Coastal Engineering Solutions for Remote Pacific Island Communities

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ABOUT THE FEATURED ARTICLE

This paper explores innovative and affordable coastal protection strategies tailored for remote Pacific atolls, particularly in Tuvalu, which face increasing threats from sea-level rise and extreme weather events. Authored by Stuart H. Bettington (AECOM Australia), William Blank (Hall Pacific), and Robyn C. Bussey (AECOM New Zealand), it focuses on the use of large sand-filled geobags as a practical alternative to conventional coastal defence structures like rubble or concrete seawalls. The authors draw from firsthand project experience in Tuvalu following Tropical Cyclone Pam in 2015, which caused widespread erosion and flooding. Two major interventions are highlighted:

- Funafuti Recreation Area Project: Involving beach nourishment and construction of groynes using over 600 geobags.

- Nukufetau Coastal Works: Replacing failed seawalls and groynes with over 2,000 geobags and nourished beaches, despite the island's extreme remoteness.

The paper provides technical insight into the design and performance of these interventions, emphasizing the importance of sustainable materials (like locally dredged sand), community participation, and cost-effective execution. The study concludes that while geobags are not permanent, they offer a robust and scalable solution that buys time for longer-term adaptation strategies.

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Tuvalu's islands are highly vulnerable to inundation and coastal erosion; issues that are worsening with climate change. These threats were highlighted when large swells associated with Tropical Cyclone Pam in March 2015 pushed high water and waves over the reefs and islands, leading to extensive damage, coastal erosion, and destruction of crops.

The Government of Tuvalu (GoT), recently undertook coastal works on two islands to improve resilience to climate change induced erosion and flooding. GoT engaged Hall Pacific, a dredging and civil contractor, supported by AECOM, to develop affordable solutions that included seawalls and beach nourishment with groynes on Funafuti and Nukufetau.

Being coral atolls, the islands lack rock or other construction materials commonly used for coastal armouring. As a result armour has historically been imported or won by mining the reef to obtain coral boulders. The only environmentally sustainable construction material that can be exploited on these islands is sand won from deeper waters. Recognising the impact of climate change and budget limitations, large geobags were identified as a suitable qasi-permanent solution. These can provide protection while longer term climate change adaptation strategies are developed and implemented. The use of this method allowed works to be planned and completed within six months. This approach has the potential to deliver affordably resilient and attractive protection in areas lacking the resources for more conventional coastal engineering solutions. This paper compares cost, and performance of these recent examples with more conventional armour solutions and discusses the application of these technologies on threatened remote islands.

1. INTRODUCTION

Remote tropical islands located on living coral reef platforms, such as coral cays or atolls, are under threat from the combined impacts of coastal erosion and marine flooding. As sea levels rise the future of the communities on these islands is threatened. This paper draws on recent experience with coastal defence projects on remote islands to examine possible solutions that utilise the available resource, namely sand.

Particular reference is made in this paper to the recent work undertaken on islands in the central Pacific nation of Tuvalu (see Figure 1). Tuvalu is made up of a series of low lying inhabited islands, which are highly vulnerable to inundation and coastal erosion. The large swells caused by TC Pam in March 2015 resulted in high water and waves over the reefs and islands, which led to extensive damage to infrastructure, coastal erosion, destruction of crops, and loss of amenity. Following this event the Government of Tuvalu (GoT), supported by the World Bank (ref AECOM 2015) and UNDP undertook works to benefit communities, starting with projects on Funafuti and Nukufetau. The works; designed by AECOM and built by Hall Pacific, included construction of seawalls and groynes using large geobag containers, and beach nourishment utilising local dredged sand.

