year forecast window is used as the terminating criterion in the case of Hong Kong. In this case, hurricane data spans over a period of 30 years from January 1961 to December 1990. This terminating criterion is applied here rather than the criterion based on the number of generated hurricanes because the later one is based on an arbitrary number. With this terminating criterion, the simulation can be classified as a terminating simulation. Thus, the sequential procedure can be applied to analyze the output of the terminating simulation. The procedure estimates the performance of the mean hazard curve for hurricane-induced wind speeds by constructing a $100(1 - \alpha)$ percent confidence interval for the curve with a relative error $\gamma \leq 0.15$. The advantage of
the sequential procedure is the simulation terminates as soon as the desired precision has been reached.

Based on the results of the analyses for Hong Kong, the following conclusions can be made:

1. The Gumbel distribution fits the historical observations for hurricane-induced extreme winds better than the Weibull distribution.
2. The non-homogeneous Poisson process fits the existing data for hurricane occurrences better than the homogeneous Poisson process.
3. One hundred and seventy six simulation runs are required to achieve the desired precision, i.e., a 90% confidence interval with a relative error $\gamma \leq 0.15$ for estimating the performance of the mean wind hazard curve for hurricanes.
4. The developed simulation model is a valid model for simulating the characteristics of hurricanes. This model can, then, be used to forecast the hurricane-induced wind hazard at the site of interest.
LIST OF SYMBOLS

\(a\)  
Multiplier of the linear congruential generator

\(a_n\)  
Inverse of dispersion of the hurricane wind speed \(V_H\)

\(c\)  
Increment of the linear congruential generator

\(C_{1i}\)  
Amplitudes of the seasonal component

\(C_{2i}\)  
Phase angles of the seasonal component

\(e_t\)  
Uncorrelated error component with zero mean and constant variance for regression model

\(\frac{dp}{dr}\)  
Radial gradient pressure in mb per statute mile

\(f(t, \beta)\)  
Function of time \(t\) and coefficients \(\beta\)

\(f\)  
Coriolis parameter

\(F_H(V_H)\)  
Cumulative distribution function of the maximal gradient wind speed \(V_H\), induced by hurricanes given that \(n\) hurricanes have occurred in time \(t\)

\(m\)  
Modulus of the linear congruential generator

\(n\)  
Number of hurricanes occurred in a given time \(t\)

\(n_0\)  
Initial number of replications

\(\Delta P\)  
Central pressure difference of a hurricane in mb, and \(\Delta P = P_n - P_o\)

\(P_o\)  
Pressure at location of maximal wind

\(P_n(n,t)\)  
Probability of having \(n\) hurricanes in time \(t\)

\(P_H(V_H > v|N)\)  
Probability of having wind speed, \(V_H\), greater than a specific value, \(v\), given the occurrence of \(N = n\) hurricanes

\(P_H(V_H > v,t)\)  
Probability of gradient wind speed, \(V_H\), of hurricanes greater than a specific value, \(v\), in time \(t\)

\(P_n\)  
Periphery pressure; \(P_n = 1014\) mb

\(r\) and \(\theta\)  
Polar coordinates, where \(r\) is in statute miles and \(\theta\) in degrees, with origin at the center of a hurricane

\(R\)  
Radius to the region of maximum wind

\(R_o\)  
Radius of the earth

\(s\)  
Seasonal period
(x + y + z)/2

$S_t$
Seasonal component for a globally constant seasonal model

t
Specified period of time

t'
Transformed time period

$T_t$
Trend component for a globally constant seasonal model

$u_n$
Mode of maximal gradient wind speeds of hurricanes

$v(r, \theta)$
Gradient wind speed of a hurricane at coordinates $(r, \theta)$ in m.p.h.

$\nu_T$
Translation speed of a hurricane in m.p.h.

$x, y, z$
Magnitudes of the sides of a spherical triangle

$X, Y, Z$
Magnitudes of the angles of a spherical triangle

$Z_0$
Seed of the random number generator

$Z_i$
IID random number

$\alpha$
Shape factor of a Weibull distribution

$\beta$
Scale factor of a Weibull distribution

$\phi$
Longitude of a point on the earth surface

$\gamma$
Euler's constant, $\gamma = 0.577216$

$\eta$
Sample mean of a lognormal distribution

$\lambda$
Mean annual rate of hurricane occurrences for a homogeneous Poisson process

$\lambda(t)$
Arrival rate of hurricanes for a Poisson process

$\mu$
Sample mean

$\rho$
Air density, $\rho = 0.00115 \text{ g/cm}^3$

$\sigma_n$
Sample standard deviation

$\omega$
Latitude of a point on the earth surface

$\psi(t)$
Expectation function of a non-homogeneous Poisson process

$\zeta$
Sample standard deviation of a lognormal distribution
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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Tropical cyclones frequently originate in warm latitudes over the oceans. They usually travel in the north-west direction towards inland over the northern hemisphere due to the effects of atmospheric circulation and the earth's rotation. In their mature stage, hurricanes will head towards the east coast of the United States if they generate over the north Atlantic Ocean; on the other hand, typhoons will pass clusters of islands over the Pacific and strike the coastal region of south-east China if they develop over the north Pacific Ocean.

Thus, infrastructure, buildings, and utilities in communities that are located within the hurricane striking zone are at risk from future attack of hurricanes. With threats from the potential hazards such as: (1) extreme winds, (2) storm surges, (3) floods, and (4) landslides, engineered mitigation measures are needed to alleviate the consequences that are associated with these hazards if they are unavoidable.

To reduce such risk, engineers need to estimate the pressure gradient and rainfall intensity within hurricanes that a structure will experience during its life time. To mitigate the related hazards, engineers need to assess the consequence resulting from a hurricane strike. Statistics of extremes is a classical probability model used by engineers in estimating the return period of various hazards that exceeds a threshold. This model considers the largest yearly hazards only. However, it does not account for the spatial and temporal effects of hurricanes.

Various researchers have examined the correlation among the following parameters related to hurricane risk assessment: (1) pressure gradient and extreme winds; (2) pressure gradient and storm surges; (3) rainfall intensity and floods; and (4) rainfall intensity and land-
slides. Russell (1971), Tryggvason, Surry and Davenport (1976), and Batts, Russell and Simiu (1980) developed systematic approaches to describe and assess the relationship between the spatial and temporal effects of a hurricane and its wind speeds over time. Russell (1969), Shemdin (1978), Young (1988), and Li and Li (1992) constructed hurricane-induced wave models to describe the spatial and temporal distribution of extreme wave within a hurricane. Kirby (1978), Cooper (1978), Freeze (1983), and Feldman (1992) set up probability models to relate flooding with rainfall intensity. Researchers such as Tubbs (1975) looked at the relationship between rainfall intensity and land sliding.

1.2 RISK ANALYSIS IN HURRICANE-PRONE REGIONS

Hurricane risk is defined as the potential danger to human beings, interference to their activities, and threat to their properties as a result of interactions between populace and hurricanes at the site of interest. Hurricane hazard is the potential occurrence of a damaging hurricane at the site of interest. Figure 1.1 shows the sequence of a natural process that leads to hurricane hazard. As long as the occurrence of a hurricane-induced event does not affect human activities or cause any damage to properties, this event does not present a risk. Gradient pressure and torrential rainfall are the characteristics of hurricanes. The larger the pressure gradient within a hurricane, the more severe the hurricane-induced extreme winds and storm surges. Furthermore, floods and landslides are common consequences of torrential rains caused by hurricanes. The figure shows the needs to construct a multiple pathway model to assess the potential human and property exposure to hurricane hazards.

The methodology used in evaluating the risk of hurricane strike includes the following three essential steps: (1) recognition of the nature and characteristics of hurricanes; (2) identification and classification of hurricane risk; and (3) assessment of hurricane-induced risk.
Figure 1.1 Hurricane-induced Hazardous Events

The purpose of doing risk analysis for hurricanes is to evaluate the potential damages and losses caused by hurricanes and to estimate the probability of potential losses and damages within a future time period. As shown in Figure 1.2, the hurricane risk analysis is a direct result of two other analyses: (1) the hurricane hazard analysis; and (2) the hurricane fragility analysis. A complete hazard analysis for hurricanes should consider a multi-pathway model to relate all the four hazardous events to the characteristics of the hazardous process shown in Figure 1.1. Moreover, the hurricane fragility analysis should include a multi-pathway model to assess the potential damage caused by various hazards due to hurricane strike.

The risk of developing properties at a site of interest within the hurricane striking zone can, then, be assessed by including the hurricane risk factor in a traditional cost-benefit analysis. When the risk factor is included, the analysis is called risk-benefit analysis. The risk-benefit analysis estimates the profitability of property develop-
Figure 1.2 The Elements of Hurricane Risk Analysis

The risk of hurricane strike, which is evaluated as the recurrence probability of hazardous events with certain intensity caused by hurricanes. The second parameter is the benefit of development, which assesses the difference between the benefit and cost incurred in the development. The cost includes the potential loss due to various haz-
ardous events. The potential loss is estimated by utility theory in terms of a "utility" function. A "utility" function represents the preference of an individual for values of finance, time, lives, etc.

Risk-benefit analysis quantifies all the significant attributes associated with hurricane strike. These attributes are used in assessing the risk of related hazards, setting up monitoring and forecasting schemes, and assessing the performance of different mitigation and management measures for risk reduction. The analysis ends by assigning explicit ranking to all the feasible alternatives in a decision tree so that the final choice is an optimal solution. The analysis allows engineers, city planners, government agents, and public officials to make decisions: (1) under uncertainty and imperfect information; and (2) on their preference and risk attitude.

1.3 SCOPE AND OBJECTIVES

In chapter 2, the author will describe the systematic methodology used in characterizing hurricanes, identifying the location at risk, and assessing the wind hazard at a site of interest. In chapter 3, a wind hazard model used to build the computer algorithm "WindHazard" is reviewed. Based on historical observations, the algorithm computes the annual probability of exceeding a threshold wind speed at the site of interest due to hurricane strike. The wind hazard model combines the work of Russell (1971), Batts, Russell, and Simiu (1980), Batts, Cordes, and Simiu (1980), Batts (1982), Cook (1983), Dorman (1983), and Simiu and Scanlan (1986). In chapter 4, a simulation model used to construct the computer program "Simulation" is discussed. Based on simulated data, the program estimates the probability of exceeding the same threshold as in the "WindHazard" algorithm at the site of interest due to hurricane strike. The simulation model is based on the theoretical formulae found in Fishman (1973), Kleijnen (1974), Ang and Tang (1975), Dorman (1983), and Law and Kelton (1992). The results of applying the wind hazard model and the simulation model to Hong Kong are presented in chapter 5. This chapter will emphasize on discussing the results of
applying the models and the needs for further research. Finally, flowcharts of the Pascal programs named "WindHazard" and "Simulation" are presented in Appendices I and II, respectively. The purpose of the first algorithm is to validate the simulation algorithm. Validation is to find out whether the actual system can be closely resembled by the simulation model. The validation procedure has to be done because of the limited amount of existing data.
CHAPTER 2
WIND RISK ANALYSIS IN HURRICANE-PRONE REGIONS

2.1 FOREWORD

In the following sections, the methodology used in assessing hurricane risk is reviewed. However, the discussion will concentrate on the nature and characteristics of hurricanes, identification and classification of hurricane risk, and wind risk assessment for hurricanes.

