Reliability Engineering and System Safety 159 (2017) 100–107

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

A decision model for intergenerational life-cycle risk assessment of civil infrastructure exposed to hurricanes under climate change

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ARTICLE INFO

Keywords:
Civil infrastructure
Climate change
Discounting
Engineering decision analysis
Hurricanes
Reliability
Structural engineering

ABSTRACT

Public awareness of civil infrastructure performance has increased considerably in recent years as a result of repeated natural disasters. Risks from natural hazards may increase dramatically in the future, given current patterns of urbanization and population growth in hazard-prone areas. Risk assessments for infrastructure with expected service periods of a century or more are highly uncertain, and there is compelling evidence that climatology will evolve over such intervals. Thus, current natural hazard and risk assessment models, which are based on a presumption of stationarity in hazard occurrence and intensity, may not be adequate to assess the potential risks from hazards occurring in the distant future. This paper addresses two significant intergenerational elements – the potential impact of non-stationarity in hazard due to climate change and intergenerational discounting practices – that are essential to provide an improved decision support framework that accommodates the needs and values of future generations. The framework so developed is tested through two benchmark problems involving buildings exposed to hurricanes.

1. Introduction

Hurricanes and tropical cyclones, which are often accompanied by coastal flooding and storm surge, are among the most devastating and costly natural disasters impacting civil infrastructure [47]. The human and socioeconomic losses they may cause are of considerable concern to structural engineers, the insurance industry, regulatory authorities, and the public. In the United States, advances in risk management of hurricanes have reduced the loss of life and injury through improvements in building design standards and construction practices, improved storm forecasting, and timely public warnings [27]. However, economic losses may increase dramatically in the future, given current patterns of population growth and urbanization in hurricane-prone areas [8]. Moreover, there is growing evidence that the incidence of strong (Category 4 and 5) hurricanes in the North Atlantic and their overall intensities have been trending upward since the early 1980s [52]; these trends are likely to continue in response to the higher sea surface temperatures associated with global warming [32]. Developing a risk-informed decision framework for civil infrastructure that takes into account the potential effects of climate change is an important and timely research challenge [36].

Risk-informed decision-making for civil infrastructure facilities has several fundamental components, among them: stochastic models of loads and structural behavior; time-dependent reliability analysis to assess future performance of a facility; and a decision-making process that encompasses these behaviors and their uncertainties for purposes of design and risk management. Models to predict extreme structural loads due to natural hazards are a critical part of life-cycle reliability and risk assessment. Although reliable models of hurricanes for wind hazard analysis and for simulating wind speeds for the design of structures under stationary conditions now are available [14,50,51], the need to address effects of climate change on hurricane formation presents significant challenges. The non-stationarity in annual frequency and intensity of hurricanes that is induced by climate change introduces increases (and additional uncertainty) to the extreme wind loads used in time-dependent reliability analysis. Finally, the potential influence of climate change on civil infrastructure increases for certain facilities with service periods of 100 years or more. The application of customary risk-informed decision methods (e.g., minimum life-cycle cost) to long-term event horizons raises ethical issues in terms of risk-sharing between current and future generations and has yet to be explored in any depth [25,35,38].

Sustainable development has become a new standard for civil infrastructure design and construction because present decisions regarding civil infrastructure may have significant consequences for the future in terms of benefits and costs. This paper focuses on socio-

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http://dx.doi.org/10.1016/j.ress.2016.10.022
Received 20 October 2015; Received in revised form 31 August 2016; Accepted 30 October 2016
Available online 09 November 2016

economic aspects of sustainability for civil infrastructure, which strive to avoid transfer of excessive burdens to future generations through responsible stewardship of limited resources. This meaning stems from the assertion of the Brundtland Report [54] that sustainable development is development that "meets the needs of the present without compromising the ability of future generations to meet their own needs."

This paper proposes a risk-informed framework that is applicable to intergenerational decision-making aimed at assessing long-term risks of hurricanes and achieving socio-economically sustainable decisions for civil infrastructure. We begin with a brief review and appraisal of conventional life-cycle engineering decision-making and suggest two elements - time-dependent reliability considering climate change effects and time-declining discount rates - that are essential for equitable intergenerational decisions and that conventional methods fail to address. Next, we introduce stochastic models that incorporate non-stationarity in demand resulting from hurricanes under climate change. This stochastic demand is integrated with existing material aging and structural deterioration models to show how time-dependent structural reliability is affected by climate change. Finally, we examine how intergenerational discounting can reflect equitable allocations of risk between generations through two relatively simple life-cycle cost assessment examples.

2. Review and appraisal of customary risk-informed decision methods

Life-cycle performance, safety, reliability and risk have become emergent issues for civil infrastructure systems. In current risk-informed design and decision-making, performance goals generally are expressed in terms of probabilities, expected losses measured in monetary terms, or a combination of these metrics [12,16,37,45,53]. Minimum expected life-cycle cost analysis is among the most commonly adopted decision models applied to civil infrastructure, and will be utilized in this paper to illustrate some of the deficiencies in current decision-making for civil infrastructure.

