Seawalls on Atolls: Lessons for Us All

C.T.Brown[1,]
[1] Seabee Developments, Plymouth, U.K.; chrisbrown.seabees@gmail.com

Abstract
This paper reviews the natural defences of atoll cays, the vulnerabilities of the inhabitants and their assets, and examines the various forms of seawall defence and their strengths and weaknesses. In the context of the large aid budget expected to be expended in the next 20 years, the potential economies to be found in developing appropriate specifications for the use and control of locally available materials in appropriately durable constructions, at least for minor works, may greatly reduce that budget and aid in building capability

Keywords: Atolls, Seawalls, Capability -Building, Appropriate Technology

1. Introduction
This paper reviews some of the issues encountered during a year in Kiribati on the Kiribati Adaptation Program (KAP), Stage III. The main objectives were to supervise a contract to build three seawalls and to help build the capability of the local engineering staff and contractors in such work. This experience brought into sharp focus some of the difficulties of delivering schemes designed to international criteria in such a remote and resource poor location.

The paper first provides a brief discussion of the significant aid budgets of the various agencies. It discusses the natural and artificial defence of atolls and cays, the development of design concepts and criteria and the unexpected pitfalls of using international standards on insufficiently co-ordinated projects. Recommendations are made for the better integration of capability building with the design, construction and maintenance phases of these projects.

2. Aid Agencies
Significant infrastructure projects in the atolls are without exception supported by overseas aid. Some aid is delivered unilaterally, for example the Nippon Causeway in South Tarawa by Japan, or the repair of the Betio Landfill seawall by NZ DFAT, others by international agencies such as the World Bank and the Asian Development Bank.

In any given year, close to $2 billion in aid is invested in the Pacific Island region by at least sixty-two bilateral and multilateral donors, not including hundreds more nongovernmental organizations and private foundations [9]. Australia contributes almost 50% of this. Of this budget perhaps 20% is spent on infrastructure, with most emphasis on transport (roads & runways). In 2016-17, shoreline protection was in third place behind transport, and water supply, with a budget of about A$1Million.

In a recent World Bank [13] release it was suggested that this may rise to be 50% of the aid budget in the South Pacific by 2040.

Many of these projects take a long time to get built, from years to decades. These islanders really do not have that much time.

3. Atolls and Cays
Charles Darwin's description [5] gives an observer's first impressions of atolls and cays, and his deductions as to their formation and evolution is scarcely bettered today:

> *April 1st: We arrived in view of the Keeling or Cocos Islands. This is one of the lagoon-islands (or atolls) of coral formation. The long strips of land, forming the linear islets, have been raised only to that height to which the surf can throw fragments of coral, and the wind heap up calcareous sand. The solid flat of coral rock on the outside, by its breadth, breaks the first violence of the waves, which otherwise, in a day, would sweep away these islets and all their productions.*

3.1 Natural defences and materials
Atolls form on the sides of sunken volcanoes. They have no continental shelf, and tsunamis do not shoal up, they just race by. But this provides no protection from storm waves or local meteorological effects, which are resisted naturally by refraction, shoaling, wave break, strands, ramparts of calcified sand (beachrock) or coral rubble and clasts, (cayrock) and natural shoreline change and retreat.

The first line of defence is the fore reef, a rampart of living and broken coral, which, rising from 20m depth or more over a distance of a hundred metres and more, slopes up to the edge of the reef flat which is above low tide level and visible from the shore. Deep sea waves encounter the fore reef at water depths of 15m or more, as can be seen from suitable aerial photography.

Not only does this break the waves, but in more severe storms serves also as a source of coral debris and sand to be thrown up on the reef flat and added to the island cays. The reef flat, of similar width, is filled with a thin drift of calcareous mud overlying the dead coral bench; this provides a zone of energy degradation.

The 32 atolls of Kiribati spring from the ocean floor at a depth of 4000m, yet the maximum elevation (Mount Tarawa) is barely 4m above mean sea level, with an average of less than 3m. Of the 500sq km of the Tarawa atoll ring, less than 31sq km is above sea level.

Figure 1 below shows a typical cay shoreline comprising the reef flat, a drift of sand or overlying a sloping rampart of beachrock, or horizons of cayrock, with a thin strand of carbonaceous sand, rising up to the berm of sand or soil or coral rubble.