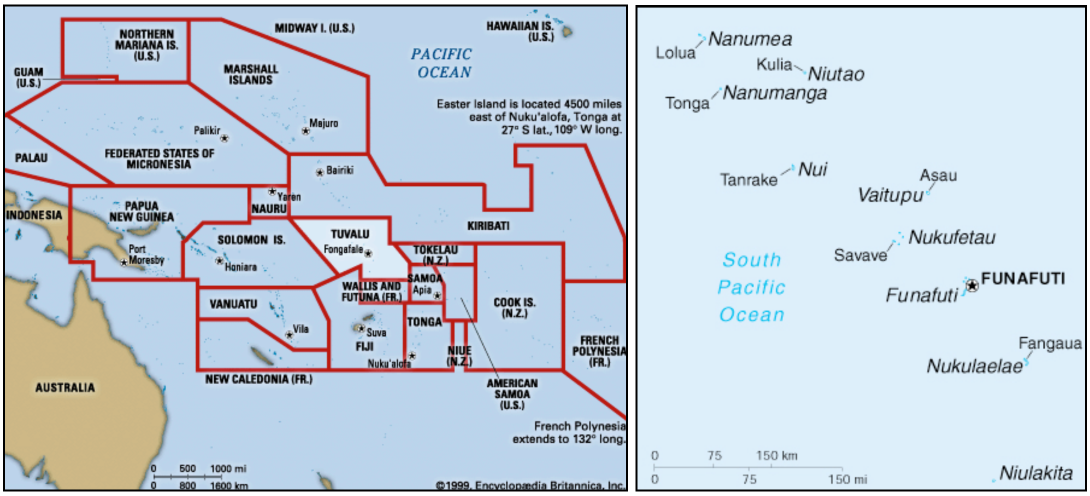

Figure 1 Location of Tuvalu in the Pacific and its islands (source Encyclopaedia Britannica 2017

2. THREATS

The islands formed on coral reefs by marine forces have always been threatened by cyclonic events that cause erosion and inundate the islands. Rising sea levels and the impact of climate change and growing populations on reef health are now threating their amenity and future existence. Because they are built up by marine forces these coral islands are low, slightly above normal tidal ranges. The shape, size and location of these islands reflect a dynamic stability between the various met-ocean forces driving sediment transport.

2.1. Inundation (Marine Flooding)

During extreme cyclonic events low lying coral islands do experience marine flooding. This flooding is caused by a combination of storm surge and wave setup on the reef top.

In March 2015 Tropical Cyclone Pam, a large Category 5 system, passed through the western edge of the South Pacific sending large swell across the region and causing extensive damage. TC Pam did not impact Tuvalu directly; rather large waves from the cyclone travelled thousand kilometres to impact the west facing reefs of Tuvalu. Wave setup on the reef flooded islands and allowed large waves to reach the shore. As seen in Figure 2 this resulted flooding and structural damage was wide spread. Longer term contamination of the water table is a greater threat. Sea level rise is increasing the penetration of seawater into the island water tables. The impact of saline ground water on gardens is presented in Figure 2 where gardens have died after TC Pam flooding. If saline water impacts gardens regularly the future of the island communities is questionable. The relationship between ground levels and tide levels on the main island of Funafuti is seen in Figure 3, revealing the vulnerability.


Figure 2 Marine flooding, caused by TC Pam on Nanumea, Tuvalu, and Gardens destroyed by

contaminated ground water on Nukulealea, Tuvalu (Source Public Works Department GoT).

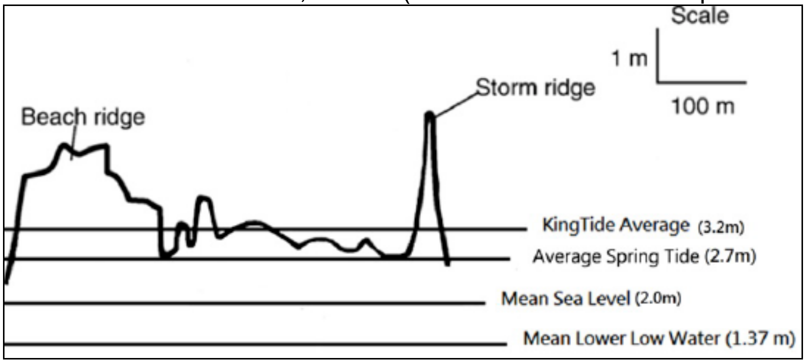

Figure 3 Section through Fongafale, Tuvalu, showing tidal planes and levels. (source Lin 2014).

2.2. Coastal Erosion

The location and shape of coral islands represents a long term balance between sand supply from the reef and the loss of sand off the reef platform. Changes in this balance are now causing serious erosion issues for the island communities.

