Application of Climate Change Adaptation, Resilience, and Beach Management Strategies on Coral Islands

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Abstract
Small Island Developing States (SIDS) are particularly vulnerable to climate change, climate variability and sea level rise. For many island nations, the very existence of some low-lying islands and their associated communities are threatened. International aid funds are now being applied to the development of climate change adaptation and resilience measures on coral islands world-wide. In many areas, identification of vulnerable sites and planning has been completed and climate change adaptation and resilience measures are being implemented. These measures are often directed at 'buying time' to develop long-term relocation strategies. However, the coastal processes on coral sand beaches and coasts are significantly different to temperate coasts. There is comparatively little information available that considers the design and application of coastal structures and the associated components of coastal climate change adaptation and resilience measures for coral beaches. Additional challenges include isolation and the lack of suitable equipment and materials with which to implement climate change resilience and adaptation strategies. This paper presents the investigations, detailed designs and implementation of climate change adaptation and resilience measures in Tonga, the Marshall Islands and Mauritius, as well as the development and application of beach management strategies in other parts of the Pacific Islands. There is a common theme between the development of climate change adaptation and resilience measures and beach management strategies for these coral sand beaches with respect to coastal processes and the physical and biological components that produce and transport sand in these systems. Coupling of physical/biological and social/terrestrial/coastal factors is an important consideration for the successful application of coastal strategies on coral sand beaches. The measures that are being applied to the different sites, in order to work with their site specific variables, are detailed.

Keywords: climate change adaptation and resilience, beach management, coral islands and beaches, coastal processes, coastal structures.

1. Introduction

Small Island Developing States (SIDS), a group of 52 separate nations, are mostly low-lying coastal countries with small but growing populations. SIDS are generally remote, have fragile environments and limited resources, making them particularly vulnerable to natural disasters as well as to sea level rise and other effects related to climate change. The climate change issues experienced by SIDS however, are primarily caused by the rest of the developed world, as their combined annual carbon dioxide output accounts for less than 1% of total global emissions. As a result, billions of dollars of international aid funding is being directed towards developing resilience and strategies to address climate change related problems in SIDS.

The wide range of issues and effects related to climate change affecting SIDS requires a broad range of solutions; for example, prolonged drought requires the development of water security measures. However, here we consider the issues of inundation and erosion on low-lying coastal areas.

Often overlooked in the application of coastal protection and management options in tropical islands are the differences in mechanics and processes operating on coral sand beaches versus temperate beaches. In terms of wave energy, temperate beaches are directly connected to incident waves through to the beach and seabed gradient from the dunes to the beach face, out to the depth of closure. In contrast, waves in tropical lagoons are regulated by the fringing reef and the depth of water above it [8].

While temperate beaches mostly rely on sediment input from terrestrial sources such as rivers and, eroding cliffs, coral sand beaches rely on biogenic systems such as coral senescence, coral grazing and excretion for sand production. For these systems to function optimally, and produce a steady supply of sand, requires a healthy reef and lagoon ecosystems.

As a result, the application of engineering solutions designed for temperate beaches on coral coasts has often resulted in unforeseen coastal responses, most often with negative impacts on beach amenity [9]. While there is a significant body of work on beach processes and sediment transport on coral beaches and atoll islands [7, 10], there has been little application of this knowledge to coastal engineering. Quantitative understanding of coastal response to obstacles/structures is still largely unknown and this is compounded by an almost universal lack of long-term beach monitoring data for SIDS.

The following sections provide case studies of recent and current climate change resilience and beach management strategies for SIDS. Each of these projects includes aspects of research, monitoring and adaptive management whereby strategies are continually modified as a greater understanding of each site is developed through comprehensive monitoring.

2. Northeastern Tongatapu

The Secretariat of the Pacific Community (SPC), specifically the Global Climate Change Alliance: Pacific Small Island States (GCCA:PSIS) project in the Strategic Engagement Policy and Planning Facility, recently funded a climate change resilience demonstration project in north-eastern Tongatapu, Tonga. The project followed on from previous investigations of the site [4]. Five villages fringe the low-lying coast (Figure 1), and 10-30 m of beach and foreshore has eroded over the past 40 years, resulting in 3-4 major over-topping and inundation events each year.

