SUSTAINABLE COASTAL INFRASTRUCTURE: BUILDING RESILIENCE THROUGH INTEGRATED ADAPTIVE DESIGN

A systems-based approach for developing resilience to climate change impacts

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Around 40 percent of the world's population live within 100 kilometres of the coast. Coastal communities often have significant economic and social importance due to the maritime and shipping trade, tourism, fishing industries and coastal real estate. However, coastal regions are among the most vulnerable locations to the impacts of climate change.

Climate change presents multiple challenges to coastal developments, including rising sea levels, increased risk of coastal erosion and increased frequency and intensity of extreme weather events. Addressing these challenges through integrated adaptive planning and design will help to protect coastlines as well as the social and economic value of coastal developments. Integrated adaptive planning and design is a strategic process that addresses the challenges of climate change through a comprehensive systems-based approach. It involves the development of adaptive solutions that can be implemented at various levels, including large-scale coastal cells, subdivided sub-cells, and individual property defences. Integrated adaptive planning requires collaboration among governments, landowners, businesses, non-governmental organizations and other relevant stakeholders.

Coastal environments are dynamic. Coastlines are naturally changing. Therefore, when managing coastal regions, there are options to resist change or to allow the coast to develop. Even when coastal defences are constructed to resist change, change can occur in adjacent areas as a result of the coastal defences.

Therefore, an understanding of the site-specific conditions is vital when exploring the various potential strategies and selecting the best option to build resilience.
Several overarching objectives can guide the decision-making process toward sustainable coastal development.

Overarching objectives

Define requirements

Defining the project requirements in a clear and comprehensive project brief is critical to shaping the bespoke vision of each coastal development project as this will form the basis of future design decisions. When defining the requirements, it is important to build a detailed understanding of the project's purpose, benefits, budget, finances and risks. While designing resilient coastal infrastructure, the impact of all design decisions should aim to align with the project vision, and any deviations to the vision should be identified, communicated and managed.

Site analysis and identifying climate vulnerabilities

Detailed site analysis is required to understand the specific characteristics of the local environment. Climate change is a global phenomenon, but the impacts and vulnerabilities caused by climate change may vary due to local site characteristics and regional weather patterns. The most notable climate-related impact to coastal developments located along the Gulf of Mexico or the Indian Ocean pertains to the risk of intense tropical cyclones, whereas small island nations in the Pacific Ocean may be particularly vulnerable to tidal inundation due to low-lying topography and limited land area.

One of the most challenging aspects of developing an understanding of the local environment is being able to make reasonable predictions to determine design conditions. Physical surveys such as wind anemometers, water level monitoring and wave buoys all can give valuable information on the present-day site conditions. However, the challenge comes in making accurate predictions for the magnitude of future water levels and extreme weather events. Typically, extreme value analysis (EVA) has been used to assess the probability of events that are more extreme than those previously observed. However, as the climate changes, so does the frequency and intensity of extreme weather events. For example, the formation of tropical cyclones is linked to sea surface temperature; and with rising global temperatures, it is unknown to what extent the frequency and intensity of cyclones may be affected. This has created a dilemma in determining the magnitude of extreme events that we can design against to provide an appropriate level of resilience. To overcome this, probability distributions can instead be modified to reflect the trends indicated by climate scientists and climate research. For example, the tail of a wind speed distribution can be modified to account for changes in the frequency and intensity of extreme events.

In order to achieve effective sustainable coastal development, a key output of the site analysis should focus on identifying and understanding both the climate vulnerabilities and any opportunities to enhance the environment. This will enable the formation of bespoke strategies that align with the site conditions.

Develop and refine strategies for adaptation and resilience

When assessing the various strategy options for managing coastal regions, following the site analysis, a decision should be made as to whether protective measures should be developed or not. In some locations in which there may be a significant ecological and financial cost to providing coastal protection with limited benefits, the most sustainable solution could be a "do nothing" approach. If this approach is determined to be the best solution, future development in vulnerable locations will need to be restricted at a legislative level.

Coastal engineers often focus primarily on providing resilience to ensure future storm events do not cause significant damage. However, to achieve sustainable development, it is important to explore how adaptation and resilience can work together in a complementary manner. In providing resilient solutions, it is important to not only look at the capacity of coastal regions to respond to climatic events but also a region's capacity for adaptive measures over the longer term. For example, ensuring suitable provisions to enable future retrofitting of existing coastal infrastructure and developing early warning systems will enable future adaptation to a changing environment.