The life-cycle cost of a structure includes initial cost, damage cost, maintenance cost, cost of life losses or injuries, and cost associated with disruption [16,48,57]. The expected life-cycle cost, $E[C_L]$, of a structure is expressed as:

$$E[C_L] = C_I + E[C_D^C] + C_M \tag{1}$$

where C_I is the initial cost, $E[C_D{}^C]$ is the expected cumulative damage cost, which includes both direct and indirect damage costs, and C_M = the maintenance cost. Cost C_I is assumed to be a deterministic value while $C_D{}^C$ is considered as a random variable due to the uncertainties in demands and capacity. C_M can be assumed to be a deterministic value if maintenance or repair is performed regularly with a standard procedure. The expected value of the cumulative damage cost from natural hazards is obtained utilizing renewal theory to model the randomly occurring extreme events. The expected total cost as a function of the service life of a new structure (or the remaining life of an existing structure), t, is [57]:

$$E[C(t, X)] = C_I(X) + E\left[\sum_{i=1}^{N(t)}\sum_{j=1}^{k}\frac{C_j P_{ij}(X, t_i)}{(1 + r(t_i))^{t_i}}\right] + \sum_{n=1}^{t/m}\frac{C_M(X)}{(1 + r(t_n))^{t_n}} \tag{2}$$

in which $\boldsymbol{X}$= vector of design variables, e.g., design loads and resistance; C_I= construction cost for a new or retrofitted structure; $N(t)$ = total number of extreme events in t; k= the total number of damage states; C_j= cost of consequence of the jth limit state at $t= t_i$; $r(t_i)$= annual discount rate at $t= t_i$; P_{ij}= probability of the jth limit state being exceeded given the ith occurrence of one or multiple hazard; m= time interval of periodic maintenance; and C_M= operation and maintenance cost.

Most life-cycle cost analyses of civil infrastructure have focused on decision models for service lives of 50–100 years. For certain civil infrastructure projects, the service periods and decision consequences may extend well beyond those time horizons, impacting future generations: Large dams and flood protection structures have design lives of 100 years, and the service periods of hazardous waste repositories are even longer. When expected cost is used as a basis for decision and future losses are discounted to present worth, it may be found that events in the distant future have little impact on present value, leading to the conclusion that such events are unimportant and need not be considered in engineering decision-making. This point can be illustrated using Eq. (2). We make several simplifying but common assumptions: resistance is deterministic and constant; a single limit state is considered and its failure cost is C_F; the probability of failure and the initial cost can be expressed in terms of a design variable, $\boldsymbol{X}$, with $P_F \approx P_O\ exp\,(-\boldsymbol{X})$ and $C_O = a + k\boldsymbol{X}$, in which P_O, a and k are constants; the discount rate is constant; the occurrence of load events can be described by a Poisson point process with a mean rate of occurrence, λ; and periodic maintenance costs are not considered. Under these assumptions, Eq. (2) can be written as:

$$E[C(t, X)] = a + kX + C_F P_0 \exp(-X)\frac{\lambda}{r}(1 - e^{-rt}) \tag{3}$$

The optimal design intensity, X_{opt}, corresponding to the minimum expected total cost can be expressed as:

$$X_{opt} = -\ln\left(\frac{k}{C_F P_0}\cdot\frac{r}{\lambda}\cdot\frac{1}{1 - e^{-rt}}\right) \tag{4}$$

and in the limit, this optimal intensity for an extended structure life becomes:

$$\lim_{t\to\infty} X_{opt} = -\ln\left(\frac{k}{C_F P_0}\cdot\frac{r}{\lambda}\right) \tag{5}$$

which is independent of time. Changes in λ or P_F as well as in time-varying discount rate, r, would cause the optimal solution to be a function of time. As a starting point, then, two elements of a decision framework applicable to situations with time horizons extending to future generations can be suggested: a time-dependent failure rate reflecting climate change effects and a time-declining discount rate. These elements will be introduced in Sections 3 and 4, respectively, and will be illustrated for two relatively simple structural engineering applications to show their effects on optimal decisions in Sections 5 and 6.

3. Time-dependent reliability assessment

When civil infrastructure facilities deteriorate over time due to aging and the loads are also time-variant, these stochastic mechanisms cause the reliability to decrease with time [30,31]. Then, the probability of failure at any time, t, becomes:

$$p_f(t) = P[R(t) \le S(t)] \tag{6}$$

in which $R(t)$ is the resistance at time t and $S(t)$ is the dimensionally consistent structural action (moment, shear, etc.) resulting from the applied load at time t. The probability of satisfactory performance over some specified period is a more useful measure of performance [11] in service life prediction and condition assessment. Under the assumption that the loads can be modeled as discrete events occurring randomly at times, t_i, the probability that a structure survives during interval $(0,t_L)$ is defined by the reliability function, $L(0,t_L)$:

$$L(0, t_L) = P[R(t_1) > S(t_1) \cap \ldots \cap R(t_n) > S(t_n)] \tag{7}$$

where n is the number of load events which occur in time $(0,t_L)$. Once the reliability function is obtained, it can be related to the conditional failure rate or hazard function, $h(t)$: