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Article

Climate-resilient infrastructure planning: Integrating climate change adaptation into engineering design

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Abstract: Climate change is an important factor that must be considered by designers of large infrastructure projects, with its effects anticipated throughout the infrastructure's useful life. This paper discusses how engineers can address climate change adaptation in design holistically and sustainably. It offers a framework for adaptation in engineering design, focusing on risk evaluation over the entire life cycle. This approach avoids the extremes of inaction and designing for worst-case impacts that may not occur for several decades. The research reviews case studies and best practices from different parts of the world to demonstrate effective design solutions and adjustment measures that contribute to the sustainability and performance of infrastructure. The study highlights the need for interdisciplinary cooperation, sophisticated modeling approaches, and policy interventions for developing robust infrastructure systems.

Keywords: climate change; engineering; infrastructure planning; adaptation; civil engineers

1. Introduction

As the impacts of climate change become more pronounced, civil engineers face the critical challenge of designing and constructing infrastructure that can withstand and adapt to changing environmental conditions. The emerging evidence of climate change, as detailed in the consensus report by the Intergovernmental Panel on Climate Change (IPCC, 2007), underscores the necessity of considering climate change impacts in current engineering designs. This need is further reinforced by government policies requiring infrastructure developments and major projects to incorporate predicted climate change effects. For instance, the Queensland Government mandates the inclusion of a Climate Change Impact Statement (CCIS) in relevant submissions, requiring detailed adaptation measures to minimize risks from climate change impacts (QOCC, 2008).

Traditionally, engineering designs have relied on historical data to predict statistical events and establish design criteria. This approach, based on analyzing historical trends and probabilities of specific design events, is exemplified by guidelines such as Australian Rainfall and Runoff and wind loading codes. However, climate change introduces new patterns and variations that historical data alone cannot capture, necessitating a shift in design methodologies to account for future conditions over the entire life cycle of infrastructure projects (Connor et al., 1990). Climate change adaptation refers to the initiatives and measures aimed at reducing the vulnerability of natural and human systems to actual or expected climate change effects (IPCC, 2007). Despite the recognized need for adaptation, specific guidance for designers of engineering works remains scarce. Design teams often navigate general frameworks, attempting to integrate specific climate considerations without the benefit of detailed, standardized guidelines (Standards Australia, 2011, 2002). This lack of specificity in adaptation guidance has limited the extent of adaptation currently occurring, as noted in the Fourth Report by the IPCC (2007).

Recent advancements in engineering practice indicate a move towards incorporating climate change adaptation into design standards. For example, Australian cyclone activity over the past two decades has led to the inclusion of an uncertainty factor in cyclone regions, adjusting predicted wind loads to account for recent events and potential future changes (Standards Australia, 2011). This arbitrary adjustment highlights the necessity for a more scientific approach to developing design parameters that incorporate projected climate change scenarios.

2. Updated guidance on climate adaptation

2.1. Lack of specific guidance and IPCC finding

Designers of engineering works often struggle to find specific guidance on adaptation, leading them to rely on general frameworks and attempt to tailor them to their needs. This departure from conventional engineering practice, which typically involves referencing specific codes or guidelines, reflects the current challenge in integrating climate adaptation into design processes. The IPCC's Fourth Report (2007) highlighted the necessity for more extensive adaptation efforts to mitigate vulnerability to climate change, emphasizing the scarcity of detailed guidance as a barrier to implementation. Despite this, the IPCC also acknowledges the existence of feasible adaptation options that offer low-cost implementation and high benefit-cost ratios, indicating the potential for effective adaptation strategies even in the absence of comprehensive guidance.

2.2. Current structural practice and risk-based approaches

A survey of the current structural practice in Australia and New Zealand reveals that most of the direction and guidance on loadings and load factors are provided by the AS/NZS1170 Structural Design Actions standards (Standards Australia, 2011, 2002). There are also specific loading standards for industries such as the AS5100 series for bridges. General Principles (Standards Australia, 2002) provides the fundamentals for design actions, load factors, and importance factors for structures, in general, for wind, earthquake, and snow loads. However, there is no information on design events that may arise because of climate change. Climate change may require another probability of exceedance table for other actions assumed to be static, for instance, liquid pressure actions that may increase due to rising ocean levels. The climate change projections in the IPCC 2007 report are in risk form, which is more suitable for a risk-based analysis of adaptation options. Because of the observed increase in cyclone activity in Australia in the last 20 years, an uncertainty factor has been added to cyclone areas (Standards Australia, 2011), which has raised previously predicted ultimate design wind loads due to the unpredictability of extrapolating historic wind data.