Figure 1 Typical hardened coastline: Reef flat, sand, cayrock, strand & berm. Note break up of cayrock. (Note: all photos by the Author except where attribution is given)

On most atolls across this region, there is an oceanward ridge built by waves to a height of 2 to 3 m above MSL on the oceanside, less or non-existent on a lagoon shore. Recent studies have found indications of long-term net accretion rather than erosion on most of these oceanside shores, but in 2016 the eastern shores of Tarawa appeared to be in retreat, with accretion in the west [1, 3, 12].

3.2 Artificial defences

As described in [1] and [3] and by numerous other authors, vernacular seawalls range from low fences of palm fronds and twigs, to substantial vertical walls of coral blocks, of such a height that the fill must have some natural cementitious properties.

3.2.1 Coral

On inhabited cays, the coral rubble and calcareous horizons are used as the prime source of inorganic materials, originally used as gravel under-flooring for meeting houses (called maneabas in Kiribati), churches and some houses.

There is now a much increased demand for natural sands and aggregates for making concrete building blocks and foundation slabs for modern buildings, and un-licensed beach mining is a serious threat to the natural shoreline defences. These natural materials are all 100% recyclable by the natural and human processes. Outer island communities unaffected by the encroachment of European style of living, live within the carbonate budgets of their local environment. Traditional houses and sleeping huts have raised timber platforms on stilts and are less affected by overwash.

This supply relies on the continuity of the biogenic processes; these are at risk from rising temperatures in the sea, gross disturbance due to inappropriate engineering works and waste of all descriptions. This author has formed the view that sea level rise (SLR) may well present an opportunity for an increase in coral mass production, providing other conditions remain benign.

The challenge is to keep as many inhabited cays as healthy and productive as we can, restore others to health, and take some tough decisions on those that have been too damaged to restore.

3.2.2 Mortar Bags

Since 1945, the use of mortar filled bags has become the norm for public works. Early examples have proved to be materially durable, but the structures less so, given the damaging effects caused by the lack of repair and maintenance.

Figure 2 Bairiki Breakwater, South Tarawa lagoon. (Sources: N Pasley, SOPAC, Author)). It survived for over 30 years before lack of maintenance took its toll.

Figure 2 above shows Bairiki Breakwater, a prime example of good bagwork and poor maintenance. Built prior to 1968, the general profile was in relatively good order until the end of the century. The 1999 photo shows the initiation of damage to the crest.

With no maintenance or repairs, each successive overtopping event led to the continuing reduction of the breakwater. This sequence shows many years good service of the structure, the continued integrity of the bags and the eventual failure of the breakwater. It is estimated that waves over 1m and up to 1.6m will have occurred at this site [10].

Other examples of mortarbag walls on South Tarawa (Betio Hospital, Bairiki harbour, Nanikai Causeways) and on the outer Islands such as Ribono and Butaritari, in [3] show a considerable variation in durability and effectiveness of this form of construction.

Important considerations for the design and building of mortarbag seawalls are: depth of toe, type of bag, design and control of mix, curing, orientation and bonding of the bag work. These all matter and affect durability, stability and environmental impact. A scour resistant toe and slope-normal placement [4] of bags should maximise stability.

3.2.3 Blockwork.
One interesting seawall illustrates the problems inherent in using locally made thin wall blocks in sea water. Over 2m tall, backfilled with coral sands and rubble, but severely eroded at the base by the motion of the sand and salt crystallisation – a major weakness of island made blocks - so that only the inner face remains It lives on, probably due to the physical-chemistry processes in the fill causing it to behave like lean mass concrete rather than sand.

3.3 Modern seawalls

3.3.1 Mass retaining walls – gravity structures:
These are the most tolerant of variable quality concrete. The results reported by Watkin [11] during KAP II showed a range between 8 and 22MPa. Figure 10 in Section 4 below shows a wall built using local aggregates to a design by an MPWU engineer.

Figure 3 The East seawalls in 2016, protecting the runway from the ocean. Note the foundation sequence of cayrock, bagwork foundations and temporary works, and seawalls, both the earlier bagwork wall and the 6 year old R.C. seawall within bagwork temporary works.

