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A Bayesian probabilistic approach for impacts of sea level rise on coastal engineering design practice

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ABSTRACT

The real impact of sea level rise (SLR) on coastal and ocean engineering infrastructures is anticipated to be significant. The associated huge costs of coastal flooding and lasting socio-economic crisis would require planners, decision-makers and engineers to use effectively all available knowledge and data to optimize flood defense protection systems. In this paper, we introduce a Bayesian approach that integrates knowledge from previous performance history of structures (data, models and analysis) with more recent information from the simulations performed using the latest data, methods and modeling technology. These two sets of knowledge and information on past and present status of system contain various uncertainties and errors introduced by different input sources and analysis methods. We employ the concept of global uncertainty to quantify the total uncertainty affecting the design, functionality and maintenance of coastal flood defense systems in order to reduce damages resulting from the SLR and other extreme water level changes (e.g., storm surges by hurricanes, increased precipitation and ice melting). Our objective in this paper is to show coastal engineers how to use the prior knowledge with the most current information to improve the safety of flood defense systems. We demonstrate the proposed method in an example for the failure analysis of the 17th Street Flood Wall in New Orleans, where we estimate uncertainties that affected the design of the I-wall. We provide a methodology that integrates the contribution of SLR with all other available prior information to determine uncertainty levels for failure analysis of the flood defenses. Various uncertainties are present in engineering practice, explicit or implicit, and quantification of these is essential to safety and efficacy of coastal flood protection systems.

1. Introduction

Sea level rise (SLR) is a universal concern to humans living in coastal areas worldwide. While studies have shown different estimates for future years, all projections agree on an increasing trend (Pachauri, 2007; Houghton and Callander, 1992; Metz, 2007). Based on available data and analysis methods, the SLR for 2100 is forecasted to be 0.5–1.4 m above the 1990 level (Rahmstorf, 2007). Although it is not possible to verify the accuracy of this long-term projection, the global mean SLR over the last decade (1993–2003) is about 3.1 mm/yr, which is significantly higher than the historical rate of sea level change (Cazenave and Nerem, 2004). However, the uncertainty in future prediction is considerably large (Convertino et al., 2012; Yohe and Neumann, 1997; Yoke, 1991), and components of uncertainty have been identified (Webb et al., 2006). The intergovernmental Panel on Climate Change (IPCC) describes the uncertainty in Fig. 1. Amongst the many causes contributing to the increasing trend in SLR are the global warming, ice melt and thermal expansion (Pachauri, 2007). However, the SLR is not geographically uniform (Cazenave and Nerem, 2004), and the SLR in some areas of world is projected to be more than 10 times of the global mean, and millions of people will be affected by it, especially those who live in the vulnerable coastal areas.

The sea level rise caused by recent world climate changes is feared to substantially increase the risk of failure of different types of flood protection systems (Webb et al., 2006; Bradshaw et al., 2007; Demirbilek, 2010). This concern is forcing authorities to plan and develop improved means for the safety of people (Wu et al., 2002). Authorities may consider more regulations and standards to ensure flood protection systems provide acceptable levels of safety. The regulatory measures will require engineers to provide coastal protection infrastructures with attractive features while improving the safety of people and their properties. In this paper, we consider coastal engineers as experts who design and maintain flood protections systems, and emphasize that politicians and decision-makers will also deal with certain aspects of coastal infrastructure safety issues.

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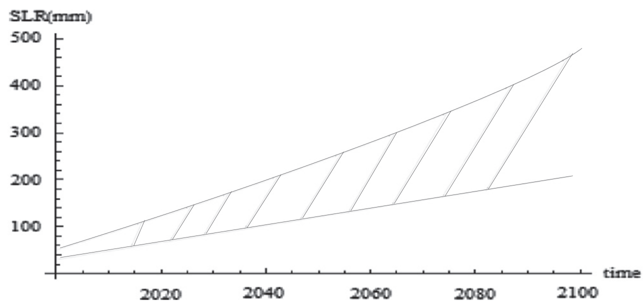

Fig. 1. Schematic of uncertainty as a function of time for predicted future SLR levels (modified from Bindoff et al. (2007)).

People are generally less tolerant to failures of the flood defenses (Demirbilek, 2010) because the extent of potential damages and very high cost associated with such events. Residents in the exposed coastal areas expect emerging technologies to help protecting them from the environmental forces, assuring the safety and well-being of coastal residents (Arthington et al., 2010; Zahran et al., 2010; Ramin and McMichael, 2009). These expectations make the design and maintenance of coastal flood protection systems a very important issue for coastal engineers. The impacted people often welcome any new knowledge and information about uncertainties that might affect their safety. This requires coastal engineers to have a good understanding of all uncertainties pertinent to the safety of flood defenses. An equally important need is the effective communication of these complex issues with the residents of flood prone communities (Demeritt et al., 2007; Keller et al., 2006). These challenges and potential solutions are discussed next.

