Gold Coast Reef: 10-year Anniversary

Executive Summary

The Gold Coast Reef at Narrowneck, Surfers Paradise Australia was the world's first multi-purpose artificial soft reef (M-ASR). M-ASR's are designed to protect the beach from erosion while simultaneously achieving other enhancements such as:

- Wider beach
- Reduced storm surge and flooding
- Enhanced ecology
- Improved property values
- Economic returns for the community
- Healthy sporting activities
- Safer swimming
- Custom-made surfing waves on the reef and better adjacent sand banks

In 1998, erosion along the northern Gold Coast required a remedy and, at the same time, they needed to maintain the beauty of the beach for tourists and the many residents who live along the foreshore and so an offshore multipurpose reef was chosen.

The Gold Coast Reef project proved to be a far-reaching and influential. The project won the Queensland State Environmental Award at the time of construction.

As 2009 is the 10-year anniversary of the reef (since the start of construction in 1999), this report examines whether the promises made during the design phase have come to fruition. The reef and shoreline have been monitored using sophisticated video camera techniques for nearly 10 years.

The monitoring report of Blacka et al. notes that on the downdrift (northern) side "*the beach width immediately north of the Narrowneck Reef was approximately the same as was recorded at the commencement of monitoring nine years earlier in August 1999*".

That is, no downdrift impacts have been observed.

At the reef itself on the updrift (southern) side, they note that "*at the completion of the current monitoring period the beach is approximately 15 to 20 m wider than at the initiation of monitoring nine years earlier in August 1999*".

That is, the beaches have widened due to the reef.

The shape of the beach is very similar to the shape predicted by the physical modelling prior to the initiation of the reef project, confirming that the computer models were correct.

Many fishing boats are using the reef as a source for their catches.

The reef is enhancing the fishing and eco-system.

A new sand dune can be seen and the beach is wider to the south than to the north.

The sand dune which protects the beach has grown substantially.

The beach is characterised by a salient of about 30 m amplitude immediately south of the reef.

…40–50 m additional beach width had been achieved at Narrowneck since 1999 …, relative to the unnourished beaches to the north and south.

Independent scientist
Dr Ian Turner, in the prestigious
Journal of Waterway, Port, Coastal, and Ocean Engineering,
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“The reef has significantly stabilized the nourishment project and reduced the total rate of beach recession rate along the entire project.” “The reef has extended the re-nourishment cycle well beyond the 10 year cycle that was experienced before the reef.”

John McGrath, Gold Coast City Engineer

Introduction

The Gold Coast Reef at Narrowneck, Surfers Paradise Australia was the world's first multi-purpose artificial soft reef (M-ASR). M-ASR's are designed to protect the beach from erosion while simultaneously achieving other enhancements such as:

- Wider beach
- Reduced storm surge and flooding
- Enhanced ecology
- Improved property values
- Economic returns for the community
- Healthy sporting activities
- Safer swimming
- Custom made surfing waves on the reef and better adjacent sand banks

That is, M-ASR's are offshore structures designed to protect the beach from erosion while simultaneously achieving other enhancements such as maintaining a wider beach, enhancing the local ecology and providing recreational opportunities.

In 1998, erosion along the northern Gold Coast required a remedy and, at the same time, they needed to maintain the beauty of the beach for tourists and the many residents who live along the foreshore. Thus, rock walls, groynes and other hard coastal protection devices placed on the beach itself were rejected by the City's beach managers. Instead, they chose the risk of a novel technique – an offshore reef. There were no precedents for such a large offshore reef with multi-purpose goals. Furthermore, the designer ultimately chose to align the reef with a cross-shore orientation, rather than running the reef longshore, which was novel and innovative.

The Gold Coast Reef proved to be a far-reaching and influential project which changed the way beaches are managed for ever. The seminal project won the Queensland State Environmental Award at the time of construction.

As 2009 is the 10-year anniversary of the reef (since the start of construction in 1999), this report examines whether the promises made during the design phase have come to fruition.

The following people are acknowledged:

- Mayor and councilors in the Gold Coast City Council
- Project manager within the Gold Coast City Council, senior beach engineer Mr John McGrath
- Reef designer Dr Kerry Black (then Professor at Waikato University in New Zealand) with close support from two of his senior students Dr Shaw Mead and Mr Jamie Hutt.

- Physical laboratory expert Dr Ian Turner at University of New South Wales.
- Construction Engineer (former Gold Coast City Council Engineer) Mr Angus Jackson.
- Video monitoring group at the Water Research Laboratory in Sydney.

Assessment guidelines

To scrutinize the project, it is essential to assess the outcomes against the original guidelines set for the reef and the expectations of the Gold Coast City prior to initiating construction. Fortunately, these expectations were well determined at the time and much was published in peer-reviewed scientific journals and conferences around 1999-2001. This report focuses on the beach protection. The reader is referred to the following scientific references:

- Hutt, J.A.; Black, K.P.; Jackson, A. and McGrath, J. (1999) Designing the Shape of the Gold Coast Reef: Field Investigations. Proceedings of the Coasts & Ports '99 Conference, 14-16 April 1999, Perth, Australia. Vol 1, pp.299-304.