3.3.2 Reinforced concrete.
During KAP II successful use of Reinforced Concrete was made with the seawall protecting the east end of the runway [11]. This used proprietary additives to protect the reinforcement and harden the concrete. Figure 3 shows the bagwork used for the foundations, on a horizon of crumbling cayrock

3.3.3 Mass concrete armour units:
Figure 4 below shows a Seabee revetment on Onotoa, made on site in 1991 using local sand and aggregate [4] and Figure 5 shows a hand-placed Seabee seawall at Cocos Keeling, built in 2001 [7, 8]: these units are royalty free have and been used at Boigu, Lord Howe and other islands, and were reported on favourably in [2].

Thus, for major projects such as at Ebeye in the Marshall Islands, the use of conventional armour units becomes practicable, based on the use of imported durable materials [2].

Figure 4 (Source MPWU) A causeway revetment (Seabees) at Onotoa. Made in 1991 [5] using local materials. Note the thick walls and abrasion – looks bad but perhaps less than 5% unit mass has been lost.

Figure 5 Seawall at Cocos Keeling. High roughness Seabees built 12 years prior to photo. Note wave wall and strand at toe [6, 7]. Simple manufacture & built by hand

3.3.4 Grout/mortar filled mattresses:
These are effective but rigid, inflexible, lack roughness and have no dynamically effective porosity. It is very difficult to check for hidden hollows or dissolution of the fill, so failure can be sudden and alarming, given prior notice only by arrays of cracks and small holes and seeps. Installed at several sites in Tarawa, including the Nippon causeway, the eastern seawall of Betio harbour and at the House of Parliament. All show minor shrinkage cracks and seeps. Figures 6 & 7

show the Nippon Causeway in South Tarawa, showing a sudden collapse in 2017 and recent repairs. Built in 1987 it suffered damage and overtopping caused by waves from Hurricane Pam, over 1000km away. It was rebuilt with Japanese aid in 2017-19.

3.3.5 Geotubes
Recent work by Hall Construction in Tuvalu has seen significant reclamation both inland and on the reef flats, the latter protected by geotubes. Geotubes have the potential to work in harmony with the natural physical chemistry to develop new horizons of cemented carbonates, similar to the beachrock in Figure 1 above.

As with the use of geofabrics, the concern is what becomes of these tough fabric materials when the atoll cays change shape, and the structures become eroded. Geotubes do not have the life expectancy of mass concrete.

Figure 6 Dai Nippon Causeway (2017), showing the size of a hidden void exposed by sudden collapse, and continuing crack towards the crest. A hidden threat.

Figure 7 Dai Nippon Causeway (2018) showing repairs with 250mm thick fabriform. Note the thickness and substrate: compare with Fig 3. (photo courtesy C.Craig)

3.3.6 Rock
As part of the Kiribati Road Rehabilitation Program (KRRP), two rock seawalls were constructed at the east end of Tarawa, as shown in Figure 8. The rock was imported in containers from Fiji, some 1500 miles away. A testing load for Betio port cranes, and the highway under construction to the sites!

Fig 8 Rock revetment protecting new road. The foundation is above a horizon of eroding cayrock.

3.3.7 Beach nourishment
In Tarawa, the final commissioning of the dredge and aggregate grading plant now provides good supplies of carbonate sand, crushed coral aggregates and cobbles. Beach nourishment was completed as part of the KRRP (Figure 9).

Fig 9 Beach nourishment site at north end of site 11. The tide took the sand away quite quickly on each shift

4. A Case Study – in brief

During KAP II, international consultants developed design standards and tools for use in conceiving, designing and constructing seawalls in Tarawa and the outer islands of Kiribati [2, 11].

The notable achievements of this period were the production of the comprehensive Shoreline Protection Manual for adoption by the Ministry of Public Works & Utilities (MPWU), and the construction of the runway seawall [11] as shown in Figure 7. KAP III was to consolidate and extend this programme.

Contemporaneously, the KRRP contract was let for the upgrading of the main road from Betio in the west to Bonriki Airport in the east. Until the adverse weather events of 2015, this work was independent of KAP III and was designed and specified differently to the Shoreline Protection Manual.

The 2015 high water levels and waves threatened the road, and two lagoon-side emergency seawalls were constructed by the MPWU, but not to the methods described in the Manual. These things happen in emergencies. No records were kept.

