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Probability-based estimate of tropical cyclone damage: An explicit approach and application to Hong Kong, China

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ABSTRACT

Tropical cyclones (TCs) are among the most costly natural hazards affecting civil construction in coastal areas, which have caused extensive economic losses and social disruption world-widely. Moreover, the intensity and/or frequency of future TCs have been projected to change with time due to the potential impacts of climate change, indicating the potential of ever larger TC damages for coastal regions. The estimate of future TC damage should be conducted under a probability-based framework, taking into account the uncertainties associated with both the TC characteristics (e.g., intensity and frequency) and the vulnerability of the coastal communities of interest. In this paper, an explicit approach is developed to evaluate the TC damage for TC-prone areas considering the potential impacts of climate change. The mean value and variance, as well as the cumulative density function of cumulative TC damage are estimated quantitatively. The proposed method is applied to TC damage assessment of Hong Kong, China – a TC-prone area which has suffered severely from historical cyclones. Sensitivity analysis is also performed to investigate the impacts of the time-variant characteristics of both the TC process and the TC damage conditional on one TC event on the cumulative damage costs for coastal areas.

1. Introduction

Tropical cyclone (TC) winds, rainfalls and storm surges are responsible for the major natural hazards in costal areas, which having caused enormous economic losses and social disruption around the world. For example, in the United States, eight out of the ten most expensive catastrophes before 2006 in terms of insured loss had been triggered by TCs (known as hurricanes in the Atlantic Basin) [1]. In China, historical records show that totally 181 TCs (known as typhoons in the Pacific Basin) made landfall during the period 1980–2004, resulting in cumulative damage costs of 422.36 billion Chinese Yuan (CNY) [2]. Moreover, the population and wealth in coastal areas (most are TC-prone regions) have a considerable steady increase, indicating the potential of ever larger economic and social losses in the future. The increasing importance is then evident to advance building and structural practice through improving predictions of TC damage for civil constructions and thereby supporting implementation of strategies for enhancing the structural performance economically [3–5].

The future TCs have been projected to respond to climate change in many studies [6–9]. For instance, Mudd et al. [10] used a regression-based approach to show that in the Atlantic Basin, the annual occurrence rate of TCs (hurricanes) may increase from 8.4/year to 13.9/year at the end of the 21th century. Knutson et al. [11] predicted that the averaged intensity of future TCs at a global scale will likely become stronger with an increase of 2–11% by year 2100 due to the potential impacts of greenhouse warming. However, there are also some arguments that the future TC intensity may increase while the frequency would decrease subjected to climate change (e.g., [12,13]). Emanuel [14] reported that despite the insignificant trend in future TC frequency, an upward trend in TC destructive potential can be observed. As a result, the time-variation of TC characteristics (e.g., intensity, frequency) should be well incorporated in terms of estimating the TC damage. Some previous studies [3,15] considered a stationary TC process with constant occurrence rate and time-invariant intensity (measured by the maximum TC wind speed) and thus failed to reflect the non-stationarity in TC process subjected to the potential impacts of climate change [16]. Later researches [17,18] took into account the roles of the time-variant TC characteristics in damage assessment, employing a probabilistic model of the ‘annual’ maximum TC wind speed to represent the TC wind risk. Such a probabilistic model, however, may lead to an overestimated TC damage in the presence of the intermittence of TCs in some regions. Li et al. [19] and Wang et al. [20–22] employed a Poisson stochastic process to model the TC occurrence and assessed the TC damage based on a vulnerability model as a function of the maximum TC wind speed. The mean value and variance of the cumulative damage have been considered in existing

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methods regarding TC damage assessment, which cannot fully reflect all the characteristics of the TC damage under a probability-based context (e.g., the upper tail behaviour or a characteristic value with a 90th percentile value). A Gamma distribution has been suggested to approximately fit the probability distribution of the TC damage [21,22]. However, the random nature associated with the TC damage has not been fully investigated. Moreover, in terms of damage assessment, especially for long-term reference periods, the utilization of a vulnerability model that was developed based on the damage reports/data associated with a single (or limited) TC event(s), as has been widely used in previous studies, would become questionable considering the time-variation of a community's vulnerability (e.g., enhanced structural design and practice), indicating the importance of developing a vulnerability model that can capture the change of a community's hazard-resisting capacity with time for use in TC damage assessment.

The scope of this paper is to develop a probabilistic approach for TC damage assessment for TC-prone areas under the context of climate change, taking into consideration the non-stationarity in the TC process. This paper is organized as follows. Section 2 presents probabilistic models for both the stochastic TC occurrence process and TC damage. Section 3 develops a moment-based approach for TC damage assessment, which gives a straightforward description of the magnitude and variation of the TC damage. In Section 4, the probability distribution of cumulative TC damage is developed in an explicit form. Illustrative analyses are conducted in Section 5 to demonstrate the applicability of the proposed method, choosing Hong Kong, China, as an example. The conclusions are finally formulated in Section 6.