Fundamentally, the 'erosion problems' and 'vulnerability' of the villages in the study area are due to both the road and the villages being built too close to the coast on low-lying land. This in turn is compounded by human activities such as sand-mining, mangrove removal and reclamation, over-fishing and pig-foraging [12]. The wave exposure of the study site decreases from the eastern villages exposed to short period waves from the east, to the western villages which border the lagoon entrance.

Figure 1 The study site (denoted by the red line), includes 5 coastal villages. Wave exposure decreases from east to west.

The aim of the GCCA:PSIS projects is to develop climate change resilience strategies that can be applied by the local population utilising local materials, and potentially be replicated where similar physical conditions exist. Unlike many previous projects on SIDS, comprehensive monitoring is being funded as a part of the project in order to determine the project's success and apply an adaptive management approach.

In order to provide climate change resilience, and 'buy time' over the next 30-35 years while longer-term strategies such as village relocation are developed, more robust erosion control was required. Since the coast has eroded to the edge of the road in many places, managed advance was required to develop a wider and healthier beach system and provide a larger buffer between properties and the sea.

Initially, the brief was to provide one hard and one soft engineering pilot studies at each of two demonstration sites within the area of interest (Figure 1); funding was not available to address the entire 8 km of coast. However, robust solutions are typically not developed with a single engineering approach, and hybrid solutions combining hard structures, renourishment and planting of coastal species were applied at both of the pilot study sites. The only part of the study site that had not eroded and had actually accreted since the 1960's was the NW facing point between the northern and western coasts of the study site (Figure 1). This is due to the convergence of western wave-driven sediment transport along the northern coast, and northerly tide and wind-generated currents along the western coast. It was therefore a good location for the borrow site for renourishment material.

While the projects have comprehensive funding for monitoring and adaptive management, funds were not available to undertake comprehensive field data collection, and so reviews of existing relevant reports and basic numerical modelling were undertaken (along with site visits) to develop an understanding of coastal processes. Consideration of how the beach responded to existing coastal features was also a useful factor for the development of designs.

2.1 Manuka Village

The first pilot site is on the eastern end of the area of interest, at Manuka Village. This is the most wave-exposed of the sites. Given the short-period wave climate, detached breakwaters were considered as a viable option to reduce the loss of sand and provide a wider buffer zone to reduce/prevent erosion and over-topping. Remnants of a failed seawall at the site indicated that detached structures could indeed capture sand behind them, and coastal plant species had also established in these protected areas (Figure 2).

A series of 9 detached breakwaters were designed for the Manuka east site, with renourishment and planting of coastal species. The aim was to form tombolos (i.e. create a beach response where the beach welds onto the shoreward side of the breakwater), since there is little to no down-coast beach in this location, just seawall, and so further negative impacts were not an issue. On temperate coasts, tombolo formation occurs when the ratio of the length of the breakwater (B) to the distance of the breakwater off of the existing coast (S) is >0.67 [6] through to when the B/S ratio >1 [15].

Figure 2 A tombolo formed in the lee of a failed seawall at eastern Manuka.

In order to provide some new understanding of how the beach responds to detached breakwaters on coral sand coasts, a variety of lengths and spaces were applied to the design. All breakwaters were placed 20 m (S) offshore, with crest lengths of 15, 20 and 25 m to result in B/S ratios of 0.75, 1 and 1.25, respectively. In addition, the spacing between breakwaters was varied between 20 and 25 m.

2.2 Makaunga and Talafo'ou Villages

At Makaunga and Talafo'ou villages (the northernmost two villages on the western coast of the study site), a combination of 15 sedi-tunnel groynes, renourishment and plantings was applied. Along this coast, tidal currents, winds and very small wind-generated waves transport sand mostly northwards. In locations where obstacles had been placed across the narrow remaining beach, significant volumes of sand was observed to have built up for considerable distances (mostly to the south).