2.2 NATURE AND CHARACTERISTICS OF HURRICANES

As summarized in French and Squire (1980), Nalivkin (1982), Simiu and Scanlan (1986), and Kiremidjian, Chiu, Lai, and Shah (1992), tropical cyclones are one of the most violent and devastating natural phenomena on earth. They are called hurricanes if they occur over the Atlantic Ocean; they are known as typhoons if they generate over the Pacific Ocean. Frequently, they originate in warm latitudes over the Oceans. Initially, they appear as small, shallow depressions. Their lateral dimensions, heights and strengths continue to grow as long as they remain over ocean waters. As they leave their primary energy source, the warm ocean waters, tropical cyclones begin to die down when they spread over land. The dissipation of their energy is so fast that they become insignificant once they are about a hundred miles inland.

Hurricanes or typhoons occur mainly between late summer and early autumn in tropical latitudes. They occur periodically over the same annual seasons frequently with a peak in August and September. Figure 2.1 shows the number of hurricanes observed in each month of the year over the western north Pacific Ocean and south China Sea from 1961 to 1990. The data were provided by the Royal Observatory of Hong Kong. The periodic nature of hurricane occurrences is obvious from this figure since over 80% of the hurricanes occurred between July and November. This implies that the distribution of hurricane occurrences is not a
stationary renewal process since the number of hurricane arrivals is seasonally dependent. This non-stationary characteristic will be modeled by a non-stationary Poisson process in chapter 5.

![Number of Hurricanes](image)

**Figure 2.1 Monthly Hurricane Occurrences over the North Pacific**

A mature tropical cyclone consists of a gigantic atmospheric vortex with large pressure gradient. The pressure inside a hurricane decreases drastically towards its center. This center is known as the "eye". Figure 2.2 shows a typical cross-section of a hurricane. The structure of a hurricane consists of three zones: (1) the "eye", (2) the vortex, and (3) the outflow zone. Lowest pressure, highest temperature, weak wind, open top and little cloud are the characteristics of the "eye". It is a high funnel-like zone surrounded by rings of steep side walls of dense cloud, which rotates at very high speed. The vortex is a warm and moist air mass convected from low altitudes to high altitudes. When the moist air rises, it causes water vapor to condense. This condensation process results in the release of huge amount of latent heat and the formation of thick and large clouds in the vortex. These
clouds, later, become torrential rainfall. The outflow zone is the zone of descending air with relative light winds and high clouds. The flow of air from the vortex to the outflow zone sets up a pressure gradient between the vortex and the outflow zone. Hence, a field of gradient wind velocity results from this pressure gradient.

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<th>Outflow Zone</th>
<th>Vortex</th>
<th>Eye</th>
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<td>Pressure</td>
<td>Zone of descending air</td>
<td>Zone of descending air;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Barometer rises rapidly</td>
</tr>
<tr>
<td></td>
<td></td>
<td>in vertical direction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and slowly in horizontal direction</td>
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<tr>
<td>Wind</td>
<td>Gale to hurricane wind</td>
<td>Calm or light winds</td>
</tr>
<tr>
<td></td>
<td>speed; winds blow in</td>
<td></td>
</tr>
<tr>
<td></td>
<td>opposite directions</td>
<td></td>
</tr>
<tr>
<td>Cloud and</td>
<td>High clouds; Fine hot</td>
<td>Sky overcast; May be</td>
</tr>
<tr>
<td>Temperature</td>
<td>and humid</td>
<td>obscured by heavy rain</td>
</tr>
<tr>
<td>Rainfall</td>
<td>No rain</td>
<td>No rain</td>
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Figure 2.2 Typical Cross-section of a Hurricane
(French and Squire, 1980)

The typical width of a typhoon is 280 to 370 statute miles and its height varies from 5 to 10 statute miles above sea level. The average diameter of its "eye" is about 10 to 30 statute miles. The vortex wind speed of a hurricane can easily go up to 150 m.p.h. and wind speeds up
to 400 m.p.h. have been recorded. The vortex wind decays rapidly in radial direction away from the center. The translation speed of a hurricane, on average, is about 110 to 135 m.p.h. and its life span is around 9 to 12 days.

2.3 IDENTIFICATION AND CLASSIFICATION OF HURRICANE RISK

Tropical cyclones rotate in anti-clockwise direction in the northern hemisphere; on the other hand, they circulate in clockwise direction in the south hemisphere. Figure 2.3 shows the mean track of hurricanes around the world. It also shows the trajectories of hurricanes, which are dictated by the rotation of the earth and local conditions. The earth rotation causes them to move in an open parabolic shape toward the East. Local conditions, such as cold fronts, distort the parabolic shape of their path. From this figure, one can also identify the high-risk hurricane striking zones around the world. These zones include: (1) the area along the east coast of north America especially around the Gulf of Mexico, (2) the coastal region of China and islands on the North West Pacific, (3) the shoreline of Australia and New Zealand, and (4) the coastal region on both sides of Northern India.

![Figure 2.3 Mean Track of Hurricanes around the World](Simiu and Scanlan, 1986)
There are three different scales used in classifying the strength of tropical cyclones. They are: (1) the general scale; (2) the adjusted Beaufort scale; and (3) the Saffir-Simpson scale. In the general scale, typhoon or hurricane is the name given to a tropical cyclone when its vortex wind speed is greater than about 73.5 m.p.h. As shown in Table 2.1, the hierarchy of tropical cyclones is classified with respect to the vortex wind intensity of a tropical cyclone. This scale, usually used by meteorologists, is not concerned with the relationship between wind speed and the distance away from the site of interest. Therefore, it is not a good indicator for wind hazard at the site of interest.

**Table 2.1**
The Classification of Tropical Cyclone
(Royal Observatory of Hong Kong)

<table>
<thead>
<tr>
<th>General Scale</th>
<th>Maximum Sustained Winds Near the Center (m.p.h.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Storm</td>
<td></td>
</tr>
<tr>
<td>Tropical Depression</td>
<td>&lt;39</td>
</tr>
<tr>
<td>Tropical Storm</td>
<td>39-54</td>
</tr>
<tr>
<td>Severe Tropical Storm</td>
<td>54-73.5</td>
</tr>
<tr>
<td>Typhoon or Hurricane</td>
<td>&gt;73.5</td>
</tr>
</tbody>
</table>

Note: 1 knot = 0.514 m/s; 1 km/h = 0.278 m/s; and 1 m.p.h. = 0.447 m/s.

Table 2.2 shows the definition and description of the 17 levels of the adjusted Beaufort scale. Each level corresponds to a wind speed experience at the site of interest and a description of the wind strength caused by a hurricane. With historical observations at the site of interest, this classification helps us in assessing the severity of individual hurricane strike and estimating the recurrence interval of hurricanes above a threshold.

The Saffir-Simpson scale is used in assessing potential damage on structures due to hurricane wind and surge. It was introduced by Saffir in 1971. In the Saffir-Simpson scale, Table 2.3, each hurricane was classified into five categories according to the vortex wind speed, possible tidal surge, and its capability to cause structural damage. This
is a more sophisticated scale than the previous two. It associates the potential damage and loss at a site of interest with the observed extreme wind speed and storm surge due to hurricane strike.

<table>
<thead>
<tr>
<th>Table 2.2</th>
<th>The Classification of Wind Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Lane, in Nalivkin, 1982)</td>
<td></td>
</tr>
<tr>
<td><strong>Adjusted Beaufort Scale</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Scale No.</strong></td>
<td><strong>Wind Speed (m.p.h.)</strong></td>
</tr>
<tr>
<td>0</td>
<td>&lt;1</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
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<tr>
<td>5</td>
<td>21</td>
</tr>
<tr>
<td>6</td>
<td>27</td>
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<tr>
<td>7</td>
<td>34</td>
</tr>
<tr>
<td>8</td>
<td>42</td>
</tr>
<tr>
<td>9</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>59</td>
</tr>
<tr>
<td>11</td>
<td>68</td>
</tr>
<tr>
<td>12</td>
<td>78</td>
</tr>
<tr>
<td>13</td>
<td>88</td>
</tr>
<tr>
<td>14</td>
<td>98</td>
</tr>
<tr>
<td>15</td>
<td>109</td>
</tr>
<tr>
<td>16</td>
<td>120</td>
</tr>
<tr>
<td>17</td>
<td>&gt;131</td>
</tr>
</tbody>
</table>

2.4 WIND RISK ASSESSMENT FOR HURRICANES

A hurricane risk assessment includes the determination of risk levels and the evaluation of social risks of a community caused by hazardous events such as extreme winds, storm surges, floods, and landslides. The assessment, also, estimates the magnitude of their potential economic and social consequences associated with a hurricane strike.

Risk assessment procedures used in estimating the wind risk is identical to the risk assessment procedures used in evaluating the hurricane risk, Figure 1.2, because wind risk assessment is a subset of the hurricane risk analysis. The wind risk assessment for hurricanes
assumes that the average frequency of hurricane strike and the average hurricane strength will not change over time. That means the assessment based on past records can be used in forecasting the future hurricane occurrences and the associated wind hazards.

Table 2.3
The Classification of Potential Hurricane Damage
(Saffir, 1983)

<table>
<thead>
<tr>
<th>Category</th>
<th>Damage</th>
<th>Wind Speed (m.p.h.)</th>
<th>Surge (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minimal</td>
<td>74-95</td>
<td>4-5</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
<td>96-110</td>
<td>6-8</td>
</tr>
<tr>
<td>3</td>
<td>Extensive</td>
<td>111-130</td>
<td>9-12</td>
</tr>
<tr>
<td>4</td>
<td>Extreme</td>
<td>131-155</td>
<td>13-18</td>
</tr>
<tr>
<td>5</td>
<td>Catastrophic</td>
<td>&gt;155</td>
<td>&gt;18</td>
</tr>
</tbody>
</table>
CHAPTER 3
WIND HAZARD MODEL FOR HURRICANES

3.1 FOREWORD

Since the process of hurricane generation and dissipation is random in nature, a wind hazard model for hurricanes needs to estimate the temporal and spatial distribution of hurricanes. If the hurricane occurrences are statistically independent, a renewal process can be used to model the hurricane occurrences. Furthermore, the wind hazard model also describes the randomness of the hurricane-induced extreme winds. If the extreme winds are independent and identically distributed, an extreme-value model can be used to describe the distribution of the extreme winds. The required parameters for modeling the wind hazard include: (1) the inter-arrival times of hurricanes; (2) the translation velocity of a hurricane; (3) the pressure difference between the center of a hurricane and its periphery; (4) the radius to the region of maximum winds; and (5) the distance between the center of a hurricane and the site of interest. With these parameters in hand, one can evaluate the wind hazards corresponding to different threshold values.

The wind hazard caused by hurricanes at the site of interest is defined as the probability that the hurricane-induced wind speed, \( V_H \), at the site of interest is greater than a threshold speed, \( v \), in a given time, \( t \), and is written as follows:

\[
P_H(V_H > v, t) = \sum_{n=0}^{\infty} P_H(V_H > v | N) P_N(n, t)
\]  (3.1)

Where:

\( P_H(V_H > v, t) \) Probability of hurricane-induced wind speed, \( V_H \), greater than a specific value, \( v \), in time \( t \);
\[ P_H(V_H > v | N) \]

Probability of having wind speed, \( V_H \), greater than a specific value, \( v \), given the occurrences of \( N = n \) hurricanes;

\[ P_N(n, t) \]

Probability of having \( n \) hurricanes in time \( t \);

Specified period of time; and

\( n \)

Number of hurricanes in a given time \( t \).

Equation 3.1 is the hazard model used to describe the wind hazard induced by hurricanes at the site of interest. This hazard model is the basis for the algorithms used to implement the Pascal programs "WindHazard" and "Simulation".

As discussed in the first paragraph, the wind hazard model consists of two sub-models. They are: (1) a stochastic recurrence model; and (2) an extreme wind model. The stochastic recurrence model can be either a homogeneous (stationary) Poisson process or a non-homogeneous (non-stationary) Poisson process. The only parameter required by both processes are the arrival rate of hurricanes, \( \lambda(t) \), at the site of interest in time \( t \). The arrival rate for the homogeneous Poisson process and the non-stationary Poisson process can be estimated by regression analysis using time series. The constant mean model characterizes the parameter of the homogeneous Poisson process. The globally constant seasonal model is applied to the non-homogeneous Poisson process. This model represents the non-stationary character of the non-homogeneous Poisson process.

The extreme wind model can be represented by either the Gumbel or Weibull distribution. Two parameters, the scale factor and the shape factor, are required to define either distribution. The method of moment or the method of maximum likelihood can be used to estimate these parameters. In the case of the Weibull distribution, a numerical method called the Newton-Raphson method is required to compute the shape factor because a close-form solution does not exist. Before any extreme wind model can be applied, the maximal gradient wind speed at the site of interest caused by a hurricane has to be estimated. The wind field model is used to evaluate the maximal gradient wind speed, \( V_H \), within a
hurricane at a particular time. To calculate $V_H$, the latitude and longitude of a hurricane center have to be recorded in advance. Thus, the shortest distance between a hurricane center and the site of interest at any time can be calculated by the method of spherical triangle in field astronomy.

3.2 STOCHASTIC RECURRENT MODELS

A stochastic process describes a randomly distributed event over time. A renewal process is a stochastic process that describes independent events of time without assuming that the distribution of the events is exponential. The most frequently used renewal processes in forecasting hurricane occurrences are the homogeneous Poisson process and the non-homogeneous Poisson process. If the arrival process is a Poisson process, the probability of having $n$ hurricanes in time $t$ is:

$$P_H(n, t) = \frac{(\lambda(t) \cdot t)^n}{n!} e^{-\lambda(t) \cdot t} \quad \text{for } n = 1, \ldots \text{ and } \lambda > 0 \quad (3.2)$$

Where $\lambda(t)$ is the arrival rate of hurricanes of the Poisson process.

Since the hurricanes occur in time-ordered sequence, $\lambda(t)$ can be modeled as a time series and estimated by regression analysis. In a regression analysis, the time dependent model can be written as:

$$\lambda(t) = f(t, \beta) + e_t \quad (3.3)$$

Where:

- $f(t, \beta)$ Function of time $t$ and coefficients $\beta$; and
- $e_t$ Uncorrelated error component with zero mean and constant variance.

The coefficients $\beta$ can be determined by fitting different time series to historical records of hurricane occurrences. The non-seasonal and seasonal time series are the most common functions used for the
homogeneous Poisson process and the non-stationary Poisson process, respectively. The constant mean model, which will be discussed in the next section, is a model for non-seasonal series while the globally constant seasonal model, which will be discussed in section 3.2.3, is a model of seasonal series.

3.2.1 HOMOGENEOUS POISSON PROCESS

The homogeneous Poisson process is the simplest of all renewal processes. If a renewal process is a homogeneous Poisson process, the events of this process are independent, identically distributed, stationary and exponentially distributed. In addition, the parameter \( \lambda(t) \) can be estimated by the constant mean model, i.e. \( f(t, \beta) = \lambda \),

\[
\lambda(t) = \lambda + e_t
\]  
(3.4)

Where:

\( \lambda \) Mean annual rate of hurricane occurrences and is time independent; and

\( e_t \) Uncorrelated error component with zero mean and constant variance.

Hence, by substituting the expected value of \( \lambda(t) \) in equation 3.4 into equation 3.2, the probability of having \( n \) hurricanes in time \( t \) becomes:

\[
P_N(n, t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \quad \text{for } n = 1, 2, \ldots \text{ and } \lambda > 0
\]  
(3.5)

If a homogeneous Poisson process is assumed, equation 3.1 becomes:

\[
P_H(V_H > v, t) = \sum_{n=0}^{\infty} P(V_H > v|N) \frac{(\lambda t)^n}{n!} e^{-\lambda t}
\]  
(3.6)
3.2.2 NON-HOMOGENEOUS POISSON PROCESS

In the homogeneous Poisson process, the arrival rate of hurricanes, $\lambda(t)$, is constant in time. However, as shown in Figure 2.1, hurricane recurrence is seasonally dependent. Hence, it is more appropriate to use the non-homogeneous Poisson process to describe this seasonal dependent characteristics of hurricane recurrence. Similar to the homogeneous Poisson process, the hurricane arrival process is a non-homogeneous Poisson process if the inter-arrival times among hurricanes are independent and identically distributed. However, they are not necessary distributed exponentially. In addition, unlike the homogeneous Poisson process, the arrival rate of the non-homogeneous Poisson process, $\lambda(t)$, is a function of time rather than being constant. In this case, $\lambda(t)$ is defined as follows:

$$\lambda(t) = \frac{d}{dt} \psi(t)$$

(3.7)

Where $\psi(t)$ is the expectation function for a non-homogeneous Poisson process and must be differentiated for all $t$. $\lambda(t)$ can be estimated by fitting the seasonal dependent model stated in equation 3.3 to a set of observed data.

3.2.3 SEASONAL TIME SERIES

The homogeneous Poisson process is suitable for predicting the extreme wind speed due to hurricane occurrences if the number of hurricanes occurred in each month of a year were fairly constant. However, Figure 2.1 shows that the rate of hurricane recurrence is much higher in the summer than in the winter over the north Pacific. Therefore, the homogeneous Poisson process is not adequate in describing this seasonal trend. This seasonal trend has a tendency to repeat itself within a certain time and can be characterized by seasonal time series. The length of the cycle of a seasonal time series is refereed to as the sea-
sonal period. For a monthly series with yearly seasonal trend, the seasonal period is 12 months.

This yearly seasonal trend of hurricane recurrence does not happen by chance. It is due to the rotation of the earth around the sun. During the summer months, the radiation from the sun hits the northern hemisphere directly and warms the Pacific Ocean around the Equator. This warm water is the main energy source for hurricanes. As a result, the seasonal pattern of hurricane occurrences is quite stable and repeats itself year after year.

The simplest seasonal time series used in estimating $\lambda(t)$ is the globally constant seasonal model. This model will be discussed in the following section.

### 3.2.3.1 GLOBALLY CONSTANT SEASONAL MODEL

As presented in Abraham and Ledolter (1983), the expected number of hurricane occurrence in a given time $t$, $\lambda(t)$, of a non-homogeneous Poisson process can be estimated by the globally constant seasonal model. The model can be decomposed into three components that account for the seasonal trend: (1) the trend component $T_t$; (2) the seasonal component $S_t$; and (3) the error component $e_t$, i.e.,

$$\lambda(t) = \frac{d}{dt} \psi(t) = T_t + S_t + e_t$$  \hspace{1cm} (3.8)

Usually, the trend component $T_t$ is modeled by a Taylor series of time $t$:

$$T_t = C_0 + \sum_{i=1}^{\infty} C_i \frac{t^i}{i!}$$  \hspace{1cm} (3.9)
The seasonal component $S_t$ can be modeled as a linear combination of $m$ sine functions with frequency $f_i = \frac{2\pi i}{s}$, amplitude $C_{1i}$, and phase angle $C_{2i}$. Therefore:

$$S_t = \sum_{i=1}^{\infty} C_{1i} \cos \left[ \frac{2\pi i}{s} (t + C_{2i}) \right]$$

(3.10)

Where the amplitude $C_{1i}$ is the weighting factor corresponding to each term in the above linear combination and $s$ is the seasonal period.

The error component $e_t$ is usually assumed to be uncorrelated and identically Gaussian distributed with mean zero and constant variance.

By substituting equation 3.9, equation 3.10 and $E[e_t] = 0$ into equation 3.8, then:

$$\frac{d}{dt} \psi(t) = C_0 + \sum_{i=1}^{\infty} C_i \frac{t^i}{i!} + \sum_{i=1}^{\infty} C_{1i} \cos \left[ \frac{2\pi i}{s} (t + C_{2i}) \right]$$

(3.11)

The globally constant seasonal model can, then, be rewritten as follows:

$$\frac{d}{dt} \psi(t) = \lambda \left\{ 1 + \sum_{i=1}^{\infty} C_{1i} \frac{t^i}{i!} + \sum_{i=1}^{\infty} C_{1i} \cos \left[ \frac{2\pi i}{s} (t + C_{2i}) \right] \right\}$$

(3.12)

Where:

- $\lambda$ Mean rate of a homogeneous Poisson process and $\lambda = C_0$;
- $C_{1i}' = \frac{C_{1i}}{C_0}$; and
- $C_{1i}'' = \frac{C_{1i}}{C_0}$.

Since the sum of the expected number of hurricanes estimated by the non-homogeneous Poisson process can be expressed as the product of
the mean rate of a homogeneous Poisson process and a uniformed time scale $t'$ after transforming from time $t$ to time $t'$, then:

$$\int_{t=1}^{\infty} \frac{d}{dt} \psi(t) \, dt = \lambda \, t'$$  \hspace{1cm} (3.13)

After integration,

$$t' = t + \sum_{i=1}^{\infty} C_{i}' \frac{t^{i+1}}{(i+1)!} + \sum_{i=1}^{\infty} \frac{s \cdot C_{i}}{2\pi i} \left\{ \sin \left[ \frac{2\pi i}{s} (t + C_{2i}) \right] - \sin \left[ \frac{2\pi i}{s} C_{2i} \right] \right\}$$  \hspace{1cm} (3.14)

Hence, equation 3.2 becomes:

$$P_n(n, t) = \frac{(\lambda t')^n}{n!} e^{-\lambda t'} \quad \text{for } n = 1, \ldots \text{ and } \lambda > 0$$  \hspace{1cm} (3.15)

The coefficients in the globally constant seasonal model are expressed relative to the origin. If the expected value other than the period between time zero and the time in question is needed, the origin has to be shifted to the desired starting point before doing the same calculation.

The amplitudes and the phase angles in the globally constant seasonal model are fixed. The values of the expected number of hurricanes will repeat every 12-month. If time-changing amplitudes and phase angles are desired, the locally constant seasonal models may be used.