4.1 The KAP III seawalls

KAP III was tasked to upgrade these sites and a portion of causeway that was considered to be under threat, and an international consultant was briefed to design and document the works.

4.1.1 The tender process

Prospective local and overseas tenderers were selected and pre-qualified by some means and invited by KAP to tender for the works.

The contract documents were for a novel blockwork and mortar impermeable revetment, to be built in a similar way to bagwork, but with the durability benefit of precast blocks laid in high strength mortar, specified to current NZ Standards.

As the same consultant had designed the rock revetment seawalls for the road project, it was doubtless assumed that the test facilities for that would be available to KAP III, but no provision was made for the test facilities to be provided by anyone, either by KAP, MPWU or within the contract.

It may be that the testing requirements led to the significant disparity in the bids, over and above set-up costs. This was most unfortunate, as by the time the tender documents were submitted, the concrete testing equipment, provided by the KRRP contractor, was out of service and no-one could be motivated to undertake repairs or provide suitable test facilities.

Although it only comprised three separate small sites, the contract was further complicated as a full design had only been prepared for one site, with a lump sum provision for the other two, pending final design and local consultations to be completed during the tender period. This led eventually to a requirement to extend the tender period.

Tenders were opened at the end of February 2016, with the overseas bidders all electing to precast the blocks in Fiji, some 1500miles away, and import them to site while local contractors, perhaps not appreciating fully what the testing requirements meant, really didn't clearly address this issue and elected to make them locally.

As the bidders had all been invited to tender, under the rules they could therefore not be disqualified on grounds of lack of competence; we had to work with the lowest conforming bidder.

The lowest bid (local) was just under half the budget, whilst the lowest overseas bidder was some 50% over budget, including heavy set-up and removal costs. The KAP budget was strictly limited, with threatened over-runs on the water supply projects.

4.1.2 Late design development

At the two sites allowed for by the lump sums, local consultations had to be carried out during the tender evaluation period for beach access, as the emergency walls had cut off the easy beach access and the residents needed an additional beach ramp for their boats.

The final evolution of these designs got to the stage where the work itself was beyond the competence of the local bidders and the bill of quantities had no items to adequately describe the work. The low tenderer eventually withdrew his bid, less than 2 months before KAP was due to finish.

4.1.3 Final design – capability built!

The design for Site 2 was taken back into MPWU and the problems of concrete quality and structural form addressed. With guidance and commentary, a young engineer in the MPWU, Mr. Nuati Lotolua developed a simple mass concrete design, with wave wall as shown in Figure 10. Advice was also given as to the provision of coral rubble nourishment to provide scour protection to the emergency walls, as and when funds became available...

Fig 10 Site 2: Anderson Causeway seawall at Nanikai showing the new mass concrete wall founded below reef flat level beside the existing bagwork wave wall overlying the old coral wall. Amazing to consider 90% cost saving that was achieved. (Source: A Webb)

This design used the designated mix proportions in the Kiribati Building Code, using lagoon derived aggregate and sands. This seawall was designed and built entirely by local staff and contractors, thus delivering the objective of building capability. The as-built cost was one tenth (10%) of the bid price of the lowest overseas bidder. In 2019 the same contractor finished the repairs to Betio landfill seawall, also damaged in 2015, using the novel blockwork design, as produced locally.

5. Discussion

Over the next 20-40 years it is forecast that a significant amount of money and effort will be spent on the coastal protection of atoll communities. We need to be clear about the purpose of this work.

Is it to be an attempt to maintain these unique island cultures in situ, or a temporary postponement of the need to emigrate? These require quite different timescales and have significant implications for what is to be done, and where, and when.

To repeat: coral islands came up (again) with rising sea levels after the last ice-age. They will continue to do so as long as their biogenic systems survive, but their shape and location will change on the atoll. So, we must minimise or eliminate our interferences with these systems: which means we must properly identify them. When we do intervene, not only must the projects be delivered efficiently, but also the competence and capabilities of the local communities must be raised and sustained so as to monitor and maintain these works at least cost, and minimum reliance on the outside world and with an enduring sense of local ownership and responsibility.