Monitor and evaluate performance

Monitoring and evaluating the performance of coastal development strategies is key to guiding adaptive management and incorporating lessons learned in future decision-making. This is needed to improve coastal management over time. Data acquired by monitoring coastal systems can be used to identify any emerging risks. The use of surveying and remote sensing techniques coupled with geographic information systems (GIS) can detect shoreline change. This can involve both land-based techniques, such as topographic surveys, and airborne methods, such as satellite imagery, LiDAR (Light Detection and Ranging) and drone photography. Assessing changes in remote sensing datasets over a period of time is referred to as multi-temporal analysis. Multi-temporal analysis can be used to assess and understand changes or trends in coastlines.

Trigger thresholds can be established in the planning stages to ensure action is taken before these emerging risks become critical. Trigger thresholds are pre-defined criteria that can be established to determine when action is required in response to the emerging risks. Trigger thresholds may include limits to shoreline retreat, rates of sediment transport or water levels.

Remote sensing techniques can identify when trigger thresholds are met or exceeded. Incremental adaptive measures such as retrofitting works or increasing cope levels may be undertaken reactively in response to trigger thresholds being exceeded.

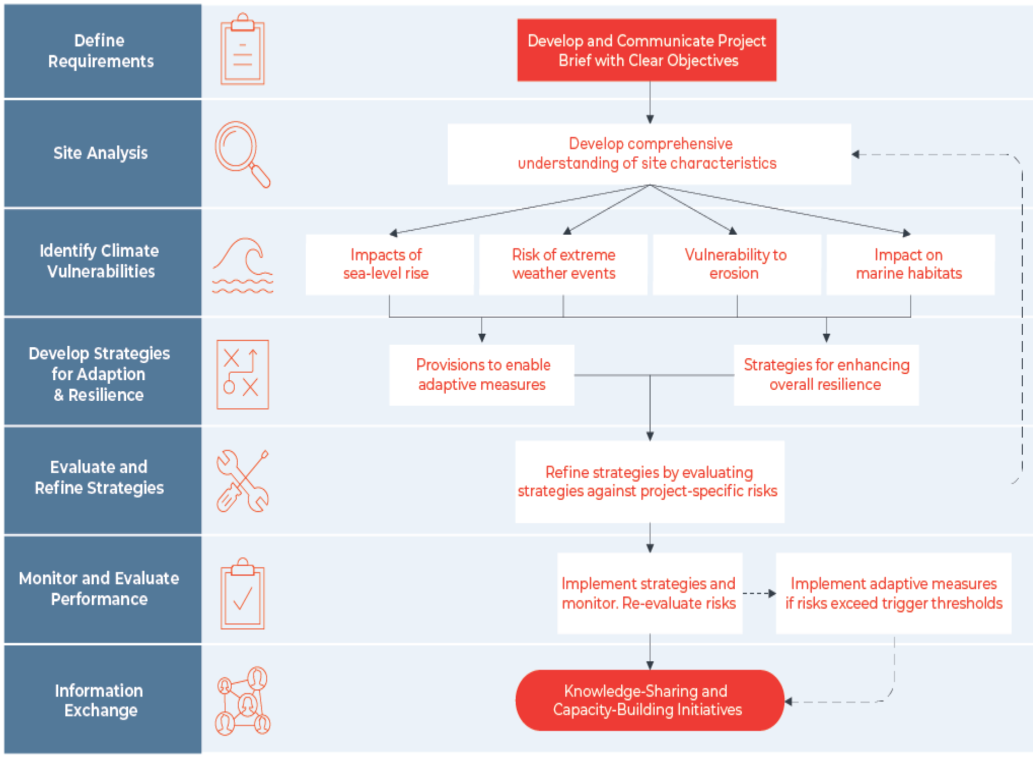

Figure 1 - A systems-based approach to integrated adaptive design in coastal development—a flowchart summarizing the key processes to guide sustainable coastal development, from defining requirements to information exchange.

Information exchange

The monitoring and evaluation of coastal developments can also be used to guide learning and capacity building. In particular, the lessons learned from the implementation of planning and design strategies aimed at building resilience can greatly enhance future decision-making.

Many decision-makers are often reluctant to introduce innovative strategies due to a perceived lack of examples and proof of effectiveness. To overcome this obstacle, it is essential to establish knowledge-sharing systems that foster collaboration with various stakeholders and coastal communities, and to make information on examples of success more widely available. Capacity-building initiatives can be used to promote the development of adaptive policy frameworks in order to respond to changing climates and evolving societal needs.

Adaptive measures

Nature-based solutions

Nature-based solutions seek to harness natural resources and natural processes to protect and manage ecosystems while providing benefits to biodiversity and human wellbeing. In the coastal environment, nature-based solutions are an effective alternative to traditional hard-engineered measures such as seawalls.