After evaluating the probability of hurricane occurrences, the next step is to estimate the extreme winds induced by the hurricanes at the site of interest. Section 3.3 will discuss the extreme wind models used in assessing the extreme winds.
3.3 EXTREME WIND MODELS

Usually, the maximal gradient winds, \( v \), of hurricanes in equation 3.1 are also assumed to be independent and identically distributed. In addition, \( F_H(V_H) \) represents the cumulative distribution function of the maximal gradient winds induced by hurricanes at the site of interest given that \( n \) hurricanes have occurred in time \( t \). Therefore:

\[
P_H(V_H > v|n) = 1 - [F_H(V_H)]^n \tag{3.16}
\]

By substituting equation 3.2 and equation 3.16 into equation 3.1, we get:

\[
P_H(V_H > v, t) = \sum_{n=0}^{\infty} (1 - [F_H(V_H)]^n) \frac{(\lambda(t) * t)^n}{n!} e^{-\lambda(t) * t} = 1 - e^{-\lambda(t)[1-F_H(V_H)]t} \tag{3.17}
\]

Equation 3.17 is known as the compound Poisson process, which is a homogeneous Poisson process with reduced arrival rate \( \lambda_1(t) = \lambda(t)[1-F_H(V_H)] \).

If the random variable \( V_H \) is independent and identically distributed, the Gumbel or Weibull distribution can be used to assess the probability of exceeding hurricane winds within a given time at the site of interest. The data are abstracted from historical observations and the gradient wind speeds are estimated by the wind field model of a hurricane.

3.3.1 GUMBEL DISTRIBUTION

For the Gumbel distribution, the cumulative distribution function for the counted number of hurricane-induced wind speed is:

\[
F_H(V_H) = \exp(-\exp(-a_n(V_H - u_n))) \tag{3.18}
\]
Where:

\[ u_n \quad \text{Mode of } V_H; \text{ and} \]
\[ a_n \quad \text{Inverse of dispersion of } V_H. \]

By the method of moments, the parameters of this extreme wind model can be estimated as:

\[ a_n = \frac{\pi}{\sqrt{6} \sigma_n} \quad \text{and} \quad u_n = \mu - \frac{\gamma}{a_n} \quad (3.19) \]

Where:

\[ \sigma_n \quad \text{Sample standard deviation;} \]
\[ \mu \quad \text{Sample mean;} \text{ and} \]
\[ \gamma \quad \text{Euler's constant and is equal to 0.577216.} \]

3.3.2 WEIBULL DISTRIBUTION

For the Weibull distribution, the cumulative distribution function for the counted number of hurricane-induced wind speed is:

\[ F_H(V_H) = 1 - \exp\left(-\left(\frac{V_H}{\beta}\right)^\alpha\right) \quad (3.20) \]

Where:

\[ \alpha \quad \text{Shape factor of } V_H \text{ and is greater than zero; and} \]
\[ \beta \quad \text{Scale factor of } V_H \text{ and is greater than zero.} \]

By the method of maximum likelihood, the shape and scale factors of the Weibull distribution can be estimated by solving the following two equations using numerical procedures such as the Newton-Raphson method:
\[ \sum_{i=1}^{n} \frac{x_i^\alpha \ln x_i}{\sum_{i=1}^{n} x_i^\alpha} - \frac{1}{\alpha} = \frac{\sum_{i=1}^{n} x_i}{n} \]  
(3.21)

\[ \beta = \left( \frac{\sum_{i=1}^{n} x_i^\alpha}{n} \right)^{-\frac{1}{\alpha}} \]  
(3.22)

Equation 3.21 can be solved for \( \alpha \) numerically, then, \( \beta \) can be calculated by solving equation 3.22 directly. The recursive algorithm given in equation 3.23, which is based on the Newton-Raphson method, is implemented in both the Pascal programs "WindHazard" and "Simulation" to find the shape factor \( \alpha \) for the Weibull model. The accuracy of the solution, if there is one, depends on the chosen criterion for convergence.

The general recursive step for solving equation 3.21 by the Newton-Raphson method as presented in Thoman, Bain, and Antle (1969) is:

\[ \alpha_{j+1} = \alpha_j + \frac{A + \frac{1}{\alpha_j} - \frac{C_j}{B_j}}{\frac{1}{\alpha_j^2} + \frac{B_j H_j - C_j^2}{B_j^2}} \]  
(3.23)

where:

\[ A = \frac{\sum_{i=1}^{n} \ln x_i}{n} ; \]

\[ B_j = \sum_{i=1}^{n} x_i^{\alpha_j} ; \]

\[ C_j = \sum_{i=1}^{n} x_i^{\alpha_j} \ln x_i ; \] and

\[ H_j = \sum_{i=1}^{n} x_i^{\alpha_j} (\ln x_i)^2 . \]
As a starting point for iterations, the initial guess stated in Menon (1963) can be taken as:

\[
\alpha_0 = \left\{ \frac{6}{\pi^2} \sum_{i=1}^{n} (\ln X_i)^2 - \frac{\left( \sum_{i=1}^{n} \ln X_i \right)^2}{n} \right\}^{\frac{1}{2}} \frac{1}{n - 1}
\]

(3.24)

With this initial value, about 4 iterations were needed to achieve four places of accuracy in the solution.

Before the application of any extreme wind model such as equation 3.18 or equation 3.20, data about the extreme gradient winds have to be available. The following section will discuss the method for calculating the gradient wind speed within a hurricane using its measurable characteristics.

### 3.4 WIND FIELD MODEL

Figure 3.1 shows the variation of maximum gradient winds within typical hurricanes at six-hour intervals. The need to describe the time effect on gradient wind speeds at the site of interest is obvious since these gradient winds may well be below the maximum speed within the life of the hurricane when the hurricane hits the site. To describe the time history of the wind speed at the site of interest, the gradient wind field at the site \((r_{site}, \theta_{site})\) has to be transformed relative to the hurricane center at a particular time.

The gradient wind speed within a hurricane depends on the following properties of the hurricane:

1. Translation velocity of the hurricane;
2. Radius to the maximal gradient winds from hurricane center;
3. Central pressure difference between the vortex and the periphery of a hurricane; and
4. Relative distance and direction between the hurricane center and the site of interest.

![Graph showing variation of maximum gradient winds for typical hurricanes at six-hour intervals.](image)

**Figure 3.1** Variation of Maximum Gradient Winds for Typical Hurricanes at Six-hour Intervals

The wind field model of a hurricane is a mathematical model describing the gradient wind speed at any location within the hurricane. Figure 3.2 shows the typical gradient wind field of a hurricane.

The gradient wind speed for a moving hurricane discussed in Tryggvason, Surry, and Davenport (1976) is:

\[
v(r, \theta) = \frac{1}{2} \left[ (f r - v_T \sin \theta)^2 + 4 r \frac{1}{\rho} \frac{dp}{dr} \right]^{\frac{1}{2}} - \frac{1}{2} (f r - v_T \sin \theta)
\]

Where:
Figure 3.2 Typical Gradient Wind Field of a Hurricane
(Trayggvason, Surry, and Davenport, 1976)

\[ v(r, \theta) \] Gradient wind speed of a hurricane at coordinates \((r, \theta)\) in m.p.h.;

\( r \) and \( \theta \) Polar coordinates, where \( r \) is in statute mile and \( \theta \) in degree, with origin at the center of the hurricane;

\( v_T \) Translation speed of the hurricane in m.p.h.;

\[ \frac{dp}{dr} \] Radial gradient pressure in mb per statute mile;

\( \rho \) Air density, \( \rho = 0.00115 \text{ g/cm}^3 \); and

\( f \) Coriolis factor at different latitude as shown in Table 3.1.
Table 3.1
The Relationship between Latitude and Coriolis Factor
(Simiu and Scanlan, 1986)

<table>
<thead>
<tr>
<th>Latitude (degree)</th>
<th>Coriolis Factor, ( f ) (hr^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000000</td>
</tr>
<tr>
<td>5</td>
<td>0.045756</td>
</tr>
<tr>
<td>10</td>
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</tr>
<tr>
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</tr>
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</tr>
<tr>
<td>30</td>
<td>0.262512</td>
</tr>
<tr>
<td>35</td>
<td>0.301140</td>
</tr>
<tr>
<td>40</td>
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</tr>
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<td>50</td>
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</tr>
<tr>
<td>60</td>
<td>0.454680</td>
</tr>
<tr>
<td>65</td>
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<td>70</td>
<td>0.493380</td>
</tr>
<tr>
<td>75</td>
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</tr>
<tr>
<td>80</td>
<td>0.517068</td>
</tr>
<tr>
<td>85</td>
<td>0.523044</td>
</tr>
<tr>
<td>90</td>
<td>0.525024</td>
</tr>
</tbody>
</table>

The radial pressure gradient of the hurricane used in Myers and Malkin (1961) can be approximated by:

\[
dP \over dr = \Delta P \frac{R}{r^2} e^{-R/r}
\]  

(3.26)

Where:

\( R \) Radius to the region of maximum wind; and

\( \Delta P \) Central pressure difference of the hurricane in millibars (mb) and \( \Delta P = P_n - P_o \). Where \( P_o \) is the pressure at location of maximal wind and \( P_n \), which equals to 1014 mb, is the periphery pressure.

To estimate the distance between the hurricane center and the site of interest, \( r \), one has to gather data on: (1) the latitude and longitude of a hurricane center at a particular time; and (2) the latitude and longitude of the site of interest. As presented in Agor (1986), the
following sections summarize the procedures to calculate the shortest distance between two points on the earth surface using field astronomy.

3.4.1 SPHERICAL TRIANGLE IN FIELD ASTRONOMY

In field astronomy, a spherical triangle is the surface of a sphere bounded by the intersection of three great circles. As shown in Figure 3.3, the arcs of three great circles, XY, YZ and ZX, on the sphere whose center is at O. The portion enclosed by these three arcs is the spherical triangle XYZ.

3.4.1.1 ELEMENTS OF A SPHERICAL TRIANGLE

A spherical triangle consists of three sides and three angles. The magnitudes of all the sides and angles are expressed in degree. The sides of the triangle XYZ in Figure 3.3 are the arcs XY, YZ and ZX. Their magnitudes are represented by the lower case characters x, y and z, respectively. The angles of triangle XYZ are the angles between the planes ZXO, XOY and YOZ, and are generally represented by the capital letters x, y and z, respectively.

Any side or angle of a spherical triangle XYZ can be calculated by any three given elements of the same triangle using one of the following three formulae:

1. Sine: \[ \frac{\sin x}{\sin X} = \frac{\sin y}{\sin Y} = \frac{\sin z}{\sin Z} \]  
   \[ (3.27) \]

2. Cosine: \[ \cos x = \cos y \times \cos z + \sin y \times \sin z \times \cos X \]  
   \[ (3.28) \]

3. Tangent: \[ \tan \frac{x}{2} = \sqrt{\frac{\sin (S - y) \times \sin (S - z)}{\sin S \times \sin (S - x)}} \]  
   \[ (3.29) \]

where \( x + y + z = 2S \).
Figure 3.3  A Spherical Triangle
(Agor, 1986)

3.4.1.2 COORDINATE SYSTEM ON THE EARTH SURFACE

The terrestrial latitude and longitude are the coordinate system used to determine the location of any point on the earth surface. Terrestrial latitude is defined as the angle subtended by the location of interest and the equator with respect to the center of the earth. The complement of terrestrial latitude, which is known as co-latitude, is the angular distance between the location of interest and the North or South pole. Terrestrial longitude is defined as the angle subtended by the meridian plane of the location of interest and a reference meridian plane with respect to the center of the earth. Traditionally, the meridian plane that passed through Greenwich in England has been chosen as the reference plane.
3.4.1.3 THE SHORTEST DISTANCE ON THE EARTH SURFACE BETWEEN TWO GIVEN POINTS

The shortest distance between two points on the earth surface, arc XY in Figure 3.4, is defined as the angular distance measured along a great circle passing through the given points. This distance is calculated by multiplying the earth radius to the angle subtended by the arc XY with respect to the center of the earth.