2.2.1. Sand Supply Deficit

Living coral reef generates approximately 5 kg to 20 kg of sand per square meter annually (refer Dudley 2003). On the coral cays this carbonate based sand accumulates on the reef platform and forms an island. The supply of sand is dependent on a healthy reef biota. Reductions in reef vigour will reduce the supply of sand. Reasons for loss of reef vigour include:

- Raised nutrient levels – is an issue for islands with large populations where effluent discharges into surface waters.
- Coral bleaching caused by high water temperatures and is becoming an issue in recent times.
- Ocean acidification is forecast to cause issues into the future.

The capital of Tuvalu is located on an atoll known as Funafuti and has a population of 6,000 people. Sewage from this densely populated community discharges via septic tanks into the islands groundwater and then makes its way into the lagoon. This nutrient rich water feeds macro algae and has killed or diminished the reef along the lagoon foreshore of the island. This loss of reef vigour has resulted in a loss of sand supply leading to erosion.

2.2.2. Changes in Sand Distribution

The distribution of sand on the reef top represents a balance of the forces, mostly currents and waves. With changes in forcing caused by sea level rise, changes in intensity and frequency of cyclones or the impact of works such as dredged channels the distribution of sand is altered. The dramatic erosion seen on many islands of Tuvalu after TC Pam is evidence of this Figure 4.

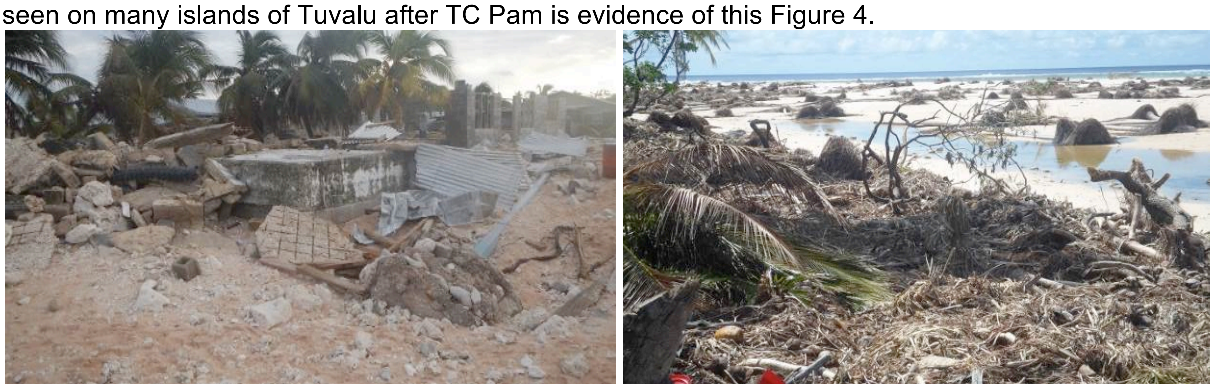

Figure 4 Erosion and damage caused by waves from TC Pam on Nui; and Sand and palm trees scattered across reef to edge following TC Pam on Nanumanga Tuvalu (Source PWD GoT).

Sand that is washed off the reef platform is lost to the system, and requires healthy coral and lengthy periods of mild conditions to be replaced. Further each time a major cyclonic system washes over the islands sand is lost to coastal processes as it is deposited on the island, raising it slightly, as demonstrated with the deposits. Coastal erosion has the dual impacts of reducing the land available on these small islands, and reducing the amenity of the islands, with the loss of sandy beaches as seen in Figure 5.

Figure 5 Sand and modified cube armour blocks deposited through community of Nukulaelae after TC Pam, Tuvalu (Source PWD GoT); failed seawall on a sand starved beach on Iama, Torres Strait.

3. RESPONSES

When considering an appropriate response the circumstance of each community needs to be considered and there is not a one size fits all approach. Typically budget constraints are very significant along with the realities of the conditions on the ground and community expectations. Another critical consideration is the life expectancy of the works, and the degree of maintenance required. For remote islands in poor nations this is particularly relevant as it is typically easier to obtain funding for capital works than ongoing maintenance.

3.1. Approaches to the Problems

Broadly the options available to the planners and governments to the issues described can be broadly split into the categories of:

- Policy response – accepting the natural forces and adapting to the changed conditions with planned retreat, and more resilient communities through betting building design and planning.
- Soft Engineering (maintenance) – refers to activities such as beach nourishment, sand bypassing and vegetation programs to combat erosion.
- Defend with hard structures – seawalls and barriers to resists the oceanic forces, commonly reserved for more serious circumstances because of the significant financial contribution required.