Hard-engineered measures, in many cases, are responsible for “coastal squeeze,“ in which coastal regions become narrower with the removal or reduction of natural coastal buffer zones. This can lead to the deterioration of natural habitats that would otherwise be able to progress landwards.

Nature-based solutions aim to address the challenges of coastal flood and erosion risk—while not only reducing the impact on the environment but also enhancing or restoring coastal ecosystems. Examples of nature-based solutions in coastal regions include the restoration or creation of beaches, sand dunes, coastal wetlands and mangrove forests.

While protecting coastal infrastructure, these solutions can help to enhance fisheries, create recreational opportunities and enable carbon sequestration. The commercial benefits of such schemes can contribute to offsetting the capital costs of the nature-based solutions. The creation of aquaculture sites, recreational and tourism potential, and new waterfront developments can generate revenue, leading to an increase in the economic and social value of coastal regions.

Floating structures

Floating structures are highly adaptable alternatives to engineered structures that would otherwise be fixed in water, suspended above water or built on land. Floating structures of different types have been developed in recent years, including:

- *Floating road & pedestrian bridges* – When bridges are required to be constructed in deep waters that prohibit the use of traditional fixed piers, anchored floating pontoon bridges such as Seattle’s SR 520 bridge can considered. Additionally, structures such as the Floating Bridge in Dubai can create a moveable bridge as an alternative to a traditional bascule or swing bridge in which the partition is moved into an open position to allow boats to pass.
- *Floating buildings* – The use of floating buildings is an innovative solution for waterfront development in which the footings of the building are usually cast-in to the floating dock. Typical construction methods can be used on top of the floating platform. The Floating Office Rotterdam is an ultra sustainable office building that stands on a floating body of 15 concrete pontoons.
- *Floating aquaculture farms* – The farming of fish and shellfish can be undertaken using floating structures comprising floating cages and nets suspended in the water column where the species can be cultivated in controlled conditions. This can be a sustainable practice as it reduces pressures on wild fish stocks.
- *Floating breakwaters* – in some cases wave attenuation can be efficiently provided by deploying floating structures such as a series of wide concrete pontoons. Floating breakwaters are most effective at attenuating short-period wind waves rather than long-period swells—and therefore are most suitable in lakes or semi-enclosed bays with limited fetch lengths.

There are many reasons why floating structures can be more sustainable than traditional designs. Undoubtedly, floating structures will adapt to varying and unpredictable variations in water levels due to their buoyancy.

Floating structures are also extremely adaptable because they can be relocated with relative ease. Furthermore, as many floating structures are modular and flexible, they can be expanded and easily modified over time by adding/removing modules. This can allow for floating structures to serve multiple uses.

Managed retreat and managed realignment

In some cases, providing robust protection against coastal erosion is not the best option. Alternatively, managed retreat and managed coastal realignment is an adaptive strategy that involves allowing the coastline to naturally evolve, but in a controlled manner. This is often a preferred solution at locations where the increased pressures of rising sea levels mean that providing enhanced protection against erosion may no longer be economically viable or sustainable.

Managed retreat typically involves the removal or re-positioning of coastal defences, allowing specific areas of the land behind to be flooded, which realigns the shoreline. Therefore, this measure is most appropriate at locations that are both low-lying and of relatively low economic value. The cost of protecting low-lying land is typically more expensive than protecting land of higher elevations, and if the land is of low economic value, then the benefits of providing protection will be limited.

In areas designated for managed retreat or managed realignment, authorities may place restrictions to prevent new developments in the most vulnerable locations.

There can be notable ecological benefits to managed retreat and managed realignment. Allowing low-lying land to flood can lead to the creation of additional inter-tidal habitats such as salt marshes or mudflats. Therefore, managed retreat and managed realignment can also be considered as types of nature-based solutions. By restoring natural coastal processes and allowing the natural creation of new habitats, managed realignment contributes to ecosystem resilience and adaptation to climate change.

Conclusion

Coastal regions, many of which have significant social, economic and ecological value, face increasing vulnerability due to the impacts of climate change. Considering the dynamic nature of coastal cells, integrated adaptive planning and design is crucial to achieve the best outcomes. Site-specific tailored strategies—such as nature-based solutions, managed realignment and floating structures—offer sustainable alternatives to traditional coastal infrastructure. The continuous active monitoring of coastlines enables informed strategic decision-making and effective risk management. Prioritizing resilient and adaptive measures will help to mitigate the risks to coastal regions while protecting and in some cases enhancing the value of coastal zones.

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