40 YEARS OF FLEXIBLE SCOUR APRONS: ATLANTIC AND PACIFIC COAST CASE HISTORIES.

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Flexible scour apron mats are sometimes used where seawalls are 'floating' in the beach, where firm rock foundations are out of economic reach. This paper reviews the use of flexible scour aprons for the toe protection of seawalls and revetments, based on some 20 to 40 years exposure at sites in NSW, Australia and in Cubut, Argentina. It contains examples of simple and compound revetments, and discusses the problems of design variations driven by cost cutting, and the risks of post-design and post- construction policy changes that critically affect the original design concepts, especially where reliance had been placed on concurrent beach nourishment, and apron elevation had been raised to take the benefit of increased protection offered by the beach nourishment.

Keywords: seawalls; revetments; gabions, Seabees, damage.

INTRODUCTION

Between 1974 and 1986 the author advised, designed, and in some instances supervised the construction of seven coastal defences using gabions and reno mattresses, either alone or in combination with other elements, at sites in NSW, Australia. Two sites fronted concrete retaining walls and two fronted Seabee revetments for the normally exposed structural elements and two were entirely gabion mesh. All the scour aprons reported here were designed and detailed to accommodate gross deflections. Subsequent to this structure have latterly been inspected via social media and Google Earth, and since 2013 by occasional visits to NSW as side-trips to other business and professional visits. The seventh case is from Argentina, where a scour apron using concrete blocks has been used.

EVOLUTION OF CONCEPT AND DESIGN RULES

It all starts with a call to protect a beach front, dune crest property from scour at minimum cost. Two proposals were considered, the first a piled foundation, the second a dune-toe scour apron and revetment. The first was a competent but costly means to protect an individual property, the second a restricted gabion-mattress solution was proposed with a scour apron protecting a dune face revetment; but the problem of end details made it apparent that it was not suitable for a single frontage on a 5 to 6m high dune. The client opted to stay with his timber shack. But the idea remained, but what were the design rules for wave action? This took some time to evolve.

The possibility of a relevant design rule emerged from a parallel project to provide a cost estimate for a coastal reclamation at Port Kembla (PPSK 1974). Evaluating various armour systems, it became apparent that a higher Kd did not necessarily mean the least amount of concrete, just the lightest elements. But it did suggest that it was the net thickness of armour that was as much the critical factor as the (submerged) weight of the individual elements.

Based on a revised linear relationship based on Hudson's equation, which suggests that the prime criterion for armour layer stability was its net thickness or surcharge on the underlayer. (Note here that Hudson's original paper related a typical linear dimension of an armour unit to the wave height; it was the need to specify a rock mass for USACE use that led to the cubic equation we know so well). This was further considering the effects of direction of water flow and element movement, the design rules were developed at home and testing at the Water Research Laboratory, Manly Vale, in parallel with the development of the Seabee armour unit system, which was a unitary development of the same concept allowing variable geometry, based on control of failure planes.

Subject to design or method of containment, armour element mass could be variable, provided the minimum surcharge was maintained. A further development of this understanding is that the layer thickness could be varied up and downslope, according to variations in wave loading; this has been reported elsewhere.

The concept of a gabion scour blanket reached fruition with the need to protect the Balmoral Seawall from scour, or to replace it entirely (PPSK 1975). The scour apron was to be established near the base of the wall (above Low Tide Level), and be capable of falling to a level 2m lower. There were no published design rules, so the gabion thickness and stone sizes was designed to resist the orbital velocities of the design waves at the mattress thickness above an impermeable bed.

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Following this, with support from the gabion supplier, a research programme was initiated at WRL to evaluate the relationship between mattress thickness and modes of behaviour. This research led to design basis using a linear relationship between thickness and wave height, and dependent on breaker type (surf similarity) for revetment use.

The scour apron concept remained unchanged, with the apron required to be of sufficient flexibility to settle, and wide enough to reach a level of -2m AHD at a maximum steepness of 1:1.5. No scour bed model tests were carried out to assess this, rather 3 prototype structures were built, two with the support of the NSW PWD and one privately, which was also a prototype for a mixed solution, using hard wearing units above the frequent exposure level, and gabion mattresses below. As with many things, these concepts came under budget pressure and reinterpretation, so that in some projects, construction levels rose to reduce costs. And with that exposure came other problems and an expectation of reduced life.

CONSTRUCTION & LIFE SEQUENCE AT SELECTED SITES

In this section a brief review of these seven sites is given.

Fig 1. The location of 7 of the sites discussed in this paper.

Balmoral Beach 1975 – date

Balmoral Beach seawall and Promenade were built between 1924 and 1926 to accommodate the increasing number of people visiting the beach following the construction of the tram line in 1922. As shown in Fig 3 below, the wall comprised reinforced concrete soldier columns with reinforced concrete panels between. In retrospect it seems to be more as a retaining wall, founded on a simple stone foundation than a serious seawall designed to resist impact of 2.4m (8ft), 16second waves.