2.3. Existing frameworks and recommendations

Numerous frameworks have emerged in recent years with the aim of facilitating climate change adaptation, yet their integration into actual engineering design practices remains limited. For instance, Smit et al. (1999) proposed a comprehensive framework designed to assess impacts and evaluate adaptive policy options in response to climate change. However, despite its theoretical robustness, this framework offers little practical guidance for engineers engaged in current climate change adaptation design endeavors. In contrast, the UK Climate Impacts Programme (UKCIP, 2003) presented a more detailed overarching framework tailored specifically to climate adaptation. This framework delineates climate adaptation strategies within the context of prevailing uncertainties. It delineates a risk-uncertainty-decision-making framework, comprising eight stages distributed across four key areas: Structuring the problem, analyzing the problem, decision-making, and post-decision actions. While this framework provides a structured approach to climate adaptation, its translation into practical design applications remains a challenge.

In Australia, the National Climate Change Adaptation Research Facility (NCCARF) has emerged as a pivotal entity spearheading research efforts to furnish decision-makers with indispensable information for managing climate change risks. Simultaneously, Engineers Australia’s National Committee on Coastal and Ocean Engineering (NCCOE) has been at the forefront of climate change engineering initiatives in Australia since 1991. Notably, the preliminary draft of the latest update to the Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering (NCCOE, 2009) introduces a methodology geared towards evaluating the potential impacts of climate change on various projects or infrastructure.

Within this context, the authors have devised a Risk Framework for Climate Change Adaptation, offering a comprehensive approach to adaptation planning and design. This framework seeks to bridge the gap between theoretical constructs and practical application by providing engineers and decision-makers with robust tools for assessing and managing climate change risks effectively. It is imperative for designers to furnish decision-makers with accurate and comprehensive information to facilitate informed decisions. Given their expertise, engineers are uniquely positioned to navigate the complexities of climate change risks and facilitate comprehensive assessments of choices pertaining to potential climate change impacts. Through concerted efforts and the integration of robust frameworks, the engineering community can play a pivotal role in fostering resilience in the face of climate change challenges.

The climate in Australia has changed over the past few decades, with general increases in average temperatures, heat wave events and the occurrence and intensity of extreme events such as floods, bush fires and storms, and alterations in the rainfall distribution. These climatic changes have implication on infrastructure planning and design of structure within the country. For instance, there are indications that extreme rainfall events together with flooding have increased in many regions in Australia. An Australian study of the period 1958 to 2017 showed that short-form extreme events of rainfall had increased by 22%, according to the Australian Bureau of Meteorology. This has a direct bearing with design floods and which affects flood immunity of structures like bridges, drainage systems, and dams among others. Designers of infrastructure must also look for larger design floods with higher peak discharge rates. Precise data must be collected and used in design and planning processes because when old floods data is used it leads to inadequate protection and can cause over topping and failure. In general, higher temperatures cause structures to degrade more rapidly, bushfires are a risk to buildings and installations near vegetation, and stronger storms impose higher loads on buildings. Taking into account the observed and expected climate scenarios in the context of Australia, in decisions about the long-term construction of infrastructure, will be crucial for future sustainability and security.