The sedi-tunnel units are already being built in Tonga, and so new construction procedures did not have to be developed. They square concrete tunnels, 1 m cubed, which are stacked end to end to provide stable underground routes for cables and pipes. One of the concerns with the application of groynes is causing down-coast problems due to blocking alongshore sediment transport. To address this effect permeable groynes have been successful in other parts of the world [5]. The sedi-tunnel permeable groyne is a novel methodology, that when set on a concrete base allows for modification to the structures permeability following construction (Figure 3). The 1 m square unit sizes also allows for easy lengthening of groynes.

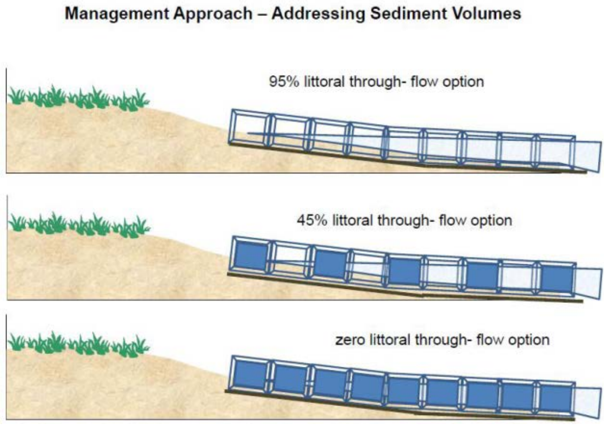

Figure 3 Schematic drawings of 1 m^3 sedi-tunnel groynes, where the units can be rotated to provide differing levels of permeability. [4].

Similar to the various lengths and spacing between the detached breakwaters at Manuka east, a range of spacing between the 10 m long groynes and permeability were developed to provide some new understanding of the effects of groyne spacing and permeability on sheltered coral sand beaches.

On temperate coasts, groynes are normally 0.33-0.5 times the length of the spacing between them [1], which would be 20-30 m in this case. However, observations indicated that along this stretch of the study area, small protrusions from the beach result in an obvious fillet of sand of greater length than 3x the obstruction. Therefore the groynes have been separated by distances of 30, 60 and 120 m in repeating sets of 3 groynes down the ~1 km length of the beach, each set with a different permeability configuration.

Construction of the two pilot studies has recently been completed, and a comprehensive monitoring strategy (based on the BACI, before/after control/impact, system) is now underway.

In addition to the structures renourishment and plantings undertaken on the northeastern Tongatapu sites, consultation, education and on-going involvement of the community is critical for the long-term success of the project. Prohibiting use of beach sand for construction, the establishment of marine protected areas (MPAs) to help recover the sand generating capacity of the area, involvement with monitoring and keeping pigs off the beach are some of the areas which the local villagers are involved with.

3. Woja Island, Ailinglaplap Atoll, Republic of the Marshall Islands

A second GCCA:PSIS funded climate change resilience demonstration project is also underway on Woja Islands, Ailinglaplap Atoll in the Marshall Islands (Figure 4). The Marshall Islands is one of the most vulnerable SIDS in the world, with many of the narrow atoll islands being no more than 2 m above current high tide levels. Similar to the Tongan projects, the aim is to develop solutions that can be applied to similar locations with similar issues – in this case designing and constructing causeways that be built with local materials and plant. Many of the narrow atoll islands are being divided into smaller islands where narrow and low-lying parts are being eroded through. As a result, some inhabitants are literally stranded without access to medical facilities, airfields, unable to transport copra or get to local supply depots during mid-high tide and storm events.

As is the case with many problem locations, construction of causeways is a measure that can be applied to 'buy time' while long-term adaptation strategies are developed. In situations such as the Marshall Islands, where much of the available land areas are already vulnerable, this presents very difficult decision-making.

Figure 4 Location of the project site and potential construction material area. (Source: Google Earth).

Woja Island is very remote, accesiible only through the once weekly flight or a ~36 hours boat journey from the main island of Majuro. Therefore, materials and methods for construction had to be conducive to what was available on site. Small diggers and trucks can be barged to site, however, fill material and structural units had to be sourced at the island.