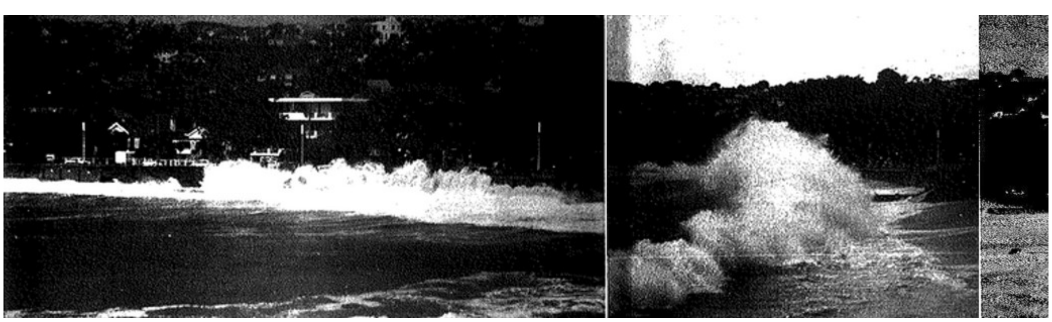

Fig 2 Long period waves, 1974 Storm at Balmoral Beach (photocopies of authors report photos)

This wall served as a quiet haven for nearly 50 years, until the sequence of severe storms of mid-1974. Between May 24 and June 16, 1974, the Sydney coastline was lashed by three storms that caused enormous damage to the coastline and altered the landscape forever, with long period waves penetrating the harbour. At times waves were breaking across the whole width of the harbour entrance, between North & South Heads. The author watched as shore break waves broke at the foot of the seawall and threw water over the top, flooding the promenade (Fig 2 above).

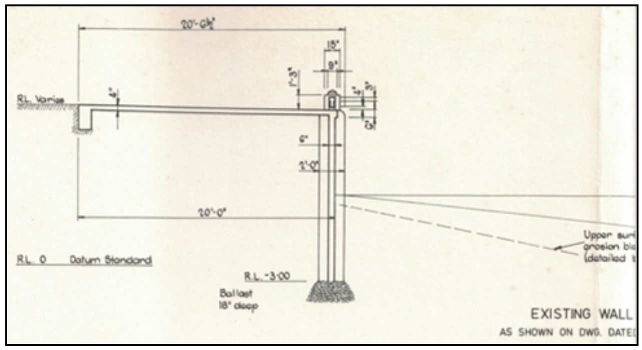

Fig3 Profile of Original seawall at Balmoral beach, c1933.

The central part of vertical concrete back beach dune retaining wall failed due to toe scour and overtopping in the 1974 event, with the result that the backfill was lost

Fig 4a, 4b Balmoral Beach after the storms n 1974

and the wall was knocked backwards. Even in its damaged state, the sheltered ambience of this beach was much appreciated by many Sydneysiders, as can be seen in Figs 4a and b above. .

Initially, three proposals were considered, to replace both the damaged sections of wall and the existing wall, either with new precast concrete contiguous sheet piles, or steps as shown in Fig 5 or a sloping solid blockwork revetment (not shown).

Whilst the vertical option retained the alignment of the existing wall, at lost some of the period features, whereas the sloping revetments completely changed the ambience, reducing the width of the Promenade. Although the steps would provide universal access to the beach it would lose its valued sheltered intimacy of the beach.

The stepped solution was highly favoured and at below design basis events, it behaved as well as the vertical walls for overtopping, but at extreme conditions with long period waves, overtopping was not well contained.

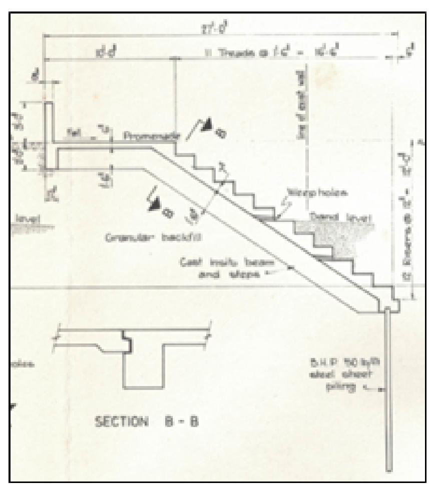

Fig5 Stepped wall option favoured in 1974.

In 1975 the author raised an objection to the loss of the intimate ambience of the existing wall, and proposed that a scour apron be installed along the whole length of the existing beach, with restoration of the promenade wall, at a significant saving to the total replacement options and reducing the amount of waste material arisings almost to zero. Two alternatives were considered, a riprap slope and a reno-mattress apron (Fig 6). The reno mattress required much less excavation and material, and the mattresses offered the added advantage of material containment.

In a further series of model tests at WRL, the scour apron was found to have the required level of performance, with much reduced wave reflection and overtopping, as shown in the Figure 7 below.

This gabion mattress was designed from first principles, as no design information was available from the Maccaferri agent. The option was adopted and completed in 1986, (the year the author left Australia for what turned out to be 25 years).

The final report to council had advised periodic inspections & renourishment if ever the mattresses became exposed, but did not advise against the use of mechanical plant to reshape the beach, or even comment on their vulnerability to mechanical damage.

No published inspection or maintenance reports were sighted until 2021, but occasional email correspondence prior to that had advised that there no significant problems; but the drainage of the fill was improved quite recently by the installation of additional high level weep-holes. The Author was able to inspect the beach in 2016, 2017 and found no issues, in fact no exposures until 2022.