![Diagram](image)

**Figure 3.4 The Shortest Distance on the Earth Surface between Two Points**
(Agor, 1986)

In Figure 3.4, SN is the great circle of horizon. EE' is the arc of equator. PP' is the axis that passed through the North and South poles. O is the center of the earth with radius \( R_0 \). \( \omega_1 \) is the latitude of point X on the earth surface, which is the angular distance XZ.
measured from Z on the equator. X and Z are on the same meridian plane. \( \phi_1 \) is the longitude of point X on the earth's surface. It is the angular distance between a chosen reference meridian plane and the meridian plane that contains points X and Z.

In the spherical triangle XYP, side XP = 90° - \( \omega_1 \), side YP = 90° - \( \omega_2 \) and angle XPY = \( \phi_2 - \phi_1 \). In the figure, XP and YP are the co-latitudes, and angle XPY is the difference in longitude. By applying cosine rule to the triangle XYP:

\[
\cos XOY = \cos XP \times \cos YP + \sin XP \times \sin YP \times \cos XPY \quad (3.30)
\]

Therefore:

The shortest distance \( XY = \frac{R_0 \times \text{angle } XOY \times \pi}{180^\circ} \) \( (3.31) \)
CHAPTER 4
SYSTEM SIMULATION

4.1 FOREWORD

System simulation provides a useful way to study the characteristics and complexities of a system when the observed data are not sufficient. This is the situation in studying the hurricane-induced wind hazard at Hong Kong. Figure 4.1 shows different approaches in studying the characteristics of a system. Simulation implies experimenting with a system model over time rather than with the actual system. The characteristics of the system model are monitored over time. It is necessary to study the system model instead of the actual system for hurricane-induced wind hazard because the actual system cannot be experimented.

According to Figure 4.1, system model can be classified into two different types. They are the physical model and the mathematical model. A physical model is usually a scale model that captures all the characteristics of a real system. Since hurricanes cannot be directly reproduced using current technology, a mathematical model appears to be the best way to study the behavior of hurricanes. A mathematical model represents the characteristics of hurricanes in terms of their logical and quantitative relationships. With these relationships, the model hurricane can be manipulated to study the wind hazard due to hurricanes. As a result, the wind hazard of hurricanes can be predicted if the mathematical model is valid.

There are two branches of the mathematical model. One of them can be obtained by analytical solutions and the other by numerical solutions. If the mathematical model is simple, it is better to use the model with an analytical solution. However, the model with a numerical solution such as simulation is recommended for the study if the observed data are not sufficient.
The subsequent sections summarize the steps in simulating the characteristics of hurricanes. These steps, as discussed in Law and Kelton (1991), Kleijnen (1974), and Fishman (1973), are:

![Diagram of simulation steps]

**Figure 4.1  Methods in Studying the Characteristics of a System**

(Law and Kelton, 1991)

1. Select input distributions for the required random variables;
2. Generate random numbers;
3. Generate required random variates from the random number generator and the selected input distributions; and
4. Determine the validity of the simulation model.
4.2 SELECTION OF INPUT DISTRIBUTIONS

The probability distribution of each input random variable has to be selected before any simulation starts. This distribution is selected by fitting theoretical distributions to the observed data of the corresponding random variable. The best fitted distribution is chosen as the input probability distribution.

In simulating the wind speeds produced by hurricanes that can cause damage to the site of interest, the probability distribution of the following random variables have to be determined in advanced:

1. Minimum pressure within a hurricane;
2. Hurricane track speed;
3. Hurricane track angle;
4. Latitude of hurricane center;
5. Longitude of hurricane center; and
6. Radius to the region of maximum wind.

In addition, the inter-arrival times of hurricanes are treated as a random process and have to be determined in advanced. The input probability distribution for each of the random variables and for the arrival process used in the case of Hong Kong are the lognormal distribution and the non-homogeneous Poisson process, respectively.

In the following sections, the method for selecting input probability distributions is discussed. The method include techniques for assessing independence of random variables, and determining the fitness of a selected distribution. Only those techniques employed in developing the "Simulation" program will be discussed.

4.2.1 TECHNIQUES FOR ASSESSING INDEPENDENCE

It is necessary to assume data independence for the random variables, such as the hurricane track speed when the data are shown to be
uncorrelated. Although this assumption is not theoretically supported, it will be used in this analysis because of its simplicity. Furthermore, extensive amount of data is required to assess data independence. A correlation plot is a graphical technique for assessing data correlation.

A correlation plot is a plot of the sample correlation $\rho_j$ for a covariance-stationary process. The sample correlation $\rho_j$ is an estimate of the true correlation, $\rho_j$, between two observations that are $j$ observations apart in time. For a covariance-stationary process, $\rho_j$ can be estimated as follows:

$$\rho_j = \frac{C_j}{S^2_n}$$  \hspace{1cm} (4.1)

In equation 4.1, $C_j$ is the covariance and $S_n$ is the sample standard deviation. $C_j$ can be estimated by the following equation:

$$C_j = \frac{E[(X_i - \mu_i)(X_{i+j} - \mu_{i+j})]}{S_i S_{i+j}}$$

$$= \frac{1}{n-j} \sum_{i=1}^{n-j} (X_i - \mu_n)(X_{i+j} - \mu_n)$$  \hspace{1cm} (4.2)

Where $X_i$ and $X_{i+j}$ are the data of two samples with $j$ observations apart; $S_i$ and $S_{i+j}$ are the corresponding sample standard deviation; and $\mu_i$, $\mu_{i+j}$ and $\mu_n$ are the sample mean.

### 4.2.2 Determining the Fitness of a Selected Distribution

Prior knowledge and information about the characteristics of a random variable can promote some distributions theoretically without any data. For instance, hurricane occurrences can be assumed to follow a Poisson process. The range of existing data can be used to rule out some distributions as well. For example, it is not appropriate to model
inter-arrival times of hurricanes using normal distribution because these times cannot be negative.

![Figure 4.2 Definition of P-P plot](Law and Kelton, 1991)

Before generating random variates from random number generator and the selected input distribution, the closeness of the selected distribution to the underlying distribution has to be assessed. This assessment can be done with either the statistical procedures such as the goodness-of-fit tests or the graphical techniques such as the P-P plot. Most of the goodness-of-fit tests like the Chi-square tests and the Kolmogorov-Smirnov tests assume data independence therefore they are not very powerful in assessing the fitness of the assumed distribution to the data when the sample sizes are small to moderate. Thus, these tests cannot directly apply to dependent data. Hence, the goodness-of-fit tests will not be discussed and used. Graphical techniques can be applied to both dependent and independent data besides their simplicity. The probability-probability (P-P) plot represents graphically the relationship between a theoretical distribution and an observed probability. As shown in Figure 4.2, the CDF corresponding to the theoretical and the
observed distributions on each random variate are recorded. Then, a plot of the exceeding probability of the theoretical against the observed distribution corresponding to individual random variate is called the P-P plot. The P-P plots for each of the required random variables for the simulation model are shown in Figure 5.5.

4.3 RANDOM NUMBER GENERATOR

After the input probability distribution for each random variable has been determined, the next and most important task is to choose the algorithm for generating random numbers. Independent and identically distributed random numbers are defined as random variates. They are generated from the uniform distribution on the interval [0,1]. The IID random numbers are the fundamental elements for generating random variates with other probability distributions or arrival processes. Linear congruential generator is one of the most popular method in generating IID random numbers, Lehmer (1951), and is used in the "Simulation" program to generate IID random numbers. The recursive formula for linear congruential generator is:

$$Z_i = (aZ_{i-1} + c) \mod m$$

(4.3)

Where $Z_1, Z_2, \ldots, m, a, c$ and $Z_0$ are the sequence of integers, modulus, multiplier, increment and seed of the generator, respectively.

The modulus, multiplier, increment, and seed must be non-negative integers. The user provides the seed, which is the initial value of $Z_{i-1}$ in equation 4.3. Then, the new IID random number $Z_i$ is used as the seed for the next iteration. $Z_i$, which lies between 0 and $m$-1, can be converted to random numbers between 0 and 1 by dividing $Z_i$ with $m+1$. The values of $a$, $c$, and $m$ are usually chosen as 16807, 1, and $2^{31}$-1, respectively.
4.4 RANDOM VARIATES AND RANDOM PROCESSES GENERATION

A simulation that has random nature must involve generating random variates from a selected probability distribution using IID random number generator mentioned in the previous section. The following sections will discuss the techniques for generating random variates and random processes using the IID random number generator with their corresponding input distributions.

4.4.1 GENERATING RANDOM VARIATES

There are many techniques for generating random variates from a specific distribution. The specific distribution dictates the choice of numerical techniques being used. The most commonly used technique is the inverse transform method. Figure 4.3 shows the transformation from the IID random numbers to the corresponding random variates according to the probability distribution $F_X(X)$. The inverse transform method includes three steps:

1. Generate a uniformly distributed random number between 0 and 1;
2. Transform the uniformly distributed random number into the corresponding random variate according to a selected distribution; and
3. Repeat step 1 and step 2.

In this thesis, lognormal distribution is used as the input distribution for each random variable in wind hazard analysis for hurricanes at Hong Kong. Thus, only the techniques applied to generate the lognormal random variates are discussed in the following sections. These techniques are implemented in the "Simulation" program.

