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Optimal maintenance policy for permanently monitored infrastructure subjected to extreme events

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ABSTRACT

Structures and infrastructure management is concerned with the actions required to maximize the system availability, which is seriously challenged by structural deterioration as a result of the normal use or due to external demands imposed by adverse environmental conditions. Given the large uncertainty in the system's performance through life, an optimal maintenance policy requires both permanent monitoring and a cost-efficient plan of interventions. This paper presents a model to define an optimal maintenance policy for structures that deteriorate as a result of extreme events (e.g., earthquakes) based on an impulse control model. Furthermore, the deterioration model takes into account the effect of damage accumulation. Hence, the time at which maintenance is carried out and the extent of interventions are optimized simultaneously to maximize the cost–benefit relationship. The model is illustrated with two examples. The results show that if there exists a good permanent monitoring system, the model provides a cost-effective and practical and long-term tool for managing infrastructure.

1. Introduction

The design criteria for new projects should lead to optimal investment decisions that balance the benefits derived from the existence of the project, the economic investment (inspection and maintenance) and the consequences in case of failure (e.g., reconstruction costs). Thus, designing, constructing and maintaining infrastructure may be viewed as a decision problem where the maximum economic benefit derived from the life-cycle of the project is achieved, while the reliability requirements are fulfilled simultaneously at the decision point [1]. In the literature, this type of analysis is referred to as life-cycle cost analysis. In the design and operation of public and essential infrastructure systems, the structural performance over time plays a key role. It defines the actual cost of the project, beyond the construction investments and the operation program (inspection and maintenance). However, in practice, a significant effort has been traditionally given to time-invariant design without considering the time-dependent structural performance; i.e., problems related to deterioration.

Infrastructure deteriorates as a result of the normal use and due to external demands imposed by adverse environmental conditions (e.g., earthquakes, hurricanes). One of the main challenges in life-cycle cost analysis is modeling the damage accumulation mechanisms and the associated uncertainties. Deterioration mechanisms can be divided into progressive (e.g., corrosion, fatigue) and shock-based (e.g., earthquakes, blasts) [2]. In the particular case of large civil infrastructure, progressive deterioration can be caused by, for instance, corrosion of steel structures or of the reinforcement in RC structures due to chloride ingress, reduction of structural stiffness due to concrete cracking, fatigue, creep and so forth [3–5]. On the other hand, deterioration caused by extreme events is usually associated with earthquakes, hurricanes or blasts (including both accidents and terrorists attacks). Extensive research has been carried out on mathematical models for shock degradation in infrastructure and in other types of engineered artifacts; for more details see [6–10,2].

The management of the physical aspects of infrastructure is frequently linked to inspection and intervention programs; the selection of a particular strategy is also called a maintenance policy. A *maintenance policy* consists of a set of actions directed to keep the system (e.g., building, bridge or pavement) operating above a pre-specified level of service; thus, maintenance is carried out to improve the availability or to extend the life of the system [11,12]. The long-term benefits of an optimum maintenance policy include: minimizing the management costs, increasing the system availability (un-interrupted operation), i.e., reducing the system's downtime and improving the time-dependent reliability [12]. Frequently, a comprehensive maintenance program includes *preventive* and/or *corrective* or *reactive* actions [13,14]. Preventive maintenance involves all actions directed to avoid

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failure or to avoid higher cost at a later stage by keeping the component in a safe or operational condition. While preventive maintenance is commonly carried out at fixed time intervals, corrective maintenance is performed at unpredictable intervals because failure times cannot be known *a priori* [15,16].

For infrastructure systems with long expected lifetimes, e.g., bridges that last on average 50–75 years; standard maintenance policies are not realistic. For example, over time, infrastructure's deterioration cannot be predicted accurately, the structure may be exposed to some unplanned demands (e.g., increment of traffic loading) and the technology involved in inspection and intervention may change. It is then very likely that these unpredictable changes end up forcing modifications to the original maintenance plans. Furthermore, the cost-efficiency of any long-term maintenance program is difficult to verify. Therefore, the best maintenance policy should be based on a permanent monitoring strategy that leads to optimum interventions.

This paper presents a maintenance strategy based on *impulse control* models in which the time at which maintenance is carried out and the extent of interventions are optimized simultaneously to maximize the cost–benefit relationship. In the model the optimal time and size of interventions are executed according to the system state, which is obtained from permanent monitoring. The model assumes that an infrastructure maintenance policy is mainly dominated by its mechanical performance.

The paper is organized as follows. The basic life-cycle cost problem is described in Section 2. In Section 3, we present an overview of infrastructure deterioration modeling strategies. Here, a novel deterioration model that takes into account the effect of damage accumulation is presented.The basic formulation and the conceptual aspects of the impulse control approach is presented in Section 4.1, where a numerical routine to calculate the optimal policy is also included. Finally, two illustrative examples are presented in Sections 5 and 6.