3. Methodology

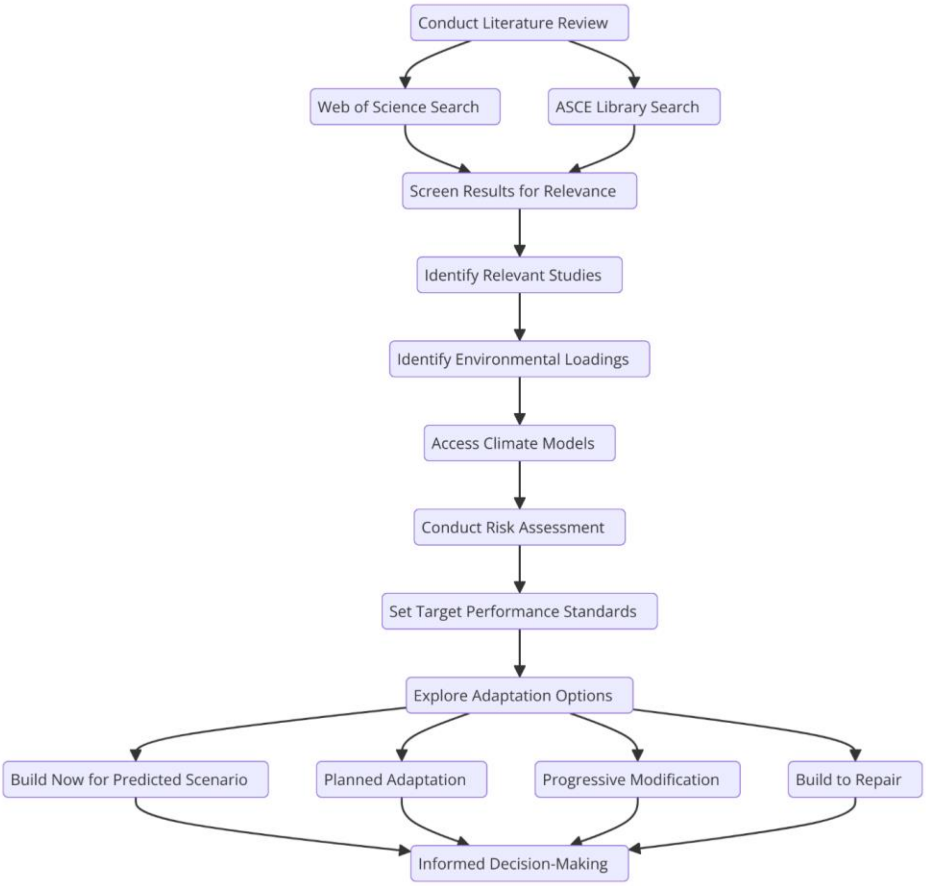

Figure 1. Flowchart illustrating the methodology for integrating climate change adaptation into engineering design for climate-resilient infrastructure.

In this systematic review, we used the Web of Science (WOS) and the ASCE library for literature search on the aim of integrating climate change adaptation into engineering design for climate proof planning of infrastructure. It is for this reason that we had devised our WOS query based on infrastructure, climate change, decision making and resilience. Thus, to expand the sources, we replaced “resilience” into “vulnerability” and ‘‘adaptation”. A similar search was also conducted for the ASCE library. We narrowed down the results by focusing only on highly related topics and the quality of the articles. An initial search of the ASCE library produced 1328 hits to the keywords and the final consisted of 69 publications which includes reviews, conference proceedings, journal articles and books. Other publications that extended topics mentioned in the WOS search results but only briefly, such as Envision and design approaches utilized in practice, were incorporated. In total, 69 publications were reviewed, categorized into reviews, conference proceedings, journal articles, and books (including two from the Manuals of Practice series: (Ayyub, 2018; Ayyub et al., 2021)). This structured approach offered valuable insights into integrating climate change adaptation into engineering design, enhancing adaptive capacity, and reducing vulnerability in infrastructure projects (Ali Akber et al., 2024) in **Figure 1**.

3.1. Identification of environmental loadings and climate change projections

During the first step of our methodology that encompassed screening environmental factors, which influence the project design, the potential risks of climate change were determined. These factors included a wide range of aspects such as availability of water, wind condition, rain intensity, temperature differences, waves or currents, sun exposure, humidity and rates of evaporation. To restore climate change’s potential impact on these loadings it was necessary to get climate models which simulated multilevel interactions between the atmosphere, ocean and the land. These models produced estimates based on the disparate emissions profiles where various assumptions were made concerning land use change, technological development, economic progress rates, population increase, and cohesiveness of global policies.

Hence, for proper incorporation of climate change projections into infrastructure, there was need to obtain extended databases and standards of the industry. Some examples that include sources for the climate change information included organizations like the CSIRO Australia offered key climatic modeling and regional climate reportage while government policies like the Draft Queensland Coastal Plan 2009 provided useful ble on how to attend to issues like sea-level rise. In this manner, design firms could narrow down to the relevant climate change scenarios and the corresponding environmental loadings for its projects in close consideration with the project owners.

3.2. Risk assessment for informed decision-making

After the environmental assessment step of the methodology it focused on performing a risk assessment of the identified environmental loadings both in terms of their impact severity and the probability of their occurrence over the life cycle of the project. It demonstrated an important background for other hazard evaluations to structure adaptation measures. In this regards, risk was described as being the probability of the hazard occurring multiplied by the level of the consequences. Risk was defined in terms of environmental loadings and the ability of these loadings to produce failure which is the transgression of design limits. A semi-structured risk assessment question format allowed the designers to sort the risks by their potential level of impact, from a modest inconvenience to economic losses or loss of human life.