A site visit was conducted from 4-6 November 2013. The field investigations had two main priorities: 1) to determine existing ground and foreshore elevations, and 2) the identification of suitable fill and armour material [13]. Accurate topographic information is critical for undertaking coastal hazard assessment and determining the volume of material and size of structural units required to construct a causeway able to withstand extreme events over the next 35-50 years, Investigations included visual and topographic surveys of the study area and inspections along both coasts of southern Woja Island. A survey of the north-western coast of the island revealed an abundance of accessible large armour rock (Figure 5), as well as shingle suitable for use in construction as core and fill material. Ecological surveys (both marine and terrestrial) were conducted at the project site as well as at source sites for construction material.

Figure 5 A large supply of rock is available on the north-western coast of Woja Atoll. The rock in the foreground is approximately 1.1 m diameter).

The reason that this part of Woja Island was experiencing accelerated erosion was found to be mostly due to a combination of the relatively low elevation of the area and the predominance of beachrock (friable sand conglomerate). Numerical modelling (open ocean on the western coast and wind-generated waves on the eastern lagoon side) was applied to develop design wave heights for rock-sizing, wind/wave set-up and wave run-up. It was found that a 1:100 year storm event with 50 years of sea level rise would cause water levels at the proposed causeway of up to 3.7 m above mean sea level (MSL). However, since the highest point on Woja Island is ~3.0 m, a causeway level of 3.0 m was selected.

Together with the realignment of the existing road 20 m to the west and planting of sand-binding species (a large fraction of sand is moved by the NE tradewind at the site), a 120 m long causeway is currently under construction at Woja Island. Similar to the Tongan projects described above, comprehensive monitoring is being undertaken to determine the success of the project. Due to the similarity of the situation to many of the other atoll islands in the Marshall Islands, with an open sea reef and lagoon/reef flat on one side and a fetch-limited lagoon on the other (Ailinglaplap has the largest fetch than any other atoll lagoon at ~46 km), this causeway design (elevation, rock-sizes, etc.) can be applied to many other sites in the Marshall Islands without the requirement for detailed investigations.

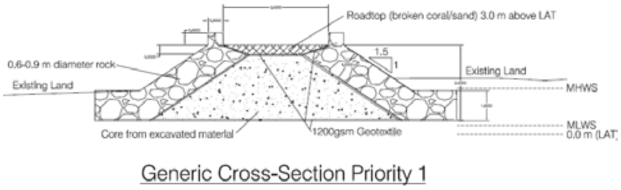

Figure 6 Generic cross-section for the Woja Island causeway.

4. Mon Choisy Beach, Mauritius

The Government of Mauritius secured a grant from the Adaptation Fund (administered by the UNDP) for the implementation of the project "Climate Change Adaptation Program in the Coastal Zone of Mauritius". The overall goal of the program is to assist developing countries that are party to the Kyoto Protocol that are particularly vulnerable to the adverse effects of climate change in meeting the costs of adaptation projects and programs in order to implement climate resilient measures. Two demonstration sites are included in the project; here we consider one of them, Mon Choisy Beach in north-western Mauritius (Figure 7).

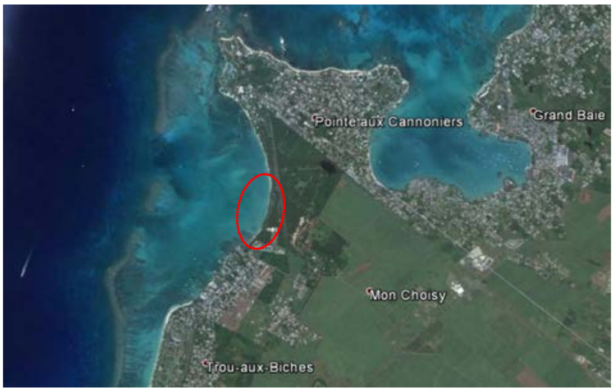

Figure 7 Location map of the project site at Mon Choisy Beach, Mauritius.

A comprehensive field programme was initiated in September 2014, which included months-long instrument deployments (wave/current/water level meters), bathymetry survey, beach profiling and ecological mapping [2] These data were utilised along with historical aerial photograph analysis, review and collation of existing data and reports and numerical modelling to develop calibrated numerical models to help determine the existing physical processes of the site and develop options for climate change adaptation.

Some 600 m of the southern end of Mon Choisey Beach has eroded up to 20 m over the past 40 years. Mon Choisy is an important public asset, as many beaches are private in this area of Mauritius.