On inspection in 2016 and 2017, the mattresses were still buried in beach, with over 400mm sand. By 2020 the series of storms had reshaped the beach, and the mattresses were exposed near to the island.

Durng 2020-21 the mattress were exposed as shown in the photograph below, but had significantly recovered by November 2022 when the author was able to visit the site again.

Unfortunately, rather than renourish, it was decided to re-shape the beach, a much simpler operation, but with the sad result that the mattresses have suffered mechanical damage, as shown in the photos shown in Fig 9 below.

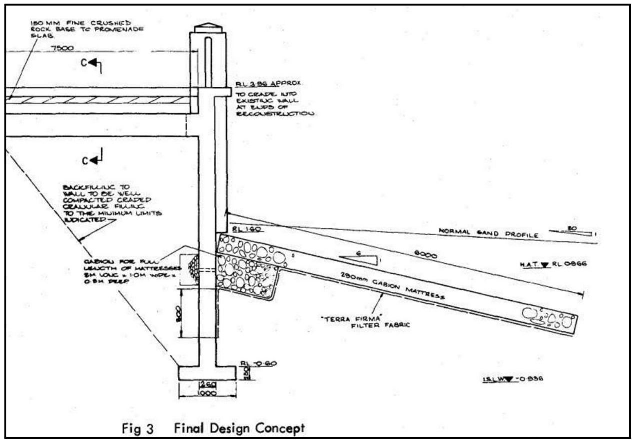

Fig 6 Final gabion mattress scour option design.

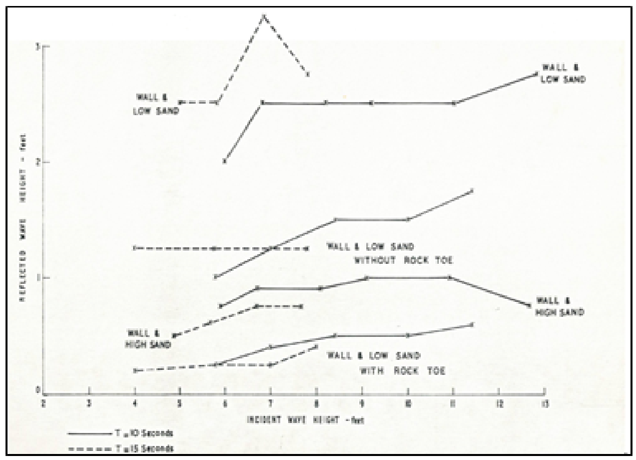

Fig 7 Reduction of reflected waves using a scour apron.

Fig 8a, As built in 1976

Fig 9 Exposed mattresses overlain by weed, 2021 (Photo courtesy Mosman Municipal Council), and as seen Nov 2022

Fig 10 Balmoral Beach, November 29 2022 (Author's photo) – almost as it was in 1926, except for the trees.

DEVEOPMENT OF DESIGN RULES. (1976-79)

As noted above, following the adoption of the scour apron concept at Balmoral, a research programme was put in hand as part of a sponsored MEngSc thesis project (Brown 1979,1983), to investigate the failure modes and stability criteria for gabion revetments under wave attack.

These tests found that stability was a function of H/t (wave height and mattress thickness and ξ, Surf similarity parameter).

At steep slopes, down slope sliding dominated, and for flatter slopes uplift failure/buckling predominated.

Detailed ultimate design chart was published in Brown (1979), and has later been adopted and published by USACE (Hughes, 2006).

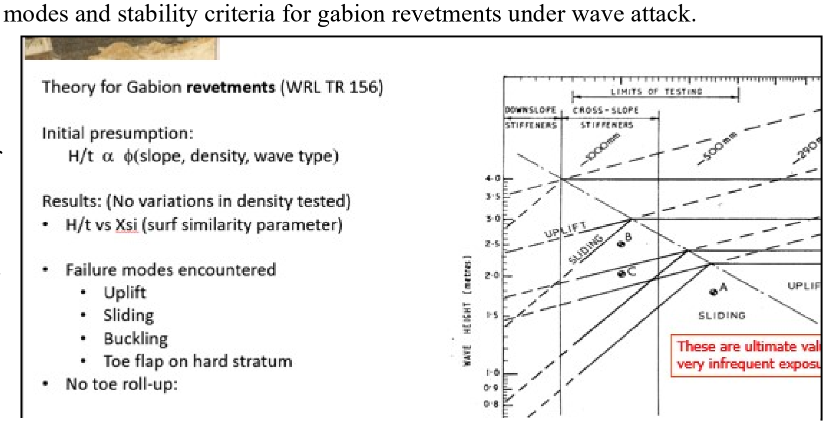

Fig 11 Summary figure of Design Rules, as reported in 1979

Wamberal Beach Ocean revetment 1978-2020 (Successful up to early 2020, 42 years)

[CB1]The brief was to design a seawall for a single property between existing rock 'revetments' of 2-3 tonne rock to be bult by hand. Because of a presumption of shortened life of gabion mesh exposed to frequent wave attack, a compound option was developed using a gabion (reno) mattress for the scour apron and using lightweight ceramic Seabee units in the subaerial section; using gabion scour aprons capable of gross deformation to the sides and at the toe. This structure was supported as a prototype test structure by Macdonald Hamilton Trading, agents for Maccaferri and PGH Ceramics, licensees for the ceramic Seabees in Australia, and Christian Brothers, Lewisham, the building owners.