In this paper it is assumed that the decision has been made to invest in an engineered solution and that planning and adaptation responses have already been discounted. Further it is assumed that relying on soft engineering solutions such as sand management has been discounted as a standalone option in recognition of the difficulty in undertaking regular nourishment campaigns.

3.2. Seawall Options

The decision to build a seawall to defend the coast is usually taken when the existing assets are considered sufficiently valuable to protected from recession and erosion. An advantage of engineered (hard- permanent or quasi-permanent) structures is that the community has a sense of security behind the seawall. Given the very high cost of permanent seawalls and possible detrimental impacts they can have on coastal processes, they should only be adopted where the need is high.

There are a few basic coastal defence structures that have been considered in this paper:

- Conventional hard engineered structures, including rubble seawalls (coral blocks, rock or concrete armour) and rigid seawalls (pattern placed concrete armour such as sea bees or stone pitching), as seen in Figure 6.
- Geo-bags – very large, robust sand bags (Figure 7).

The use of hard engineering structures should not be seen as inconsistent with the use of softer solutions such as vegetation management or beach nourishment, rather it is the last line of defence.

3.2.1. Conventional Hard Seawalls

The conventional rubble mound breakwater is the most common coastal defence structure built around the world, as it is an economic and robust solution. However, on remote islands landing the armour units is a major economic cost. The use of large coral blocks as rock armour is wide spread on tropical islands. The coral blocks are commonly a by-product of channel excavation but are not seen as a sustainable source of armour.

The use of smaller armour units constructed into a rigid face represents a compromise that requires significantly less material, and can utilise local labour. A major issue with light armour solutions that relay on interlocking to achieve stability is the vulnerability to rapid failure mechanisms. This was evident on a number of islands in Tuvalu after TC Pam (Figure 5). An example of a more successful rigid or pattern placed seawall, with suitable edge details, is presented in Figure 6.

Figure 6 Hard seawalls with rock armour seawall with concrete barrier to exclude high water levels on Saibai, and a rigid seawall of small pattern placed Seabee armour units on Boigu, Torres Strait.

3.2.2. Geobag structures (qasi-permanent)

Large geobags have been used for several decades in Australia as a coastal armour unit, however, concerns over the longer term performance of the bags has limited their application. Experience and testing of the geotextile material from bags after decades in use indicates that the UV degradation rate is not rapid and that the bags would be expected to last for more than 40 years, especially if buried initially to allow impregnation of material with sand. A second issue with the geobags is uncertainty regarding their performance under wave attack. Although there is anecdotal evidence of structural performance under storm conditions there is very limited published data on the appropriate design characteristics. The primary reference relates scaled physical modelling undertaken at WRL and published by Coghlan et al (2009).

The bags are mounted in special frames to be filled with sand, as seen in Figure 7, before being sealed with stitching. The bags need to fill completely to achieve a good performance in the face. A significant advantage of this armour solution is that sand is typically a resource that can sustainably won on coral islands. Once filled excavators place the bags in a stretcher bond pattern, see Figure 7.

Because minimal materials need to be shipped to the islands the construction cost per meter for a geobag seawall is significantly less than conventional armour solutions on most remote sandy islands. This cost saving needs to be weighed against the limited life expectancy of the bags (40 + years), meaning they offer only a quasi-permanent solution.

Figure 7 Filling 2.5 m^3 (~4 T) Geobags in a special frame and placing in a seawall - Nukufetau, Tuvalu. Note special attachment on excavator.

4. EXPERIENCE IN TUVALU

Following the impact of waves from TC Pam the GoT, supported by the World Bank commissioned AECOM to examine the coastal hazards and assess options for action (ref. AECOM 2015). At the same time this study was undertaken Hall Pacific were undertaking a dredging project in Funafuti, using sand dredged from the lagoon to fill borrow pits left after the construction of the islands airstrip in WWII. The GoT, with funds from the World Bank, saw an opportunity to economically undertake foreshore improvement works utilising the plant on the island. This was the Funafuti Recreation Area Project. Separately the UNDP decided to provide support for coastal works on Nukufetau. Again the logistical and economic advantage of utilising plant and expertise already in Tuvalu meant that Hall Pacific supported by AECOM were able to propose and deliver an economic solution.