The technical assessment concluded that the erosion at Mon Choisy is mostly due to anthropogenic influences and that the underlying root causes of the erosion at Mon Choisy are the result of large-scale systemic problems that cannot be simply 'fixed' and may take decades to fully address. These problems are:

1. The health of the reef, the 'sand-engine', has been reduced by over-fishing and degradation of water quality. This means there is less sand available in the system.
2. Multiple structures south of Mon Choisy block sand transport and further reduce the supply to the beach, leading to to erosion.
3. The natural dune system has been flattened and planted in trees and therefore cannot respond to cyclonic events or chronic erosion due to the deficit of sand.
4. Due to the reduced sediment supply, the beach will continue to erode, although some factors such as nearshore beach rock and basalt boulders may act to reduce erosion rates.
5. Anecdotal accounts suggest that reef passes have been deepened, thereby increasing the offshore sediment gradient and loss of sand from an already starved system;
6. Due to the reduced natural capacity of the beach, it cannot recover as quickly from extreme events.
7. As sea level rises due to climate change, there is the potential for enhanced erosion of Mon Choisy beach due to increased wave penetration.
8. There are a range of factors contributing to the continued erosion of Mon Choisy requiring a range of measures to address them. This includes both physical and biological approaches and continued management.

An options assessment was undertaken to identify a range measures to address the immediate erosion issue and the long-term problems at the site [3]. These included beach nourishment, beach realignment through the removal of *casuarina* trees and the re-establishment of a dune system planted with native sand-binding species. Offshore structures, such as submerged rubble mounds or arrays of pre-cast units (i.e. ReefBalls or WADs) were also considered as a means to reduce incident wave energy and help retain the renourishment. The small tide range and evidence of beach stability in the lee of natural structures suggests that submerged offshore structures will likely be functional at this site [3].

Longer term measures include the establishment of marine protected areas (MPAs), seagrass and coral restoration initiatives, the installation of fixed moorings to reduce reef damage caused by the anchoring of tourist dive boats and the development a beach management strategy focused on sand redistribution and introduction of appropriate coastal plant species.

Of the options above, beach renourishment proved to be particularly problematic. For one, Mauritius, like many other SIDS, lacks access to the specialised and expensive equipment necessary to access offshore sand sources in deep (12-15 m) water. A land-based sand source was considered, however, the high cost and transport issues notwithstanding, the available supply and production rates did not meet the project demand. Furthermore, the material contained a large fraction of fines which would increase turbidity and affect the local ecology. Similarly, lagoon based sand dredging for fill material was also rejected due to potential ecological effects.

As a result, the final project design which is still under development, may feature, the application of a more aggressive beach realignment (i.e. a large set-back and removal of casurina trees) in conjunction with some form of submerged offshore structures to attenuate wave energy and reduce future erosion rates.

As with the other sites, a monitoring programme has been designed, which will provide valuable information on beach processes and how this site responds to extreme events, as well as help to guide and adapt the beach management strategy.

5. Summary and Conclusions

SIDS are particularly vulnerable to climate change, climate variability and sea level rise. This has been recognised by international aid efforts geared towards the development of climate change adaptation and resilience measures. In many situations these measures are directed at ‘buying time’ in low-lying coastal areas to develop long-term relocation strategies.

The case studies presented here demonstrate issues associated with the remoteness and limited resources available to develop climate change adaptation responses. In addition, they all include collecting data to help better understand and quantify the shoreline responses to structures and other interventions on coral sand beaches, which can be markedly different from those that occur on temperate beaches. In coral coast situations, it is important to couple the physical/biological factors of the coral reef environment, as well as the social/terrestrial/ coastal factors to successfully apply coastal adaptation strategies.

In many cases, human activities have caused or contributed to increased coastal erosion and reduction in coastal resilience. This necessitates on-going management, in a manner similar to the way beaches created for hotels or resorts need to be continually managed [11, 14]. The projects presented here and many others SIDS focus on the development of sustainable beach management strategies and learning more about beach responses to intervention on coral coasts in order to increase the capacity for climate change adaptation and resilience.

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