Beach excavation was by Caterpillar D6 bulldozer, all other work by hand. Excavation was not allowed more than 3m below existing beach level due to risk of getting below toe of adjacent constructions, and limited n seaward extent. The scour blanket extended 6m from a location 1m below beach level. Design life 25year, expecting that a defined seawall proposal for Gosford Shire Council to be achieved by year 2000.

The revetment endured several major storms, including the 2016 event (Fig 13a,b below) without any notified problems until 2020, when scour appeared to descend below the toe reach of the scour apron, which then appeared to fail by down-slope sliding, leaving a gap between it and the revetted upper slope (Fig 14). The filter-cloth membrane maintained a seal on the face for three days, but eventually tore and the revetment was scoured out. The used of double stitched folded seams greatly enhanced the post-failure performance of this membrane

In photos taken before complete failure, it can be seen that the side gabions were anchoring the sides well, but the middle of the slope was unrestrained. It is probable that had a layer of mesh been used under the Seabees, or indeed had gabions been used throughout, this structure would have survived this storm in a more deformed state, but would still have been affected by the problems with adjacent structures. As might adherence to the originally intended extent of the apron.

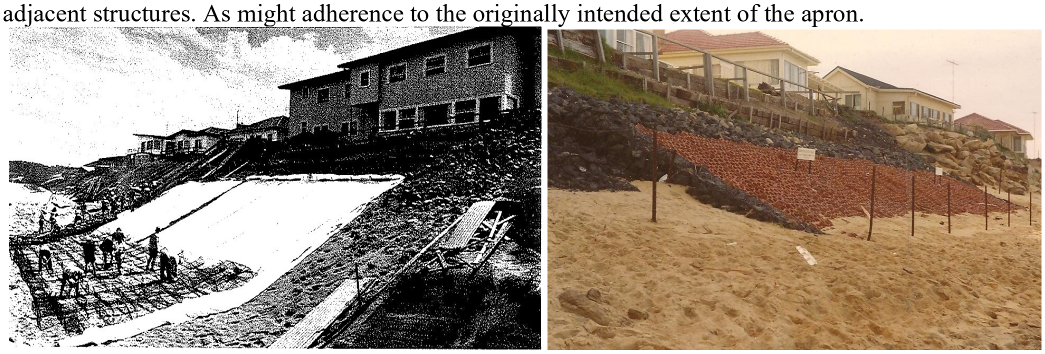

Figure 12a,b 1978 Prototype revetment, showing installation of limited scour apron and after backfilling with excavated sand, with the gabions buried completely buried.

Figure13a,b June 2016 After design storm (38 years), showing gross deformation of side and toe scour aprons. Note the depth of sand on the revetment above. Photo 13a taken 1 day after the storm subsided, photo 13a two weeks late after author arrived from overseas.

Figure 14 Wamberal prototype, last days 2020 (42 years) Photo courtesy Doug Lord. Note slippage of middle of gabions, and constant slope: compare with Photo 12a above. This gives credence to assumptions about slope angle after scour.

Galvin Park 1979- date (Towradgi Creek 1979 – date, similar)

In 1979 NSW PWD commissioned design for a gabion revetment to protect a stand of Norfolk Island Pines at Galvin Park, and the dunes south of the sacred black rocks at Towradgi, using the recently published design rules.

At Galvin Park, the dunes had been badly eroded and were threatening the roots of a stand of Norfolk Island Pine trees, which were to be saved. The dune face was prepared to an agreed stable profile with any arisings being placed on the beach, and filled with blast furnace slag advancing the face of the dunes. A two stage mattress revetment with gabion wave absorber at beach berm elevation was constructed, with a flatter wave absorbing lower section. The two were separated by a 1m gabion, to provide an uprush absorber to protect the vegetated sand cover placed over the upper slope.

With the advent of Google Earth, the author was able to monitor this structure from UK, but never succeeded to establish any communication with those responsible. This structure was inspected by Author in 2016, and found to be in acceptable condition with some surface mesh repairs apparent. Inspected again in 2020 in the week before the conference, it was found to be in excellent condition

Fig 15 1974 Storm erosion threatens Norfolk Island Pines, Galvin Park (Photo Illawarra Mercury via Report to PWD)