3.3. Determining environmental loadings and climate change projections

In the context of climate-resilient infrastructure planning, the specific strategy of setting target performance standards (TPS) was central to assessing whether designed constructed could effectively withstand pressures from the climate in question. Thus, the definition of the environmental loadings relevant to a project or activity and the evaluation of their potential vulnerability to climactic changes were elemental activities. These loadings included factors ranging from water, wind, temperature, Rainfall and water infiltration rates. Working with climate models and future forward projections, the designers could foresee how these loadings would probably change throughout the project cycle and then choose the most suitable TPS methodologies to manage these changes.

3.4. Exploring target performance standards: TPS-A and TPS-B

Two main methods, TPS-A and TPS-B supplied divergent ways of achieving the organizational performance standards within changing climate contexts. TPS-A focused on achieving and maintaining the established design standards by aiming to keep the probability of failure of the system in response to various annual environmental loads. However, TPS-B took the probability of failure at given stages of the project development and adjusted for changes in environmental risk assessment over the duration of the undertaking. Whereas TPS-A placed strong emphasis on keeping to standards, TPS-B permitted occasional departures from standards as long as the average risk was within acceptable limits. Therefore, designers had to consider the consequences of each methodology in details and then choose the most appropriate method depending on project conditions and the results of risk analysis. First, there was an understanding of the fact that the further outcomes of action or inaction on climate change are highly unpredictable, and therefore required constant monitoring and adjustments throughout the different phases of the project life cycle.

One of the fundamental questions that the decision of utilizing TPS-A instead of TPS-B stirred was that of risk acceptance and design conservativeness. Some might have insisted on maintaining high standard throughout the process (TPS-A) while others might have preferred a flexible standard which could take into considerations the prevailing weather conditions (TPS-B). This balance between perspectives was not very hard to strike, but it necessitated a good understanding between the objectives and scopes of the projects and the organizational/communal risk indices that the designer was willing and able to take. Also, the climate change being a dynamic issue highlighted the benefits of cyclical design and the constant enhancement of the adaptation frameworks to enhance the sustainability of infrastructure systems in an environment characterized by present and future change.

3.5. Exploring adaptation options for climate-resilient designs

In the final phase of the adaptation process, designers must consider various options for adapting projects to climate change. Four primary adaptation approaches are outlined:

1) Build Now for Predicted Scenario: This approach involves designing infrastructure to meet predicted climate conditions throughout its projected lifetime. It ensures resilience against future climate impacts but may require a higher initial investment.
2) Planned Adaptation: Anticipating increased climate risks, this approach entails designing infrastructure with the capability to adapt progressively over its lifespan. It involves careful planning of upgrade programs and may incur moderate initial investments.
3) Progressive Modification: In response to verified climate change, this approach involves redesigning and reconstructing infrastructure as required. It allows for flexibility in adapting to evolving climate conditions but may lead to higher maintenance costs.
4) Build to Repair for Lifetime: Under this approach, infrastructure is constructed to accept damage from climate impacts, with repairs carried out as needed. It prioritizes minimizing initial investments but may result in higher long-term repair costs.

3.6. Exploring implications of climate change adaptation

Exploring the ramifications of adapting to climate change offers decision-makers a comprehensive understanding of its impact on both projects and businesses. This discourse often delves into nuanced aspects like recalibrating expectations regarding the lifespan of designs, prompting owners to potentially entertain the notion of shorter design cycles. Such deliberations inevitably trigger shifts in financial assessments, adding layers of complexity to the task of delivering a design that adequately addresses the challenges posed by climate change. Moreover, as the Climate Change Adaptation Process progresses to its final phase, evaluating available adaptation options becomes paramount. This stage necessitates thorough evaluation by project teams, decision-makers, and stakeholders, considering various factors such as life cycle cost, value, and social and environmental implications. The intricacies involved in this phase underscore the need for meticulous decision-making processes, often requiring substantial effort to navigate effectively.

As designers immerse themselves in the realm of adaptation design, they are poised to glean valuable insights and refine approaches tailored to specific sectors. This iterative process of learning is anticipated to pave the way for the emergence of more efficient and effective measures within each adaptation approach. It is widely acknowledged that innovation will be instrumental in shaping the landscape of climate-resilient designs, underscoring the dynamic nature of this evolving field. Expanding upon these considerations highlights the multifaceted nature of addressing climate change adaptation and the ongoing quest for innovative solutions to mitigate its impact on infrastructure and society.

