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Damage risks and economic assessment of climate adaptation strategies for design of new concrete structures subject to chloride-induced corrosion

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ABSTRACT

Reinforced concrete (RC) structures are subject to environmental actions affecting their performance, serviceability and safety. Among these actions, chloride ingress leads to corrosion initiation and its interaction with service loading could reduce its operational life. Experimental evidence indicates that chloride ingress is highly influenced by weather conditions in the surrounding environment and therefore by climate change. Consequently, both structural design and maintenance should be adapted to these new environmental conditions. This work focuses on the assessment of the costs and benefits of two climate adaptation strategies for new RC structures placed in chloride-contaminated environments under various climate change scenarios. Their cost-effectiveness is measured in terms of the benefit-to-cost ratio (BCR) and the probability that BCR exceeds unity – i.e., Pr(BCR > 1). It was found that increasing concrete strength grade is more cost-effective than increasing design cover. The results also indicate that the cost-effectiveness of a given adaptation strategy depends mainly on the type of structural component, exposure conditions and climate change scenarios.

1. Introduction

Concrete is the predominant construction material for buildings, bridges, wharves, and other infrastructure in Europe, Australia and elsewhere. A potentially important factor for asset management is the possible influence of climate change. This may alter the environment to which infrastructure is exposed, and in turn may alter the factors known to affect the corrosion of reinforcing steel, including atmospheric CO_2 concentration, temperature, humidity, ocean acidification, airborne pollutants, etc. Depending on the precise exposure conditions, each of these can influence initiation or progression of corrosion and thus have a detrimental effect on maintenance costs and remaining life. The annual cost of corrosion worldwide is estimated to exceed \$1.8 trillion, which translates to 3–4% of the Gross Domestic Product (GDP) of industrialised countries [1]. Since the direct and indirect costs of corrosion are immense, a climate-change induced acceleration of the corrosion process by only a few percent can result in increased maintenance and repair costs of hundreds of billions of dollars annually.

Until recently all corrosion research assumed constant average climatic conditions for the development of deterioration models. However, even under an optimistic scenario where CO_2 emissions are abated to reduce temperature increases to 2 °C by 2100, the International Panel on Climate Change (IPCC) [2] reports that such a scenario (B1 or A1T) is likely only if non-fossil energy sources dominate. An increase in temperature will increase the rate of infiltration of deleterious substances (increased material diffusivity) and increase the corrosion rate of steel. Optimum relative humidity levels may also increase the rate of infiltration of deleterious substances [3]. Typically these parameters must be considered as random variables or stochastic processes, and their statistical characteristics will gradually change with time. An appropriate framework for dealing with this problem is structural reliability and risk-based decision analysis.

Bastidas-Arteaga et al. [4] proposed a stochastic approach to study the influence of global warming on chloride ingress for RC structures. They found that chloride ingress could induce reductions of the corrosion initiation stage varying from 2% to 18%. Concerning corrosion propagation until failure, Bastidas-Arteaga et al. [5] found that global warming could reduce the time to

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failure by up to 31% for RC structures subject to chloride ingress. Recent work also focused on the assessment of climate change effects on the durability of concrete structures in specific locations. Stewart et al. [3] found that the temporal and spatial effects of a changing climate can increase current predictions of carbonation-induced damage risks by more than 16% which means that one in six structures will experience additional and costly corrosion damage by 2100 in Australia and presumably elsewhere. Wang et al. [6] studied the impact of climatic change on corrosion-induced damage in Australia. They proposed a probabilistic approach to assess corrosion damage taking into account the influence of climate change on areas characterised by different geographical conditions. Talukdar et al. [7] estimated the effects of climate change on carbonation in Canadian cities (Toronto and Vancouver). They found potential increases in carbonation depths over 100 years of approximately 45%. However, this work did not consider the uncertainties related to climate, materials and models.

A benefit of a probabilistic approach to damage prediction is that it enables a risk-based economic assessment of climate adaptation strategies. In addition to reducing environmental exposure as much as possible, practical adaptation solutions in new designs may come from increasing cover and strength grade, or any approaches that reduce material diffusion coefficient without compromising the reliability and serviceability of concrete. Stewart et al. [8] considered the effect of climate adaptation strategies including increases in cover thickness, improved quality of concrete, and coatings and barriers on damage risks. It was found that an increase in design cover of 10 and 5 mm for structures where carbonation or chlorides govern durability, respectively, will ameliorate the effects of a changing climate.