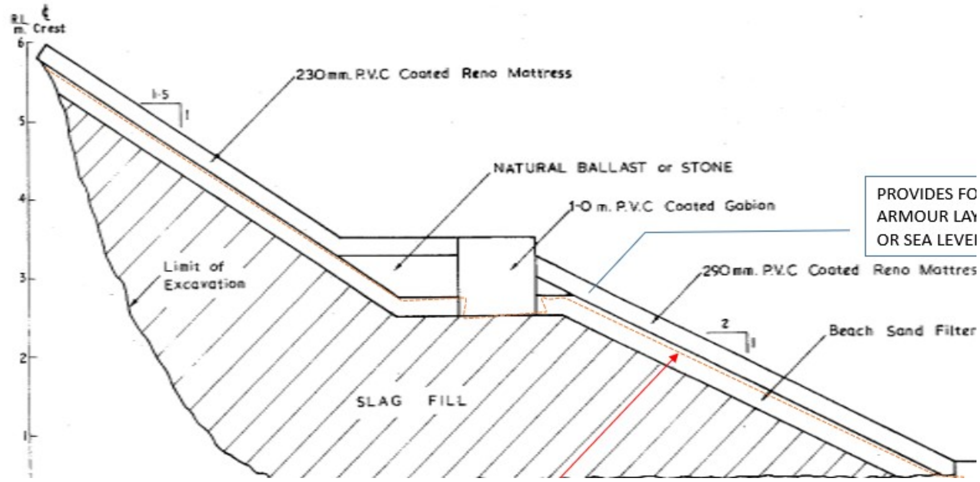

Fig 16 1979 Final Design Profile: no beach sand to be incorporated (filter cloth under gabions bot shown

Figure 17 Galvin Park revetment October 2016. (Author's photo)

Fig 18 Author's inspection November 29 2022, with detail of exposed mesh. Not the perching of the foredune, and healthy vegetation, including many of the species originally specified before client change to spinifex! R.B Waite accompanying.

Cronulla Seawall & apron 1985-2007

Following the collapse of the Prince Street seawall in 1974, WRL were briefed by Sutherland Shire Council to develop a solution suitable for construction by the Council's direct labour team. At this time NSW Government policy disallowed the use of public funds to protect private property, so this scheme was ostensibly to protect the Prince Street car park, (Foster 1977, Brown 1980). The car park was significantly reduced in size by the final design.

By 1983, cost pressures had further affected the design, and the top of the gabions had been raised and the crest lowered, while the proposed beach nourishment had already been cancelled. Lowering of the wave return wall would mean that during storms at high water levels, wave reflections would be increased.

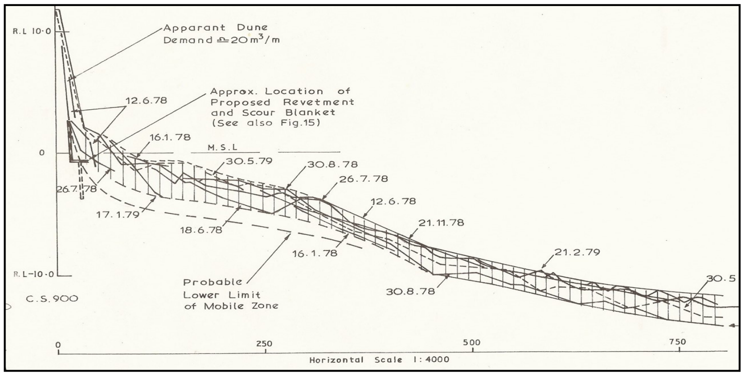

Figure 19 Original 1979 proposal for Cronulla revetment, showing revetment location in the beach prism (distorted scale). Note that the gabion scour apron in the 1980 proposal was to be located at ISLW, below the 1% scour profile.

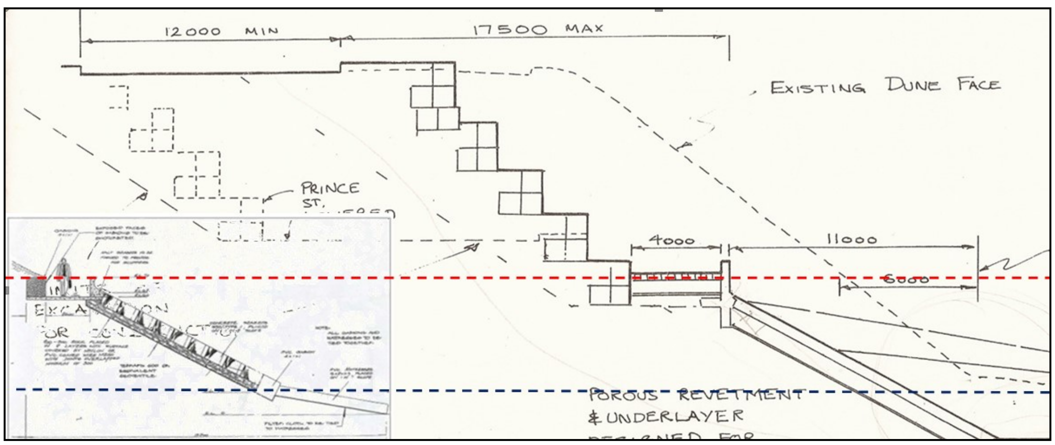

Figure 20 1979 design to scale compared with the Final Design cross-section, transition at HWM. (Report Hirst & Foster 1987 overlaid). Seabee thickness yet to be determined in 1979.

It was finally constructed in 1986 and exposed by storms almost immediately in August of that year (Fig 22a), with large boulders being thrown up on the gabions. What was to have been a scour apron became a sloping tidal revetment with reduced scour resistance, and increased vulnerability.

Fig 21 Cronulla seawall during construction. Underlayer blinded with sand to get an aesthetic appearance. Note the Netlon mesh, which served A0 to prevent theft of underlayer and B) was to link the gabion toe to the crest wall as a tension link.