4. Results

Table 1 presents out four key strategies relevant to the integration of climate change considerations within the design, construction and maintenance of infrastructure assets throughout their life cycle. It also contains the anticipated financial exchanges themselves; this work also also contains case studies that would show how we can apply each of the approaches exemplified above to a culvert project; there is also a case of applying the approaches to a wharf project.

Table 1. Proposed climate change adaptation approaches.

Approach	Description	Expected Financial Implications	Case Study 1—Culvert	Case Study 2—Wharf
Build Now for Lifetime	Construct infrastructure immediately to meet predicted climate conditions throughout its lifespan.	Relatively high initial investment, long-term security dependent on subsequent adaptation.	Design and construct culvert providing capacity for climate change variation over project's life.	Design and construct wharf to meet prevailing climate scenario, plan for future environmental loading requirements.
Planned Adaptation	Design infrastructure to progressively adapt over its lifespan, with planned upgrade programs to accommodate climate changes.	Medium relative initial investment, implementation of project changes to occur reasonably.	Implement progressive modifications to culvert and renovate wharf to meet mid-life span climate change variation.	Redesign and reconstruct wharf pylons in response to verified climate change, adapt functionality over life span.
Progressive Modification	Redesign and reconstruct infrastructure as required in response to verified climate change, ensuring functionality and resilience.	Lower initial investment, but ongoing redesign and reconstruction costs may accrue during life cycle.	Measure tail water level, redesign and reconstruct culvert as needed to adapt to changing climate conditions.	Construct wharf suitable for existing climatic conditions, accept damage and carry out repairs as needed.
Build to Repair for Lifetime	Construct infrastructure with the understanding that repairs will be needed over its lifetime due to climate impacts.	Low initial investment, but potential for higher financial loss due to damage during asset's life cycle.	Allow culvert to fail under existing climatic conditions, accept damage and carry out repairs as needed.	Construct infrastructure to withstand existing climatic conditions, accept damage and carry out repairs as needed.

These adaptation options provide a framework for designers to tailor climate-resilient strategies to specific projects, balancing initial investments with long-term resilience and sustainability.

5. Adaptation approaches

5.1. Build now for lifetime

This approach involves the provision of climate infrastructure immediately according to forecast adverse climate conditions regarding the life cycle of the concerned asset. The cost is relatively high in the initial phase and offers great long term protection against the effects of climate provided that subsequent changes are brought forward.

5.2. Planned adaptation

With this approach, infrastructure is created in a way that allows for improvement in accordance with current constant climatic changes. Initial costs are moderate, and adjustments in the light of new database are undertaken from time to time and in a rather reasonable manner.

5.3. Progressive modification

This approach is reasoned that structure is adapted using redesign and reconstruction when climate changes are proved and verified to maintain proper functionality of the structure. upfront costs are cheaper than in centralized systems while there are costs that pile up over the system's life cycle which require repeated upgrading of systems.

5.4. Build to repair for lifetime

They do this to be able to create infrastructure that can withstand the current climate prevailing in the region, but they know that these are going to require form climate change related damages which will require repair during the useful life of the infrastructure. This approach has the least investment to start with but the most expensive after damages are frequently incurred.

6. Case study examples

The table also provides two examples of how these approaches could be applied to a culvert project and a wharf –illustrating specific examples of how those climate adaptation options might be put to use in unique contexts.

7. Financial considerations

However, the table aims at showing that climate adaptation decisions mean making compromises and choose between certain parameters such as the cost of the project, its durability and security and the possibility of having to make repair investments in cases where climate models are exceeded. These financial aspects may make the difference when planners decide that financial constraints are paramount.

8. Conclusion

It is argued that climate change should be considered in current engineering design, even if the outcome does not specifically cater to climate change. A risk-based approach and careful consideration of the target design standard led to robust outcomes, enabling project owners to make well-informed decisions about likely whole-of-life financial outcomes. While the proposed approach is comprehensive, factors to be incorporated are specific to potential environmental loadings at the site. This process guides stakeholders through a thorough decision-making journey by delineating key stages such as determining environmental loadings, conducting risk assessments, exploring adaptation options, and assessing recommended methods. The delineation of adaptation options, from building for predicted scenarios to adopting progressive modifications, empowers decision-makers to tailor strategies that align with their specific project needs and risk tolerances. The role of designers is to facilitate a comprehensive assessment of choices by the owner, focusing on potential climate change and consequent project performance and costs.

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