On both projects AECOM sort and achieved approvals and undertook detailed design, while Hall Pacific undertook construction. The issues and delivery method were similar, with concerns dredging may impact healthy reef (Figure 8). The dredged sand was managed on shore with bunds to minimise plumes as seen in Figure 8, and then used to nourish beaches, reclaim land and fill geobags for seawalls or groynes. Further the opportunity to use local labour is also a critical aspect on these large projects and as seen in Figure 9, the enthusiastic team were very proud of their involvement in protecting their home and improving the amenity of their island. The project construction was a big event for the local community and beyond the physical works capacity building though works workshops and training has left lasting positive impact in the community. Overall the government is very pleased that their concerns could be addressed with a timely and affordable solution that people liked. Because geobags have a limited life the design life of the structures was set to 40 years with associated allowance for impacts, including sea level rise.

Figure 8 Healthy corals in Nukufetau's lagoon and Dredged sand delivered into a bund to minimise environmental impacts, Funafuti.

Figure 9 Works in progress and the local construction team on Nukufetau.

4.1. Funafuti Recreation Area Project

The foreshore of the main island of Funafuti has experienced extensive loss of sand since the 1940's due to loss of reef vigour in the lagoon as described previously. This had left the community with an unattractive lagoon side foreshore that offers little protection from storm conditions. The window of availability between the decision to undertake the project and the Hall Pacific equipment needed to move on was short, and AECOM undertook detailed design and the required environmental approvals in just a few months.

The adopted design involved:

- Dredge 180,000 m^3 of sand, for reclamation and nourishing 1,500 m of foreshore.
- Construction of two 100 m long groynes utilising 608 2.5 m^3 geobags to contain reclamation.

The finished product as seen Figure 10 was delivered just 6 months after being initially discussed. The works improve the resilience of the community from lagoon side wave action and flooding and was well received by the 6,000 inhabitants in this land starved community. The project is significant for the islands coastal systems, and though currently not underway, monitoring of impacts would be prudent.

Figure 10 Completed Funafuti Recreation Area with groynes and nourished beaches, Tuvalu.

4.2. Seawalls and beaches for Nukufetau

Nukufetau is a very remote community that was severely impacted by the waves from TC Pam. With no access by air and only a limited marine access the options for affordable solutions was very limited. Based on work undertaken in the broader Tuvalu study (ref AECOM 2015) AECOM, working with Hall Pacific were able to develop a solution that addressed erosion issues on both the northern and southern ends of the island within the budget expectations. The final solution involved:

- Old damaged seawall buried.
- Construction new seawalls and groynes using 2,020 2.5 m^3 geobags.
- ~20,000 m3 beach nourishment.
- Recycled coral armour used to repair seawalls.

The finished product as seen in Figure 11 is attractive and was well received by the community. The seawalls address erosion concerns while the beaches improve the immunity of the community to flooding. Monitoring of impacts on the coast is not currently undertaken, though would be informative.

Figure 11 Finished works on Nukufetau, Tuvalu.

5. CONCLUSION

Communities on remote coral atolls and coral cays are facing an uncertain future. Climate change and anthropogenic impacts are adversely impacting the delicate balance between the living coral producing sand and the reef top morphology that creates and maintains the islands. Exactly how these systems will respond to climate change is not known, but we do know the erosion and marine flooding issues will worsen, and combined with the additional threat of ground water contamination, the long term viability of communities on these islands is threatened.

Once the decision to defend the coast with engineered structures has been made, the prohibitive cost of constructing conventional seawall defences on these remote islands combined with uncertainty over the long term viability of these islands leads us to consider cheaper less permanent solutions. On most of these islands sand is the one resource that can be sustainably exploited for engineering works. The use of large geobags, filled with sand won by dredging deeper reserves or the beach, offers an economical solution, though with a limited design life (<50 years). The experience in Tuvalu demonstrated that this approach offers a solution that, while not as permanent as conventional rock armour structures will give the communities, governments and agencies a robust outcome and time to develop longer term plans to address the threats that future climate change impacts will bring.

6. ACKNOWLEDGMENTS

The authors also acknowledge the role of World Bank and UNDP in funding these projects and the GoT in driving these projects. Preparation this paper was aided by the ongoing support of Hall Pacific.

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