Figure 22a Gabion exposed: photo dated 14 August 1986! This is not the way to treat gabions
22b The end of the line after a severe storm in early 2000s. Note the disruption at the downdrift end.

Bondi Beach Seawall scour apron 1986- date

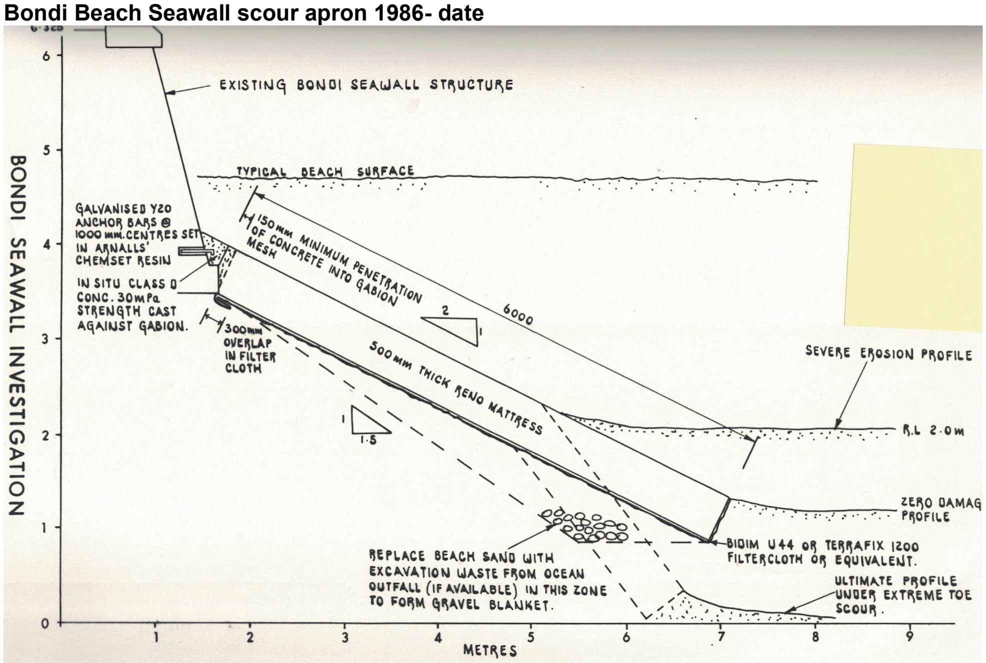

Figure 23 Bondi seawall scour apron. The seawall floats in the beach above HWM. Now 38 years old.

Bondi beach seawall was constructed in stages between the two world wars. Its foundation level is generally in sand above High Water Level, generally about the phreatic level, and is thus very vulnerable to beach erosion, especially when exacerbated by stormwater runoff via outfalls through the wall (PWD 1988). Following the successful implementation of the gabion schemes at Balmoral, Galvin Park and Towradgi, the NSW PWD commissioned the design of a scour apron to ensure the scour resistance of the seawall. A heavy duty revetment was selected to ensure against toe-curl, and tension restraint was incorporated to resist sliding failure in the event that scour exceeded the -2m level. The scour apron was installed between 1988 and 1992, but as far as can be determined, has not yet been challenged by the sea.

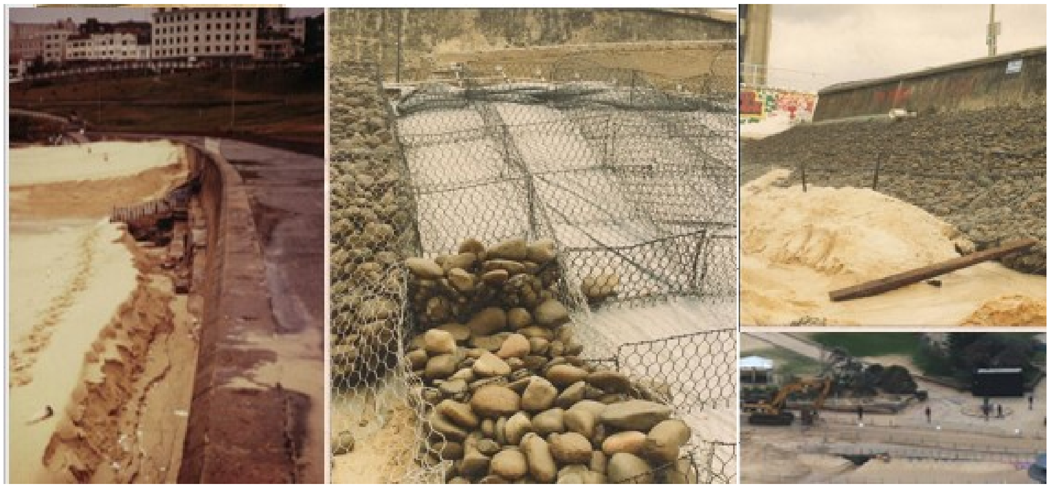

Figure 24 Bondi seawall scour apron under construction. The In 2015, the sea brought in the sand: one of the original reasons for the wall was to keep the sand on the beach!