To do this, the thorough integration of Capability Building is needed in all stages of a project, from concept through design and delivery to monitoring, maintenance and record keeping. This is essential to minimise the future reliance on overseas inputs, which may well be diverted elsewhere. Record keeping may require off-island storage and archiving of records and the like. In the Design and Specification of projects, care is needed to maximise the use of local materials, both to minimise the costs of maintenance, but also because transport and bio-security costs can overwhelm the budget.

We are all used to major projects requiring quality controlled materials and processes and continuous testing during and construction, usually with access to recognised central services, or to facilities provided within the contract. On island projects, these dependencies and requirements need to be explicitly provided for, or avoided altogether.

This was achieved at Site 2 in Tarawa (Figures 10 & 11) by changing from a standard specification requiring testing during the works, to adopting the Island Building Code, with prescribed standard mix proportions, utilising improved sources of locally produced crushed aggregates and sands. These are considered to be more than adequate for the works required.

6. Conclusions and Lessons

6.1 Aid

In remote locations such as Kiribati, Aid needs to support not only a specific project, but also the support services that enable testing, monitoring, maintenance and repair. The essence of this is training, record keeping and continuity. For the best results, this needs to be integrated through all stages of a project. The learning associated with un-supported projects gets lost in the sands of time, and very quickly too. However, this requires co-ordination between aid agencies and their projects; it became apparent that the procedures of various agencies were not necessarily mutually acceptable.

6.2 Natural processes

Atolls are self-constructed and thus have their own in-built defences, as long as the bio-chemistry of the oceans survives. The cays are dynamic and freely adapt and change in response to the ocean waves. While we may develop predictions about future sea levels, we are less certain about future weather and resultant changes in the weather, resulting changes wave climate and perhaps even more importantly, wave direction. These will affect the cays. We must be careful to site our defensive structures and means so as to minimise interference with these processes.

The natural inshore protection of the atoll comprises not only sand but layers of beach rock and horizons of cay-rock. These are of variable thickness, and by the nature of their formation have lower vertical permeability, but high lateral porosity in the lower layers where the native coral rubble is only partially cemented. These horizons are vulnerable to scour and undermining. A seawall founded on a cayrock horizon may provide protection against overtopping and overwash, but it will not prevent saltwater intrusion, and may eventually scour and collapse.

6.3 Concept and design

The choice of appropriate shoreline protection must acknowledge the nature and importance of the assets to be protected as well as the associated timeline's constraints and desired outcome. A balance needs to be struck between durability, the need for imported, but biologically hazardous, hard-wearing materials and the much lower cost, and hopefully more readily available, local materials. For a mass concrete structure, it is a simple matter to add extra thickness as sacrificial wearing coat. The physical chemical processes briefly alluded to above may well degrade the future performance of porous seawalls, by cementing up the voids.

Seawall designs need to provide adequate protection against both high water levels and wave attack: specifically the effects of overtopping, out-flanking, scour and percolation. They are also required to minimise effects on both the natural processes and the local culture. A new seawall needs to allow the fishermen access to the sea with their fishing boats.

6.4 Freshwater & agricultural assets

The uncontaminated freshwater lens is the major natural asset that requires protection and cannot easily be relocated or raised – although that latter possibility exists. With the switch on many atolls to imported rice as the staple diet, away from the slow growing babai or taro, it is the breadfruit, pandanus and banana that are most in need of protection. It may be possible to protect these from overwash and percolation by judicious siting of bunds, as at Kiebu and Ribono and improved by the use of grout curtains to close off the lateral permeability of the cayrock and coral rubble [3].

6.5 Combining benefits

Integration of land-use planning, set-back zones and minimum floor and formation levels for both domestic and critical assets, may allow for fewer seawalls to be built, and replaced with protective bunds and cut-offs. Plentiful quantities of useable fill material often exist in the lagoons. The Temaiku project allows for a major reclamation, but has been pending for over ten years due to its high cost originally some A$100M, but now risen to A$200M.

Decaying seawalls protecting single assets could be repositioned seaward on the reef flat, providing for an area of reclamation free from the problems of land ownership and existing habitation [3].

An example of this is the Oceanside seawall of the Anderson Causeway, as shown in Figures 5 and 10 and 11. This causeway seawall is showing signs of degradation along its length and will need restoration in the near future [3]. Relocating, rather than replacing, existing seawalls may provide smaller scale distributed reclamation areas, within the capabilities of the local or regional contractors to complete, and for the aid agencies to fund.