2. Probabilistic models of TC process and TC damage

2.1. TC occurrence model

For a specific region of interest, TC events occur randomly in time. A Poisson point process can be used to describe the TC occurrence process [19–24]. With a mean occurrence rate of λ, the probability that k events occur within a time interval of $(0,T]$ is determined by

$$\Pr(N_T = k) = \frac{(\lambda T)^k}{k!}\exp(-\lambda T), \quad k = 0,1,2,... \tag{1}$$

in which $\Pr(\bullet)$ denotes the probability of the event in the bracket, and N_T is the number of events within $(0,T]$. Wang et al. [21] examined the historical TC data for both the Miami-Dade County (Florida, USA) and the Florida State respectively. For both scales of region, they found that a Poisson point process can reasonably model the occurrence process of TCs that made landfall. Herein, we examine the distribution of annual number of TCs that have caused direct economic losses to Hong Kong, China – a region that has suffered severely from historical cyclones. The probability mass function of the annual TC numbers is plotted in Fig. 1,

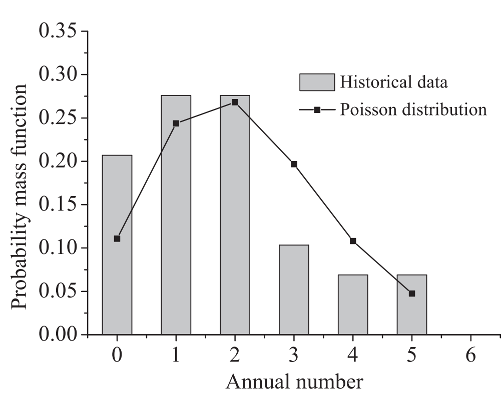

Fig. 1. Probability mass function of the annual number of TCs that caused economic losses to Hong Kong.

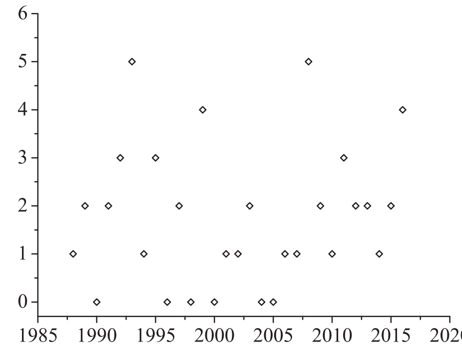

Fig. 2. Annual number of TCs that caused economic losses to Hong Kong: from 1988 to 2016.

where a historical period of 1988–2016 is covered. The data are available from the annual reports on TCs released by the Hong Kong Observatory of HKSAR (http://gb.weather.gov.hk/publica/pubtcc.htm) [25]. Totally 51 TC events had triggered direct damage losses within the considered 29 years, yielding an annual occurrence rate of 1.76/year. Fig. 1 shows that the annual number can be well modeled by a Poisson distribution with $\lambda = 2.2$/year (c.f. Eq. (1))[1] at a significance level of 20%.

Further, taking into account the potential impacts of climate change, the occurrence rate of future TCs may vary with time correspondingly. In such a case, a non-homogeneous Poisson point process can be used to describe the non-stationarity in the TC occurrence. With a time-variant occurrence rate of $\lambda(t)$, Eq. (1) is rewritten as follows,

$$\Pr(N_T = k) = \frac{\left(\int_0^T \lambda(t)\mathrm{d}t\right)^k \cdot \exp\left(-\int_0^T \lambda(t)\mathrm{d}t\right)}{k!}, \quad k = 0,1,2,... \tag{2}$$

For illustration purpose, we examine the annual numbers of historical TCs that affected Hong Kong, as have been reported in [25]. Fig. 2 presents the annual number of TCs that resulted in direct economic losses to Hong Kong within a time period of 1988–2016, where a slightly upward trend can be observed, with a R-square value of 0.011. This trend is not strongly evident of the non-stationarity in the TC occurrence from a view of statistics, due to the relatively small sample size and short duration that have been considered. The non-stationarity in the TC occurrence process will, however, be discussed in the following to illustratively investigate its role in TC damage assessment, taking into account the potential changing scenarios of TCs in the future, as observed elsewhere [13].

2.2. TC damage model

The TC-induced damage for a specific region of interest associated with one TC event is by nature random, with uncertainties arising from both the TC intensity and the hazard-resisting capacity of the area. One of the methods to quantitatively measure the TC damage, under a probability-based framework, is to use a vulnerability model which links the possibility of occurrence of certain levels of damage to the maximum TC wind speed [3,26–28]. For instance, Stewart et al. [3] used the claim and loss information from Hurricane Hugo (1989) and Hurricane Andrew (1992) that were obtained from an insurer and developed a damage model as a function of the 10-min mean surface wind speed, where the 'damage' was defined as the amount paid out by the insurer divided by the total insured value. This regression-based vulnerability model was further used in damage assessment of coastal

[1] While the mean value of the samples is 1.76/year in Fig. 1, due to the dependence of the mean value and variance of a Poisson distribution (both equal to λ), $\lambda = 2.2$/year instead of 1.76/year is found to maximize the p-value (0.5053) from a view of goodness-of-fit test. This observation suggests that the TC risk may be underestimated if one simply set λ in Eq. (1) as the mean value of the samples.