Rada Tilly Seawall 2000-Date (toe scour damage 2017 to date)

This project is included for comparison, as the concept is similar, but used a short articulated block apron, sited high in the beach above mid tide level. Rada Tilly beach is very flat and has a high tide range of almost 6m. The seawall was designed to harden the face of an existing dune. The seawall s constructed using geotubes filled with beach sand, overlain with a geotextile and a rock underlayer, protected by a carapace of small extruded concrete Seabees at a flat slope of 1:2.5. The toe of the revetment is supported by a horizontal row of toe blocks, protected from scour by a Flexmat apron, a proprietary Argentinian system using precast concrete blocks cast on to the geomembrane, to which they are attached by raised fabric loops around which the blocks are cast. This system is supplied to site in truck-wide panels, with geomembrane overlaps on two sides. Field stitching of the overlapping joints has not been observed.

Fig 25 Flexmat – Design details, installation, and problems at a stormwater outfall.

This design was tested at the WRL (WRL 1998), and some effort was expended to provide a solution that ensured that the toe of the apron fell down during wave attack and did not curl up, and to this end a tubular toe gabion was advised, having a mass in excess of 1 tonne/m. Site video footage of the construction details all phases of the work, except for the installation of the toe gabion. It also demonstrates the difficulty of obtaining complex sand profiles when working within the phreatic zone of a beach.

Figure 26 – Disturbed Flexmat toe at Rada Tilly, before rotation of toe blocks occurred. Those look like loose blocks in this photo. Note also the ringed section showing the scour apron being pulled away seawards These and 200 other photos from searched from facebook & Instagram following a chance observation on Google Earth n January 2021, allowed the date of onset and following history on inaction to be documented from UK..

SUMMARY

Seven sites with deformable scour aprons have been discussed, six in NSW with Maccaferri gabions and or mattresses and one in Argentina with a deformable block mat: the gabion and reno mattress structures discussed here have endured at 4 sites on the coast of NSW for over 40 years, and the two failures met their design conditions before failing. The prototype structure failed as expected due to limitations placed on its construction, whilst the more significant failure was accelerated by changes to the original design profile without adequate review of the combined effect of these changes.

The block-mat system started failing in three sections after 17 years, either due to incomplete construction, damage during construction, or due to separation of the blocks from the geotextile. Five years on from initial damage it is ineffective, as it is not restraining the toe beam blocks and the revetment behind them from a slow creep towards the sea.

1. Balmoral has met its design objectives but may be replaced due to physical damage caused by beach scraping rather than the beach nourishment recommended in 1976. Times change: beach scraping is simple; beach nourishment requires a lot more work. It pays to supervise the operators of mechanical plant, and organise tool-box talks to identify the risks.
2. Wamberal prototype construction was restricted by Council & neighbours and did not extend far enough to reach the long term scour depth. It survived 3 or 4 Design Storms before failing by sliding, after 42 years of service, so validating the model tests. It demonstrated the deformable competence of the mattress system. It only had tension restraint at the sides, which was not enough. A single layer of mesh between the side panels may have been enough, or an all mattress design. The terminal revetment never got out of the flume due to the inability to source funding.
3. Galvin Park is in good condition and meeting all of its design objectives.
4. Towradgi is still extant, but has far too much debris on it from recent storms: it suffered less damage than the tidal pool adjacent. A lot of debris may be from the unauthorised removal of the sacred Black Rocks due to a failure to restrain the excavator driver's enthusiasm in 1979.

Another consequence of inadequate briefing and supervision.

Fig 27 Towradgi: Then (1979) and now (Nov 29 2022)

5. Cronulla: this design was conceived in a period of financial strain, and was pushing the envelope to start with. Over a period of six years, it suffered design mission creep under financial pressure; the scour apron level was raised so that it was fully exposed in the tidal zone, the crest level was lowered and the beach nourishment was cancelled and debris was left on the beach. In effect the scour apron became a tidal revetment, so reducing the extent of the main working revetment, and reducing its ability to resist scour by the raising of its landward end by 2m. During a storm in its first year of service the gabion mesh was attacked by large rocks. It is reported that several repair programmes were undertaken in subsequent. Years, but no records have been sighted by the author. That the gabions lasted 21 years (with repairs) and might be considered a marvel; they have been replaced by contiguous piles, which have their own problems.
6. Bondi has never been tested but looks good and has a tension restraint. Large rounded stones were used to increase resistance to movement, and minimise sharp edge damage to the gabion mesh and prevent toe curl.
7. Rada Tilly is a must visit place in Verano (Summer): take a thick coat in Winter. Detail testing of the short scour apron led to a recommendation for a toe-gabion to prevent toe-curl or flapping. But it seems that this was not installed as recommended; probably subject to cost cutting. After several storm cycles, it has slowly succumbed and is may not be adequate for wave action above 1m, as the blocks do not appear to be adequately attached to the geotextile. Given the absence of the toe gabion, the apron is probably too short, but the geometry was 'interesting', as are the politics of not undertaking obvious repairs over a period in excess of five years.

CONCLUSIONS

The use of scour aprons was shown at the start of the campaign at Balmoral to significantly reduce reflections, by the simple expedient of limiting water depth in front of the structure and so ensure the dissipation of wave energy by breaking the waves.

The use of gabions, a low input technology, limited by the durability of the mesh, has been compared with the use of block-on- textile or articulated block solutions and found to be comparable, and have achieved reasonable outcomes, beyond the common expectations of durability.