In terms of strong societal demand about the impacts of SLR, engineers must consider extreme forcing conditions for designing and maintaining safe flood defenses. The extreme sea level changes, such as storm surges (Demirbilek, 2010) can be predicted reasonably well by combination of numerical modeling capabilities using state-of-the-art knowledge and experience. Coastal design predictions obtained by advanced models include uncertainties because the design of flood defenses requires using large data sets and computational tools. These introduce errors in data and assumptions and approximations in the modeling technology used. It is well-understood that there are uncertainties in the data, material properties, geotechnical data and conditions, predicted extreme values, and the validity of models used in design studies. Understanding that uncertainties are present in all aspects of engineering practice, coastal engineers are required to perform a thorough reliability assessment of the flood defenses.

On the other hand, the construction, repair and maintenance of massive flood defenses can impose a heavy financial burden on coastal communities. This necessitates the optimization of design and maintenance process for flood defense systems by integrating the best applicable state-of-the-art models and data with the prior knowledge and experience. By integration of prior knowledge, data and modeling/simulation results in different stages of design and maintenance process, engineers can develop more accurate safety level estimates for coastal flood defense systems.

The use of emerging technologies, such as remote sensing in monitoring the flood defenses, is also growing in response to the above-mentioned needs and challenges (Smith, 1997; Hess et al., 1990). A continuous stream of data from these sources and efficient use of such large data sets in modeling have been reported (Mason et al., 2010). Consequently, the integration of the so-called new and prior data, models, analysis methods, and interpretation of results from these means has become an increasing challenge for everyone involved in the field of coastal flood defenses (Brocca et al., 2010). Such an integrated probabilistic approach is necessary for estimate of the system safety, decision-making and emergency management planning (Pavanasam et al., 2010; Rajabalinejad and Spitas, 2012). Therefore, we will next provide the framework of a probabilistic design approach for taken into account uncertainties in the design and maintenance of flood control systems.

2. Probabilistic approach

Acknowledging the presence of uncertainty in information, methods and technology is the first step to considering a probabilistic design framework in engineering practice. There are additional uncertainties associated with the functionality and performance of flood defenses (Demirbilek, 2010; Brocca et al., 2010; Pavanasam et al., 2010). It is not possible to design and build a structure that would never fail, but engineers can design for a sustained performance during the life cycle of a structure. Generally, this may require processing large and complex data to develop estimates such as "average" or "maximum" values, an approach that is desirable for shortening the time spent in structural design. However, this simplified thinking can produce less reliable estimates as it would mask uncertainties in the data. Likewise, using the safety factor would be fast, simple and less costly in engineering works, but the safety factor alone is insufficient for a reliable decision-making process. Engineers are expected to quantify and document the uncertainties in data, assumptions used in modeling tools and interpretation of results (Morss et al., 2005) in design and maintenance of flood systems.

The demands on the safety of flood defenses could impose serious cost constraints in engineering practice, requiring engineers to optimize their procedures or designs. Any optimization generally requires a detailed knowledge about the specifics of the system, and those with high uncertainties are generally more difficult to optimize. It has been suggested that in system optimization it is necessary to integrate information from different sources in order to obtain reliable system responses (Néelz et al., 2006). In other words, engineers have to be able to systematically develop different sources of information based on a sound understanding of system's features when they try to provide affordable and cost-effective solutions. System design data and operation and maintenance records are necessary for the integration of information with the methods and tools to be used in system optimization. Models and tools available for flood defenses can process a large amount of data as stochastic variables, which enable engineers to consider different scenarios, structural options, combination of forces, stresses, resistances etc. As shown in Fig. 2, the expected outcomes are also stochastic variables, covering different scenarios and possible model responses.

Fig. 2 shows a typical stochastic system where input variables are processed in the simulation process and final estimates are the output variables. There are a number of state-of-the-art stochastic finite element tools available (Bergman et al., 1997; Vanmarcke et al., 1986), and one has been specifically recommended for calculating the safety of flood defenses (Rajabalinejad et al., 2010a). However, this tool has been used without including prior simulation knowledge in calculated final estimates. To address this important deficiency, we present an approach in the next section for integrating the information obtained from knowledge, data and simulation models. We propose a method based on the Bayesian statistics for integration of the prior knowledge and data together. In the current practice, the prior knowledge from models is used as benchmarks, but the information is not included in the analysis because it is not striaghtforward to do so. Engineers often compare results from new tools and techniques to those obtained from existing tools intuitively but not systematically. In Fig. 3, we provide the schematic of a tool for integration of information in three stages of simulations.