2. Life-cycle cost formulation

The cost-based analysis of the investments in the design and operation of a structure throughout its lifetime is based on the following basic cost–benefit formulation:

$$Z(\mathbf{p},T) = B(\mathbf{p},T) - C_0(\mathbf{p}) - \sum_{i=1}^{N(T)} C_{L_i}(\mathbf{p},\zeta_i), \quad (1)$$

where T is the structure's lifetime; $\mathbf{p}$ is a vector parameter that takes into consideration the structural properties (e.g., geometry and material properties); $B(\mathbf{p},T)$ is the total benefit derived from the existence of the structure; $C_0(\mathbf{p})$ is the initial investment cost (e.g., design and construction); $C_{L_i}(\mathbf{p},\zeta_i)$ is the cost associated to the i-th intervention (e.g., maintenance or failures) with ζ_i being the extent of the intervention, which does not necessarily takes the structure to an 'as good as new'' condition; $N(T)$ is the number of interventions in the time window T. Clearly, both benefits and costs (losses in particular) are random variables (usually time-dependent) and therefore, Z is also random. Therefore, according to statistical decision theory, Eq. (1) should be evaluated using the discounted expected net present value.

The continuous discounting function can be expressed as: $\gamma(t) = \exp(-\delta t)$, where δ is the discounting rate. The discount rate is in general difficult to estimate since it depends on many factors but typical values are within the range $0 < \delta < 7\%$. For instance, for bridge investments in the United Kingdom a common discount rate varies between 4% and 6% [17]. An interesting discussion on the selection of the discount factor can be found in [18,19].

An investment in the construction and operation of the facility makes sense only if the discounted (to the decision point, e.g., $t=0$) expected value of the objective function, $E[Z(\mathbf{p},T)] > 0$; and it is financially optimal for the value of $\mathbf{p}$ that maximizes Eq. (1).

3. Structural deterioration

Infrastructure *degradation* is referred as the process of decay, or loss of value, of one or more structural properties (e.g., stiffness, resistance). Degradation is measured mainly in physical units (e.g., inter-storey drift, loss of stiffness), although analytical assessments such as the reliability index [5], may be used also to describe the overall performance of the system. There are two distinct types of degradation models: (1) progressive (graceful) and (2) shock-based, which may or may not occur simultaneously (Fig. 1) [2].

3.1. Progressive degradation

Progressive (graceful) degradation is the result of a continuous reduction in the structure's capacity/resistance. Most progressive degradation models available in the literature assume that the *form* of the degradation process is known, but the parameters are uncertain. The solution to this problem conveys to a parameter estimation problem. Thus, if $R_p(t)$ is the state of the system at a given time t, which in practice, may be expressed in terms of, for example, remaining capacity, reliability, safety, durability, etc., then these type of models have the following general form:

$$R_p(t) = \begin{Bmatrix} r_0 & 0 \le t \le t_e \\ r_0 - D_p(\mathbf{p}, t - t_e) & t > t_e \end{Bmatrix}, \quad (2)$$

where r_0 is the remaining life of the system at time $t=0$ and t_e is the time of degradation initiation (e.g., time of corrosion initiation). The function D_p may take a linear, non-linear, exponential

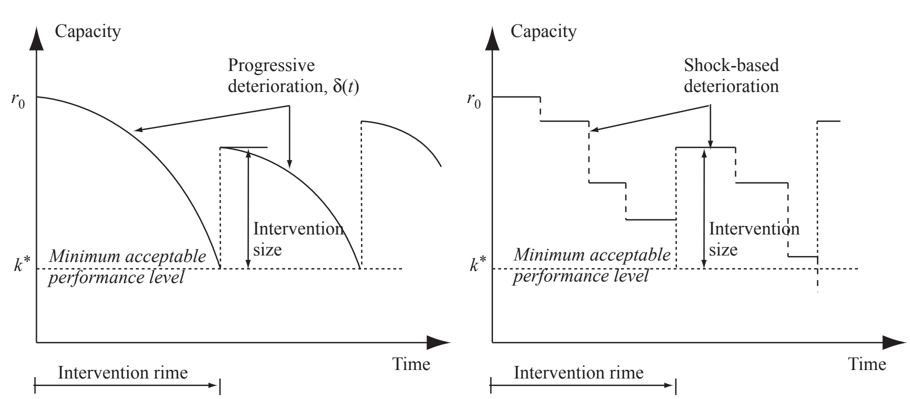

Fig. 1. Description of degradation mechanisms.