4.4.1.1 LOGNORMAL RANDOM VARIATES

A random variable $X = e^Y$ has a lognormal distribution if $\text{LN}(X)$ is normally distributed. That means $X$ belongs to $\text{LN}({\eta},\xi^2)$ if $Y$ belongs to
$N(\mu, \sigma_n^2)$. This relationship between normal and lognormal distribution is used to generate the lognormal random variates as follows:

1. Generate $Y$ from $N(\mu, \sigma_n^2)$;
2. Return $X = e^Y$; and
3. Repeat step 1 and step 2.

---

**Figure 4.3** Inverse Transform Method for Random Variable $X$

(Ang and Tang, 1975)

To accomplish step 1, the polar method discussed in next section for normal variate generation can be used. $\mu$ and $\sigma_n$ are the sample mean and standard deviation for normally distributed random variates. On the other hand, $\eta$ and $\zeta$ are the mean and standard deviation for lognormally distributed random variates. The relationships between $\mu$, $\sigma_n$, $\eta$ and $\zeta$ are given as follows:

\[ \zeta^2 = \ln \left(1 + \frac{\sigma_n^2}{\mu^2}\right) \]  \hspace{1cm} (4.4)

\[ \eta = \ln \mu - \frac{1}{2} \sigma_n^2 \]  \hspace{1cm} (4.5)
4.4.1.2 NORMAL RANDOM VARIATES

To generate the lognormal random variates, the normal random variates have to be generated first. The original method for generating normal random variates was proposed by Box and Muller in 1958. However, the author prefers the polar method described by Marsaglia and Bray in 1964. Thus, the polar method is used to implement the "Simulation" program. As stated in Law and Kelton (1991), the polar method is faster than the Box and Muller method in computer implementation because the polar method does not use any trigonometric functions. Similar to the Box and Muller method, the polar method generates \( N(0,1) \) random variates in pairs. The polar method consists of the following steps:

1. Generate \( U_1 \) and \( U_2 \) as IID \( U(0,1) \);
2. Calculate \( V_1 = 2U_1 - 1 \) and \( V_2 = 2U_2 - 1 \);
3. Compute \( W = V_1^2 + V_2^2 \);
4. Repeat step 1 to step 3 if \( W > 1 \); otherwise, go to step 5;
5. \( Y = \sqrt{-\frac{2\ln W}{W}} \);
6. \( X_1 = V_1 Y \) and \( X_2 = V_2 Y \); and
7. Repeat step 1 to step 6.

Where \( X_1 \) and \( X_2 \) are IID \( N(0,1) \) random variates, too.

4.4.2 GENERATING THE RANDOM ARRIVAL PROCESS

As discussed before, the non-homogeneous Poisson process is a better model for non-stationary arrival processes. The inter-arrival times of such a process are independent but not necessarily exponentially distributed. If the arrival process is a non-homogeneous Poisson process, the inter-arrival times of the process are IID exponential random variables with a transformed time scale \( t' \) and common mean \( \frac{1}{\lambda} \), equation 3.13, where \( (t'_{i} - t'_{i-1}) \) for \( 1 \leq i \leq \infty \) and \( \lambda > 0 \). Hence, \( t'_{i} \) can be generated recursively using the following three steps as in Law and Kelton (1991):
1. Generate $U$ from $U(0,1)$ independent of any previous random variates;
2. Return $t'_i = t'_{i-1} - \frac{1}{\lambda} \ln U$; and
3. Repeat step 1 and step 2.

The initial value $t_0$ for the recursive algorithm is zero.

The above recursive algorithm is employed to generate the inter-arrival times for hurricane occurrences in Hong Kong because the non-homogeneous Poisson process, as shown in Figure 5.2, is a better approximation to the arrival process based on observed data.

4.5 MODEL VALIDATION

Model validation concerns whether the simulation model can approximately represent the system under study. On the other hand, output analysis measures the performance of a simulation model. There are two essential steps for model validation. They are: (1) information gathering; and (2) output analysis.

4.5.1 INFORMATION GATHERING

Information gathering includes: (1) searching for appropriate existing theories and models; and (2) collecting historical records for existing systems.

Existing theories and models can be found in published papers from previous researchers. For example, the relevant papers for wind hazard model are Russell (1971), Tryggvason, Surry and Davenport (1976), and Batts, Russell and Simiu (1980).

Data for individual random variable of an actual system should be used in constructing the simulation model. These data can be recovered from historical records. For instance, the data for constructing the
wind hazard model is collected and supplied by the Royal Observatory of Hong Kong.

4.5.3 OUTPUT ANALYSIS

The best method to validate a simulation model is to compare the output of the wind hazard model based on historical observations with the output of the simulation model. If the simulation model can capture the characteristics of the actual system, the two sets of output should resemble each other. Thus, the simulation model can be considered as a valid model.

A number of statistical tests have been suggested in model validation literature by comparing the output from a simulation model with those from a model based on the observed data. However, almost all the output of the actual system and of the simulation model are non-stationary and correlated therefore none of the classical statistical tests are directly applicable. As a result, it is more important to assess the difference between a system and its corresponding simulation model and to determine if this difference is significant.

Due to the nature of the existing data, the simulated process in the case of Hong Kong can be classified as terminating simulation. Terminating simulation is a simulation that has a clear terminating event. For the hurricane data of Hong Kong, the terminating event is 30 years. In terminating simulation, the sequential procedure with \( \gamma \leq 0.15 \) and \( n_0 \geq 10 \), which is recommended in Law and Kelton (1991) for the construction of a confidence interval with a small relative error \( \gamma \), is used.

An output analysis is called a sequential procedure if new replications are added one at a time to the existing replications. The procedure estimates the mean value of the output with a confidence level of \( 100(1 - \alpha) \) percent and relative error of \( \gamma \). Where \( \gamma \) lies between 0 and 1. With an initial number of replications \( n_0 \geq 2 \) and the confidence
interval half-length \( \Delta(n, \alpha) = t_{n-1,1-\alpha/2} \sqrt{\frac{S^2_n}{n}} \), the sequential procedure is as follows:

1. Make \( n_0 \) replications and set \( n = n_0 \).
2. Compute the mean and the confidence interval half-length from \( X_1, X_2, \ldots, X_n \).
3. Terminate if \( \frac{\Delta(n, \alpha)}{\mu} \leq \gamma' \); otherwise, replace \( n \) by \( n+1 \), make an additional replication, and go to step 2.

Where \( \gamma' = \frac{\gamma}{1 + \gamma} \) and \( I(\alpha, \gamma') = [\mu - \Delta(n, \alpha), \mu + \Delta(n, \alpha)] \) is an approximate 100(1 - \( \alpha \)) percent confidence interval for \( \mu \) with the desired precision.

The advantage of the sequential procedure over other procedures for output analysis of a terminating simulation is the simulation stops as soon as the desired precision has been reached.
CHAPTER 5
APPLICATION OF WIND HAZARD ANALYSIS TO HONG KONG

5.1 FOREWORD

The wind hazard caused by hurricanes at the site of interest is defined as the probability of exceeding the maximal gradient winds induced by hurricanes. Each of these maximal winds is the maximum value recorded at the site of interest and the maximum value within the lifetime of individual hurricane. Furthermore, these wind speeds are going to cause certain damage to the site of interest. It is assumed in this analysis that a hurricane wind speed that exceeds 74 m.p.h. will cause damage to the site of interest. Thus, an event is defined as the occurrence of a hurricane that will produce a gradient wind speed at the site of interest greater than the category 1 wind speed, i.e. 74 m.p.h., in the Saffir-Sampson scale. In addition, this gradient wind speed must be a maximal value throughout the lifetime of the hurricane.

In this chapter, the general features around the site of interest and the observed data of hurricanes, which are supplied by the Royal Observatory of Hong Kong, are described. Then, the algorithms for the "WindHazard" and "Simulation" programs, and the results of the wind hazard analysis using these two programs are presented. Finally, the chapter will conclude with model validation, discussions and conclusions.

5.2 DESCRIPTION OF THE SITE OF INTEREST

The site of interest is Hong Kong, which is located at 22.3° latitude and 114.1° longitude. Figure 5.1 is a map of the western north Pacific Ocean and the south China Sea. It shows the location of Hong Kong and other major cities in this region such as Tokyo. In addition, a few typical hurricane paths are also plotted on the same map. It is obvious that Hong Kong, Tokyo, Taipei and Manila are located within the hurricane striking zone. In the "WindHazard" and "Simulation" programs,
the users need to enter the latitude and the longitude of the site of their interest and the gradient wind speed below which they want to study.

![Diagram of typhoon track]

**Figure 5.1** Typical Track of Typhoons in the North Pacific

5.3 DESCRIPTION OF DATA

A sample of the original database supplied by the Royal Observatory of Hong Kong is shown in Table 5.1. It consists of records of tropical cyclones over the western north Pacific and the south China Sea. Each line of data in the original database consists of the name of a tropical cyclone, time of its occurrence (year, month, day and hour), its position at a particular time (latitude and longitude in one-tenth of a degree), maximum sustained wind near its eyes (in knot from 1961 to 1985; in meter per second from 1986 to 1990), minimum pressure near its center (in hectoPascal) and its track information (the direction of movement in degree; the track speed in 0.1 knot). The data is recorded in six-hour intervals.
Table 5.1
Sample Input Data for "WindHazard"

Six-Hour Typhoon Record over
Western North Pacific and South China Sea
from January 1961 to December 1990

<table>
<thead>
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<th>Name</th>
<th>Year</th>
<th>Mon.</th>
<th>Day</th>
<th>Hr</th>
<th>Position</th>
<th>Max. Wind</th>
<th>Min. Wind</th>
<th>Direct.</th>
<th>Track Speed</th>
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Notes:
1. Maximum Wind Speed is in knot from January 1961 to December 1985 and in meter per second from January 1986 to December 1990;
2. Position (Latitude and Longitude) is in 0.1 degree;
3. Minimum Pressure is in hPa (1 hPa = 1 mb);
4. Track Direction is in degree;
5. Track Speed is in 0.1 knot; and
6. All data are measured in six-hour intervals.

Unfortunately, the radius to the maximum wind speed of a tropical cyclone has not been recorded by the Royal Observatory of Hong Kong. This radius is essential in constructing the wind field model of indi-
vidual tropical cyclone. As a result, the radius of maximum wind speed has to be estimated from the following linear model with respect to the central pressure difference stated in Dorman (1983):

\[ R = 50 - 0.5 \Delta P \]  

(5.1)

Where \( R \) is in km and \( \Delta P \) is in mb.

Equation 5.1 is based on the data from Graham and Nunn (1959) and on data from Gomes and Vickery (1977). The two computer programs for wind hazard analysis use this linear model to estimate the radius of the maximum winds.

5.4 WIND HAZARD RESULTS WITH OBSERVED DATA

There are 924 tropical cyclones in the database provided by the Royal Observatory of Hong Kong from January 1961 to December 1990. Four hundred sixty out of the 924 tropical cyclones can be classified as hurricanes according to Table 2.1. Forty-three out of the 460 hurricanes caused damage to Hong Kong.

The following sections discuss: (1) the application of Poisson processes to describe the recurrence of hurricanes at Hong Kong; (2) the implementation of the programs "WindHazard" to estimate the hurricane hazard in Hong Kong; and (3) the results of these analyses based on existing data.

5.4.1 APPLICATION OF THE POISSON PROCESSES

The constant mean model is used to estimate the arrival rate of hurricanes for the homogeneous Poisson process; on the other hand, the globally constant seasonal model is applied to evaluate the arrival rate of hurricanes for the non-homogeneous Poisson process. After fitting the constant mean model to the observed data, the mean monthly rate of
hurricane occurrence is 1.28. In parallel, after fitting the globally constant seasonal model to the observed data, equation 3.11 becomes:

$$\lambda(t) = C_0 + C_{11} \cos \left[ \frac{2\pi}{12} (t + C_{21}) \right]$$  \hspace{1cm} (5.2)

The second and higher terms of the trend component in equation 3.9 were found to be zero. Furthermore, only the first harmonic of the seasonal component in equation 3.10 is significant because the amplitudes of the second and higher harmonic of this component are close to zero. Therefore, with $E[\epsilon_t] = 0$ and $\lambda(t) = \frac{d}{dt} \Psi(t)$, equation 3.11 reduces to equation 5.2.

Based on the results of the analyses, the mean values for $C_0$, $C_{11}$ and $C_{21}$ in equation 5.2 are 1.28, 1.46 and 39.27, respectively. These mean values can be used in the "Windhazard" and the "Simulation" programs to evaluate the wind hazard curves if the non-stationary Poisson process is preferred. The results, also, show the uncorrelated characteristics of the parameters $C_0$, $C_{11}$ and $C_{21}$ of the globally constant seasonal model. Thus, the parameters $C_0$, $C_{11}$ and $C_{21}$ can be assumed to be independent of one another although it is not necessary for uncorrelated random variables to be independent.

Figure 5.2 plots the estimated number of hurricane occurrences based on the constant mean model for the homogeneous Poisson process, the globally constant seasonal model for the non-stationary Poisson process, and the observed number of hurricane occurrences in the western north Pacific. The figure shows the number of hurricanes that occurred in a 60-month period from January 1961 to December 1965. It is apparent that the seasonal trend of hurricane occurrences is well represented by the globally constant seasonal model. On the other hand, the constant mean model is not an appropriate model for predicting the recurrence of hurricanes. Hence, the non-homogeneous Poisson process rather than the homogeneous Poisson process is used to implement the computer programs "WindHazard" and "Simulation".
Figure 5.2 Estimated Number of Hurricane Occurrences

5.4.2 ALGORITHM FOR WIND HAZARD ANALYSIS OF HURRICANES

Appendix I shows the flowchart for "WindHazard", which implements the wind hazard analysis of hurricanes using observed data. The steps in "WindHazard" include:

1. Input the location (latitude and longitude) of the site of interest in degrees. The site of interest for the sample run is Hong Kong. Its latitude and longitude are 22.3° and 114.1°, respectively. The result for the sample run are presented in Figure 5.3.

2. Input the level of gradient wind that the user is interested. The selected level of gradient wind for the sample run is 150 m.p.h.
3. Read the required data for the wind hazard analysis from a data file. The required data consist of the latitude and longitude of a hurricane, its minimum pressure at the region of maximum wind, and its translation velocity. All the data for the sample run are recorded at six-hour intervals for each hurricane and the data are supplied by the Royal Observatory of Hong Kong.

4. Calculate the shortest distance between the site of interest and the center of a hurricane at a particular time using equation 3.31; in addition, the angle between the vector of this shortest distance and the North pole is evaluate using equation 3.30.

5. Compute the pressure difference between the region of maximum wind in a hurricane and its periphery.


7. Calculate the gradient wind, \( V_g \), induced by a hurricane at the site of interest and at a particular time using equation 3.25.

8. Check if \( V_g \geq (\text{maximum } V_g) \). If it is, make \((\text{maximum } V_g) = V_g\).

9. Repeat step 3 to step 8 until no more data for the same hurricane and store \((\text{maximum } V_g)\).

10. Repeat step 3 to step 9 for the next hurricane until the end of the data file. As a result, a new database consists of these \((\text{maximum } V_g)\) is obtained.

11. Calculate the probability of having wind speed, \( V_g \), greater than a specified value, \( v \), given the occurrences of \( n \) hurricanes in time \( t \), \( P(V_g > v, t) \) using equation 3.17 with equation 3.18 or equation 3.20.
12. Compute the number of hurricanes, \( n \), causing damage to the site of interest.

13. Calculate the mean number of hurricanes, \( \lambda \), causing damage to the site of interest.

14. Evaluate the probability of having \( n \) hurricanes, \( P(n, t) \) in time \( t \) using equation 3.15.

15. Calculate the wind hazard curve for hurricane occurrences, \( P(V, t) \) using equation 3.1.

![Graph showing probability of exceeding a threshold speed per year vs. maximum gradient wind speed in m.p.h.]

**Figure 5.3 Hurricane Wind Hazard Curve for Hong Kong**

Figure 5.3 shows the output from "Windhazard", which is the probability of exceeding a threshold speed in one year. For instance, the probability of having a wind speed greater than or equal to 105 m.p.h. is 0.2 per year for the Gumbel distribution. Furthermore, the probability of having no hurricane, which corresponds to the zero value of maximum gradient wind speed in Figure 5.3, in one year is 0.22. The figure
consists of three hazard curves based on different extreme wind models with the non-homogeneous Poisson process as their recurrence model. The three extreme wind models are: (1) the empirical model using observed data; (2) the Gumbel model; and (3) the Weibull model. The figure shows that the Gumbel model fits the observed data better than the Weibull model. As a result, only the Gumbel model will be used to implement the "Simulation" program. The empirical model using observed data will be used to validate the simulation model in the next section.

5.5 WIND HAZARD RESULTS WITH SIMULATED DATA

The wind hazard curves calculated in the last section are particular realizations of the time series of hurricane occurrences. Thus, the uncertainty associated with this wind hazard curves is unknown. As a result, simulation is employed to study the long term hurricane-induced wind hazard at Hong Kong.

The input probability distribution for each of the required random variables of the simulation was chosen by fitting theoretical distributions to observed data. Only those data that produce maximum wind speeds throughout the life-time of a hurricane as well as at the site of interest are used.

The terminating criterion for the simulation models constructed by other researchers such as Russell (1969) is the number of simulated hurricanes equal to 1,000. Thus, a set of 1,000 such extreme winds is obtained in the simulation. This set of extreme winds is used to estimate the wind hazard at the site of interest caused by hurricanes. However, this terminating criterion is quite arbitrary. Hence, the sum of the inter-arrival times of hurricanes equal to 30 years will be used as the terminating criterion in this study. Since the length of data supplied by the Royal Observatory of Hong Kong is 30 years, according to Law and Kelton (1991), the output analysis techniques for terminating simulations can be applied.
The sequential procedure described in chapter 4 is used to estimate the mean hurricane-induced wind hazard. The simulation stops when the desired precision, i.e. a 90% confidence interval with a relative error $\gamma \leq 0.15$, for the mean value is reached. Three hundred simulation runs have been performed to achieve this precision.

The following sections will: (1) discuss the selection of input probability distribution for each random variable; (2) describe the algorithm for implementing the wind hazard analysis using the simulation model; (3) validate the simulation model.

5.5.1 SELECTING INPUT DISTRIBUTION FOR RANDOM VARIABLES

Graphical plots can be used to assess the goodness of fit of the chosen lognormal distribution for the random variables. The parameters for describing a distribution have to be evaluated as well. There are five random variables required to be simulated. They are: (1) the latitude of a hurricane center; (2) the longitude of a hurricane center; (3) the track angle of a hurricane; (4) the track speed of a hurricane; and (5) the minimum pressure within a hurricane.

As discuss in chapter 4, the input probability distribution for the above five random variables have to be determined before the start of the simulation. In the case of Hong Kong, the lognormal distribution is used as the input distribution for each of the random variables. The selection procedures for the five random variables include assessing the data independence, and plotting the probability-probability plot.

5.5.1.1 ASSESSING SAMPLE DEPENDENCE

Since $p_j$ is biased and correlated, it has a large variance unless $n$ is very large. Therefore, the values of $p_j$ will be significantly differed from one another unless $n$ is very large and $j$ is small relative to $n$. Thus, the values of the $p_j$ vary significantly as $j$ approaches to $n$. 
Figure 5.4a to Figure 5.4e are the plots of the correlation coefficients, $\rho_j$, against the lag between any two observations, $j$, for the five random variables, which are required to calculate the maximal gradient winds within a hurricane. Since the number of observations, $n$, for each of the five random variables are 43, large variation of $\rho_j$ is expected as the lag between any two observations approaches 43.

If the observations are independent, $\rho_j = 0$. However, $\rho_j$ will not be exactly zero even when the data are independent since $\rho_j$ is an observation of a random variable whose mean is not equal to 0. If the observations are linearly dependent, $\rho_j = 1$. If $\rho_j$ lies between 0 and 1, the observed data are neither independent nor linearly dependent. It is obvious from those figures that the data of each random variable are weakly correlated. They are weakly correlated because most of the values of the correlation function for each of the five random variables are less than 0.5 except those $\rho_j$ with large lag between observations. To simplify the simulation process, data has to be assumed independent although they are weakly correlated.

![Figure 5.4a](image1.png)  
**Figure 5.4a** Correlation Function for the Track Speed
Figure 5.4b  Correlation Function for the Track Angle

Figure 5.4c  Correlation Function for the Minimum Pressure
Figure 5.4d  Correlation Function for the Latitude

Figure 5.4e  Correlation Function for the Longitude
5.5.1.3 PROBABILITY-PROBABILITY (P-P) PLOT

A lognormal distribution is fitted to the data for each of the five random variables required for the wind field model. As shown in Figure 5.5a to Figure 5.5e, the results of distribution fitting are quite satisfactory for the track speed, track angle, minimum pressure, the latitude and longitude of the hurricanes, respectively.

5.5.2 ALGORITHM FOR WIND HAZARD ANALYSIS OF HURRICANES WITH SIMULATED DATA

Appendix II shows the flowchart for the "Simulation" program, which implements the wind hazard analysis of hurricanes using simulated data. The steps of analysis used in "Simulation" include:

1. Input the location (latitude and longitude) of the site of interest in degree. The site of interest for the sample run is Hong Kong. Its latitude and longitude are 22.3° and 114.1°, respectively. The results for the sample run are presented in Figure 5.6.

2. Input the level of gradient wind of interest. For example, the selected level of gradient wind for the sample run is 150 m.p.h.

3. Input the seeds for the arrival process and the following five random variables: (1) the minimum pressure in a hurricane; (2) the track angle of a hurricane; (3) the track speed of a hurricane; (4) the latitude of a hurricane center; and (5) the longitude of a hurricane center.

4. Generate the inter-arrival times of hurricanes in a period of 30 years according to a non-homogeneous Poisson process discussed in section 4.4.2 using the linear congruential generator.
Figure 5.5a  P-P Plot for Track Speed

Figure 5.5b  P-P Plot for Track Angle
Figure 5.5c  P-P Plot for Minimum Pressure

Figure 5.5d  P-P Plot for Latitude
5. Generate the five required random variables identified in step 3 according to a lognormal distribution and a linear congruential generator for each individual hurricane.

6. Perform step 4 to step 7 of the "WindHazard" program.

7. Check if the sum of inter-arrival times ≥ 30. If true, simulation ends. Otherwise, go to step 11 of the "WindHazard" program.

8. Repeat step 3 to step 7 for the next hurricane in the database until the sum of the inter-arrival times is greater than 30 years.

5.6 MODEL VALIDATION

When validating the simulation model for hurricane-induced wind hazard, the output from the simulation model has to be compared with the output from the historical data. After the model has been validated, it is used to forecast the exceeding probability of a certain wind speeds produced by hurricanes at the site of interest. The historical record represent a sample of the population. Each simulation also generate a sample of this population.

![Probability of Exceeding a Threshold Speed per Year vs Maximum Gradient Wind Speed in m.p.h.](image)

Figure 5.6 Model Validation

Figure 5.6 shows the wind hazard curves for hurricanes at Hong Kong. The solid curve in Figure 5.6 is the fitted Gumbel model for hurricane wind hazard to observed data. The other curves in Figure 5.6 are the mean, lower and upper bound of the 90% confidence interval for the mean hazard curve. According to this figure, the simulation model is fairly close to the wind hazard model. The sequential procedure for estimating the mean hazard curve of the terminating simulation has been
performed. One hundred and seventy six simulation runs have been performed to obtain the desired precision.
CHAPTER 6
DISCUSSIONS AND CONCLUSIONS

It has been shown by other researchers that hurricane-induced extreme winds at a particular site cannot be satisfactorily assessed by the statistics of extremes using the largest annual wind speeds recorded at the site of interest. The difficulties arise because the largest annual wind speed model does not consider the spatial and temporal effects of hurricanes. Therefore, a better methodology used to forecast the wind hazard caused by hurricanes is introduced in chapter 3. The wind hazard model for hurricanes presented in this thesis is modified from several previously published models. The model presented herein is more effective because it considers both the temporal and spatial effect of hurricane-induced wind hazard at the site of interest when the hurricane is closest to the site of interest. This model evaluates the probability of exceeding a particular hurricane-induced wind speed at the site of interest over a time period t.

The wind hazard model consists of: (1) a stochastic recurrence model; and (2) an extreme wind velocity model. The recurrence model describes the randomness of hurricane occurrences over time. The most frequently used recurrence models are the homogeneous Poisson process and the non-homogeneous Poisson process. The only parameter required by both processes are the arrival rate of hurricanes, $\lambda(t)$, at the site of interest in time t. The arrival rate for both processes can be estimated by regression analysis using time series. The constant mean model characterizes the parameter of the homogeneous Poisson process. The globally constant seasonal model is applied to the non-homogeneous Poisson process. This model represents the non-stationary character of the non-homogeneous Poisson process. As shown in Figure 5.2, the non-homogeneous Poisson process with the globally constant seasonal model fits the historical data better than the homogeneous Poisson process with the constant mean model. Hence, only the non-homogeneous Poisson process is used as the recurrence model in the implementation of the programs "WindHazard" and "Simulation".
The extreme wind model estimates the exceeding probability of a particular wind speed produced by hurricanes. The Gumbel distribution is chosen as the extreme wind model because it fits the existing data better than the Weibull distribution.

It is desirable to perform wind hazard analyses with both existing data and with simulated data. Observed data, however, are limited in number and are usually available for short periods of time. Thus, it is difficult to obtain reliable statistics on the model parameters. However, the wind hazard analysis for hurricanes assumes that the average frequency of hurricane strike and the average hurricane strength will not change over time. That means the assessment based on past records can be used in forecasting the future hurricane occurrences and the associated wind hazards in different forecast windows. In contrast to simulation provides a method to study the long-term characteristics of hurricane occurrences if data are insufficient. The analysis with existing data is used to validate the simulation model.

Most simulations performed in the past have chosen 1,000 storms as the stopping criterion. This criterion is quite arbitrary. Instead, the sum of the inter-arrival times for hurricanes reaching thirty years is used as the terminating criterion for the simulation to match the period of existing data. The time period of thirty years is used because the historical records are collected over a 30-year period from January 1960 to December 1990. Since the initial conditions are unknown, the author assumes that there is no hurricane present at time zero.

The sequential procedure discussed in chapter 4 is employed to validate the simulation model. As a result, 176 simulation runs are required to achieve the desired precision, i.e. a 90% confidence interval with a relative error less than or equal to 0.15, for estimating the mean hurricane-induced wind hazard. Since simulation measures the long-term characteristics of the actual system, the resulting probability of exceeding is a mean performance of the system under study.
To improve the performance of the wind hazard model and the simulation model, the wind field model in those two programs can be extended to include the following properties discussed in Batts, Russell and Simiu (1980): (1) the surface wind speeds at 10m above the ocean surface caused by the gradient wind speeds using an empirical transfer function; (2) an empirical storm decay function; (3) a frictional function describing the movement of a hurricane from ocean into land.

In addition, the extreme wind model can be expanded to include the directional effect by dividing the recorded extreme wind speeds into eight directional sectors as discussed in Cook (1983), and Simiu, et al. (1985). The directions of the gradient wind speeds can be calculated using the wind field model presented in Trayggvason, Surry and Davenport (1976). With the wind field model and the extreme wind model, the directional effect of hurricane-induced wind hazard can be assessed at the site of interest.

The needs to construct a multiple pathway model to assess the potential human and property exposure to hurricane-induced hazards are addressed. The model should relate the characteristics of hurricanes such as gradient pressure and torrential rainfall to the hurricane-induced hazards. These hazards include extreme winds, storm surges, severe floods and land slides.

Figure 6.1 shows the hurricane wind hazards in different forecast windows. The innermost curve in Figure 6.1 represents the hurricane-induced wind hazard in the next year; the outermost curve in the same figure corresponds to the wind hazard in the next 1000 years. For instance, the basic design wind speed for a structure with a 5% chance of being exceeded in 50 years is about 175 m.p.h. Figure 6.2 shows hurricane wind hazards for different return periods. The basic design wind speed with a return period of 1000 years is 175 m.p.h.

To select a basic design wind speed for a structure, engineers should consider the expected level of performance of the structure after the strike of a hurricane with the design wind speed. For example, an
Figure 6.1  Hurricane Winds in Different Forecast Windows

Figure 6.2  Hurricane Winds for Different Return Periods
important structure such as a hospital is expected to function normally after a major hurricane strike. Thus, a wind speed with a return period corresponds to the design life of the structure is an appropriate basic design wind speed. In this case, if the design life of the hospital is 50 years and a 5% exceedance of the basic design wind speed is an acceptable level of performance, the basic design wind speed is 175 m.p.h. as shown in Figure 6.1. According to Figure 6.2, the return period of a 175 m.p.h. design wind speed is 1000 years. However, if the structure is a temporary structure, its expected level of performance is much lower than that of a hospital. In this case, if the design life of the structure is one year and a 25% exceedance of the basic design wind speed is an acceptable, the corresponding wind speed is 100 m.p.h. as in Figure 6.1. As shown in Figure 6.2, the return period of a 100 m.p.h. design wind speed is 4 years.

Based on the developments presented in this thesis, it can be concluded that the non-homogeneous Poisson process is a better recurrence model for hurricanes since it fits the historical observations better than the homogeneous Poisson process. The mean rate of hurricane occurrences for the non-homogeneous Poisson process is estimated by one of the seasonal time series called the globally constant seasonal model. However, the mean rate of hurricane occurrences for the homogeneous Poisson process is estimated by one of the non-seasonal time series called the constant mean model. The Gumbel distribution is a better extreme wind model because it fits the existing data for Hong Kong better than the Weibull distribution. Moreover, the developed simulation model is a valid model for describing the characteristics of hurricanes. To achieve the desired precision, i.e., a 90% confidence interval with a relative error $\gamma \leq 0.15$ for the estimation of the performance of the mean wind hazard curve, one hundred and seventy six simulation runs are required.
APPENDICES
APPENDIX I

THE FLOWCHART FOR

THE PASCAL PROGRAM

“WindHazard”
Start

User Input: [1]
Latitude and Longitude
of the Site of Interest,
Level of Gradient
Wind Speed Interested

Read Hurricane Data from File:
Lat, Long, Min. Pressure, Track
Direction, Track Speed, etc.

Compute the Central
Pressure Difference [2]
of Hurricane, $\Delta P$

Calculate the Distance and Angle
between the Hurricane Center and
the Site of Interest in Polar Co-
ordinates $(r, \theta)$ from Lat and Long

Calculate the Radius of
Maximum Wind, $R$ [3]
and the Radial Pressure
Gradient, $dP/dr$

$\Delta P = P_n - P_o$, where
$P_n$ is the Periperal Pressure
($= 1014$ mb), and
$P_o$ is the Min. Central Pressure

[2] Relationship between
$\Delta P$ and $R$ :
$R = 50 - 0.5 * \Delta P$

[3] Last Storm?

Yes

No
Calculate the Probability of having wind speed, $V_H$, greater than a specific value, $v$, given the occurrence of $n$ hurricanes, $P(V_H > v | n)$ \[5\]

Compute the Number of Hurricanes Affecting the Site of Interest, $n$

Calculate the Mean Number of Hurricanes Affecting the Site of Interest, $\lambda = n/t$

Calculate the Probability of Having $n$ Hurricanes in Time, $t$, $P(n,t)$ \[4\]

Calculate the Probability of Hurricane Wind Speed, $V_H$, Greater than a Threshold, $v$, in Time $t$, $P(V_H > v, t)$ \[6\]

End

---

**[4]** Assume Non-homogeneous Poisson Distribution for Hurricane occurrences

**[5]** Assume Gumbel or Weibull Distributions for the Maximum Wind Speeds of Hurricanes

**[6]** The Wind Hazard Curve at the Site of Interest
APPENDIX II

THE FLOWCHART FOR

THE PASCAL PROGRAM

"Simulation"
Start

Linear Congruential Random Number Generator with Uniform Distribution

Generate a Uniform Distribution Function for the Poisson Arrival Process

Generate the Inter-arrival Times of Hurricanes in a Period of 30 Years according to a Poisson Arrival Process

Yes

No

Σ Inter-Arrival Times > 30 yrs?

B

A

C
For Each Single Hurricane Corresponding to an Inter-arrival Time, Generate the Hurricane Track Location, Minimum Central Pressure and Track Velocity at Which the Gradient Wind Speed Produced by the Hurricane at the Site of Interest is Maximum

- **Generate Minimum Central Pressure**
- **Linear Congruential Random Number Generators with Uniform Distribution and Independent Seed**
  - **Log-normal Distribution for Minimum Central Pressure**
  - **Generate Latitude**
  - **Generate Longitude**
  - **Log-normal Distribution for Longitude**
  - **Calculate the Distance and Angle from Hurricane Center to Hong Kong in polar Coordinates \((r, \theta)\)**
  - **Hong Kong's Lat and Long (22.3, 114.1) in degree**
  - **Log-normal Distribution for Track Angle**
  - **Generate Track Angle**
  - **Generate Track Speed**
  - **Log-normal Distribution for Track Speed**

- **Calculate the Maximum Gradient Wind Speed at the Site of Interest for a Single Hurricane**

- **Compute the Central Pressure Difference of Hurricane**
- **Calculate the Radius of Maximum Wind and the Radial Pressure Gradient**
Calculate the Probability of having wind speed, $V_H$, greater than a specific value, $v$, given the occurrence of $n$ hurricanes

Compute the Number of Hurricanes Affecting the Site of Interest

Calculate the Mean Number of Hurricanes Affecting the Site of Interest

Calculate the Probability of Having $n$ Hurricanes in Time $t$

Calculate the Probability of Hurricane Wind Speed, $V_H$, Greater than a Threshold, $v$, in Time $t$ [1]

End

APPENDIX III

REFERENCES


Li, Y. S. and Li, C. W. (1992), "The Measurement and Analysis of Waves in the Coastal Waters of Hong Kong under the Northeasterly Monsoon," Hong Kong Engineer, 27 (7), Transactions No. 1.