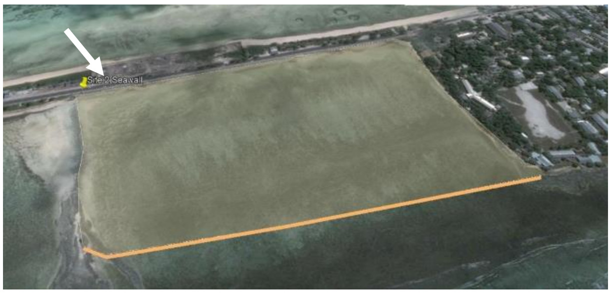

Figure 11 Site 2 shown by white arrow. This causeway wall is failing: if the 500m causeway seawall is rebuilt to seaward, an area of 16 Ha could be provided for reclamation. (Google Earth)

6.6 Major assets

If new major building assets are to be planned, not only should floor levels be carefully considered, but it may be wise to consider using floating structures to ensure continuity of usage of major buildings.

7. Summary

This paper presents a review of seawalls and bunds as used on atolls, from the perspective of a year on an atoll and a lifetime involved with seawalls. It is hoped that some relevant issues of atoll processes and working have been highlighted.

A case study has been briefly presented which, it is hoped, shows the pitfalls which await at every step of the way in the provision and maintenance of seawalls on atoll cays. The use of appropriate forms of construction can enable the use of local skills and materials at substantial cost savings.

The opinions expressed here are entirely those of the author, with the hope of prompting debate and developing more integrated policies of Capability Development. We must make use of and develop indigenous talent if we are to succeed in adapting to future changes.

8. References

[1] Biribo N & Woodroffe C.D. (2013) Historical area and shoreline change of reef islands around Tarawa Atoll, Kiribati, Sustainability Science pp345–362 Springer Japan

[2] Blacka, M & Shand, T & Howe, D & Coghlan, I & Carley, J & Estigarribia, L & Whalley, O. (2017). Affordable Coastal Protection in the Pacific Islands Testing and Design of Alternative Protection Options for Low-Energy Coastlines.

[3] Brown, C.T. (2017) The Coastal Challenges of Adaptation for Sea Level Rise in Kiribati in Coasts, Marine Structures and Breakwaters 2017. January 2018, pp 235-244 Conference Proceedings ICE Publishing

[4] Brown C.T. (1978). Blanket Theory & Low Cost Revetments. 14th ICCE Hamburg

[5] Byrne G (1991) Sediment movement on Tarawa, Kiribati. In: Workshop on coastal processes in the South Pacific island nation (Lae, Papua New Guinea, 1–8 October 1987). SOPAC, Suva, Technical Bulletin, vol 7, pp 155–159

[6] Darwin, C (June 1845). Naturalist's Voyage round the World, pp. 452-482.

[7] GHD (2001) Cocos (Keeling) Islands - Storm Surge Study Systems Engineering Australia Pty Ltd

[8] Jones, Chris and Seman, Peter. Design and Construction of West Island Seawall - Cocos (Keeling) Is [online]. In: Kench, Paul S. (Editor); Hume, Terry M (Editor). Coasts & Ports 2003 Australasian Conference : Proceedings of the 16th Australasian Coastal and Ocean Engineering Conference, Barton, A.C.T.: Institution of Engineers, Australia, 2003: [1287]-[1295].

[9] Pryke, J and Dayant, A. (Oct 16, 2018) Lowy Institute

[10] Ramsay, D (2016) pers comm – update of Coastal Calculator: subsequently [10a] Allis, M J; Stephens, Scott; Ramsay, D; Gorman, Ri and Bell, R. The coastal calculator: A user-friendly tool for estimating coastal storm-driven water-levels [online]. In: Australasian Coasts & Ports Conference 2015:. Auckland, New Zealand: Engineers Australia and IPENZ, 2015: 1-7. 4]

[11] Watkin S, (2011) KAP II SCE Final Report MPWU Kiribati.

[12] Woodroffe C.D. (2008) Reef-island topography and the vulnerability of atolls to sea-level rise in Global and Planetary Change Volume 62, Issues 1–2, May 2008, Pages 77-96

[13] W.B Release (2018).