Corrosion rates of the PVC coated galvanised wire gabion mesh have been much lower than expected. The mesh is vulnerable to abrasion and mechanical damage, but is repairable: a low tech problem and in two instances has sustained a significant period of exposure to sea washed stones. Compared with corrosion of sheet piles and problems with contiguous concrete piles: it has survived longer than expected by this author.

The only mechanical plant necessary is for earth moving and materials handling: beware of the digger driver's enthusiasm for his task!

If the design depends on other factors, such as beach nourishment, ensure that they are still in place when final design approval is given: But can they be relied on in the future? Beware of underestimating the scour depth.

The author argues the need for continuing monitoring and responsible reaction to beach level changes, with special reference to recent scour events and the importance of periodic review of design assumptions and changing climate. The undercurrent of many of the sites discussed is that the owners of the structures do not have the same understanding as those who designed, and tested them, yet only too often the designer is not retained to ensure that the details are carefully adhered to in the construction phase. This can allow simple errors to go uncorrected, which may be almost impossible to correct after completion. If the designer is not allowed to supervise, a vital safety net has been removed.

Continued involvement of the original designer in supervision and monitoring must be encouraged, especially when compared to the costs incurred by ignorant or negligent mistakes. With this in mind, feel free to contact the author by mail or email to discuss any matter arising from this paper.

Don't expect your successors to follow your recommendations; they may not have the budget or the time, especially if adequate advice was not given at the beginning,

ACKNOWLEDGMENTS

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More recently to my intended co-authors, whose input got delayed due to COVID, Hugo Donini and Leandro Foletto, who sourced original data regarding Rada Tilly, and Jorge Alperin for making available the video of the construction of the Rada Tilly seawall. Also acknowledged are the scores of people in Rada Tilly who have helped by posting photographs on social media, and answering questions arising from the videos and photos.

APPENDIX

Although not a project with any input from the author, it is interesting to review the 1997 & 1998 reports from WRL (1997) regarding the construction of a proposed terminal revetment. One option was to have had a gabion mattress scour apron almost identical to that proposed in 1979 for Cronulla. See WRL 1998. Fully tested at WRL. Now that we all accept an interminable rise in sea levels, it is probable that the design criteria would be much greater today. It is the loss of beach amenity that matters, so perhaps its back to the example of Balmoral and Bondi, (and now Collaroy, on rock) that we return.

Scour will always be a threat; Gabions now, rock later, lift the small armour and replace with bigger, reuse elsewhere? Questions for the today's generation. Ours went unanswered for too long.

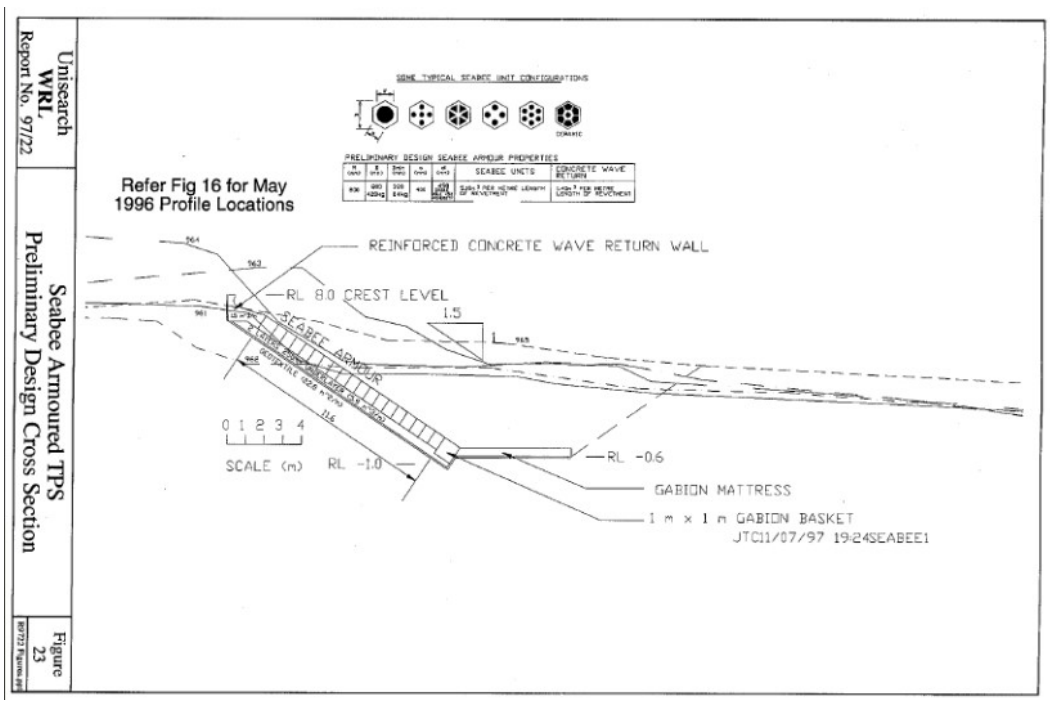

Fig 28 1998 Proposal for a Terminal Revetment at Wamberal – not proceeded with. Compare to Figs 19 & 20 (Cronulla)

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