The present paper extends this decision framework considerably to assess the costs and benefits of two climate adaptation measures aiming to reduce the impact of chloride-induced corrosion damage: (i) increase in design cover, and (ii) increase in strength grade of concrete. The cost-effectiveness is measured in terms of benefit to cost ratio (BCR) equal to benefits divided by the cost. The stochastic analysis also enables the probability that BCR exceeds unity to be estimated as $\Pr(BCR > 1)$. In this case, while mean BCR can be high, there may be a likelihood of BCR less than one (net loss) which is risk-averse decision-maker may need to consider when making a decision. To be sure, other decision metrics can be used, such as maximising net present value (net benefit), or minimising life-cycle costs. While the formulations may differ, the decision outcomes will be identical, and BCR is selected as this seems to be a metric that government and policy makers are familiar with. The results of the paper will help provide practical advice to policy makers to help 'future proof' built infrastructure to a changing climate.

Section 2 describes the main considerations for climate change modelling based on the recommendations of the IPCC. The deterioration models used for the probabilistic assessment of BCR under climate change will be presented in Section 3. Section 4 depicts the repair strategy, the probabilistic framework and illustrates the assessment of time-dependent damage risks due to climate change. Finally, Section 5 describes the proposed framework for the BCR analysis and details the assessment of the adaptation costs that are used in the illustrative example (Section 6).

2. Climate change modelling

2.1. IPCC climate change scenarios

The future climate is projected by defining carbon emission scenarios in relation to changes in population, economy, technology, energy, land use and agriculture, represented by a total of four scenario families, i.e., A1, A2, B1 and B2 [2]. Sub-categories of the A1 scenario included differing energy sources (fossil intensive, non-fossil energy and a balance across all sources, for example, A1FI, A1T and A1B, respectively). In addition, scenarios of CO_2 stabilisation at 450 and 550 ppm by 2150 were also introduced to consider the effect of policy intervention [9]. Hence, the A1FI or A2, A1B and 550 ppm stabilisation scenarios represent high, medium emission scenarios and policy intervention scenarios, respectively. The IPCC Fifth Assessment Report (AR5) [10] uses Representative Concentration Pathways (RCPs) where RCP 8.5, RCP 6.0 and RCP 4.5 are roughly equivalent to A1FI or A2, A1B, and A1B to B1 emission scenarios, respectively [11]. These RCPs were considered to be representative of the literature, and included a mitigation scenario leading to a low forcing level (RCP 2.6), two medium stabilisation scenarios (RCP 4.5/RCP 6) and one high baseline emission scenarios (RCP 8.5) [12].

2.2. Uncertainties for climate projections

Climate projections are subject to considerable uncertainty that depend on CO_2 emission scenarios and accuracy of general circulation models (GCM). These uncertainties can be classified into three types [13,14]:

- I*nternal uncertainty* is related to the natural variability of the climate system without considering any anthropogenic climate change effect. There are weather disturbances of different duration, size and location that turn climate into a chaotic system. Consequently, it is currently impossible to predict future climate at different scales (daily, monthly, yearly, etc.) even for the more complete climate models and short-time windows.
- *Model uncertainty* (also known as response uncertainty) is associated to the fact that GCMs simulate different changes in climate in response to a given radiative forcing. This kind of uncertainty depends mainly on the simplifications and assumptions that are implemented for each GCM to simulate natural systems.
- *Scenario uncertainty* is related to the assumptions made to define each climate change scenario that determine the future radiative forcing used in climate projections (e.g., future emissions of greenhouse gases, population growth, introduction of clean technologies, changes in land use, etc.).

Fig. 1 illustrates how these uncertainties interact over time for surface temperature projections and two different scales: global (earth) and regional (British isles) [13]. At a global scale, it is observed that model and internal uncertainties are initially predominant (Fig. 1a). However, scenario uncertainties grow considerably and become the most important source of uncertainties after 50 years. A regional scale changes the relative importance of uncertainties. Internal uncertainty has initially the largest importance because regional weather is largely affected by random weather and climate fluctuations. Model uncertainties have the largest importance from 20 to 70 years. The importance of scenario uncertainties grows significantly during the latter part of the century (after 70 years).

Complexity of these uncertainties implies several considerations for the assessment of climate change effects on civil infrastructure:

- Use of several climate trajectories from a same GCM to account for internal uncertainty.
- Use of several climate trajectories for various GCMs to account for model uncertainty.
- Consider several climate change scenarios to account for scenario uncertainty. A scenario of no change in climate may make economic sense as a 'no regrets' policy even if climate predictions are wrong.