- Black, K. (1999) Designing the shape of the Gold Coast Reef: sediment dynamics. Proceedings of the Coasts & Ports '99 Conference, 14-16 April 1999, Perth, Australia. Vol 1, pp.58-63.

- Journal of Coastal Research, Special Issue No. 29, edited: K.P Black. 2001.

- Black, K.P.; and S. Mead (2001) Design of the Gold Coast Artificial Surfing Reef: Surfing Aspects. In: K. Black (ed) Natural and Artificial Reefs for Surfing and Coastal Protection. Special Issue 29 , Journal of Coastal Research, pp 115-130.

- Turner, I. L., Leyden, V.M., Cox, R.J., Jackson, A, and McGrath, J.F. (2001) Physical model study of the Gold Coast Reef. In: K. Black (ed) Natural and Artificial Reefs for Surfing and Coastal Protection. Special Issue 29 , Journal of Coastal Research, pp 131-146

- Jackson, A. (2001) Special construction requirements for artificial surfing reefs. In: K. Black (ed) Natural and Artificial Reefs for Surfing and Coastal Protection. Special Issue 29 , Journal of Coastal Research, pp 147-150

Reef shape

The shape of the Gold Coast is shown in Figure 1. The designer chose to align the reef cross-shore, rather than longshore to improve the coastal protection and enhance the surfing. At the completion of the computer design, ASR Ltd handed the shape over to the Gold Coast City and their Engineer who undertook the construction independently of ASR.

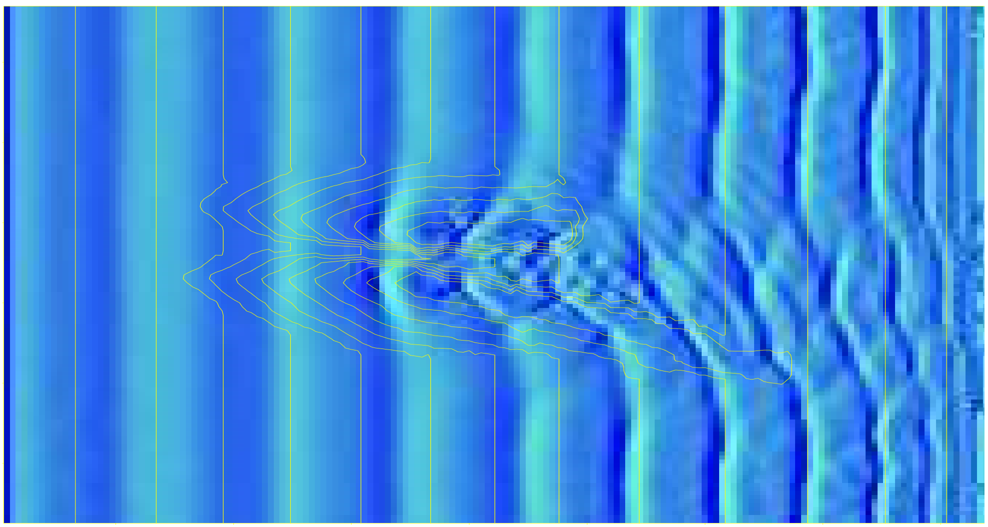


Figure 1. Shape of the Gold Coast Reef, showing the computer design (upper image) and the geobags on the seabed (lower image, looking to the south). Notably, the inner shallow segment of the northern arm was not built as it was predicted from the computer modelling that sand would deposit there naturally and so a cost-saving was made

Construction method

The reef was constructed using mega-geocontainers filled with sand (Figure 1). The bags were geotextile "sausages" filled in a split hull hopper barge and dropped to the sea bed. A total of 430 sand-filled megacontainers (each weighing about 350 tonnes) were placed for a total sand weight of some 150,000 tonnes (Figure 2).

Construction of the reef started in August 1999 and the major phase of reef building was concluded by December 2000. To more closely approximate the computer design, some 45 additional geobags were placed after 2000, with the last bags being dropped in August 2004.

The constructed reef never achieved the designed shape (Figure 3). The reef remains between 1 m and 7 m deeper in the water than the computer design. The split hull barge with deep draught could not create the required shallow reef crest, which was designed to be 0.5 m below the low tide level. With the deeper reef than the computer design, the impact of the reef on the shore may be somewhat less than anticipated, e.g. size and shape of salient could be reduced.

In response to the problems confronted by the Construction Engineer at the Gold Coast, ASR subsequently undertook independent research to develop a patented "Rapid Accurate Deployment (RAD)" method. ASR also established its own construction team in late 2007. The RAD technique allowed the crest to be brought up to the required levels, rather than using the split hull barge system. The RAD method also deploys a geomat under the containers and the containers are laid touching which prevents sand being suspended around the bags and causing them to sink. The ship deployment produces a substantially less precise layout of geobags with gaps between each (Figure 1). The RAD method was successfully adopted to build the Mount Maunganui Reef (www.mountreef.co.nz).

In designing the bag layout, the Construction Engineer made allowances for the anticipated sinkage which he noted was exacerbated by placing nourishment which falsely elevated the beach levels before geobag deployment. However, the volume of the reef rapidly rises if the bags are allowed to sink, as extra bags need to be deployed on top of the sinking layers to bring up the crest height. The RAD method traps the sand under the tightly packed geobags and geomat, making the volume for construction much less. This can represent more than a 50% saving in construction volume.

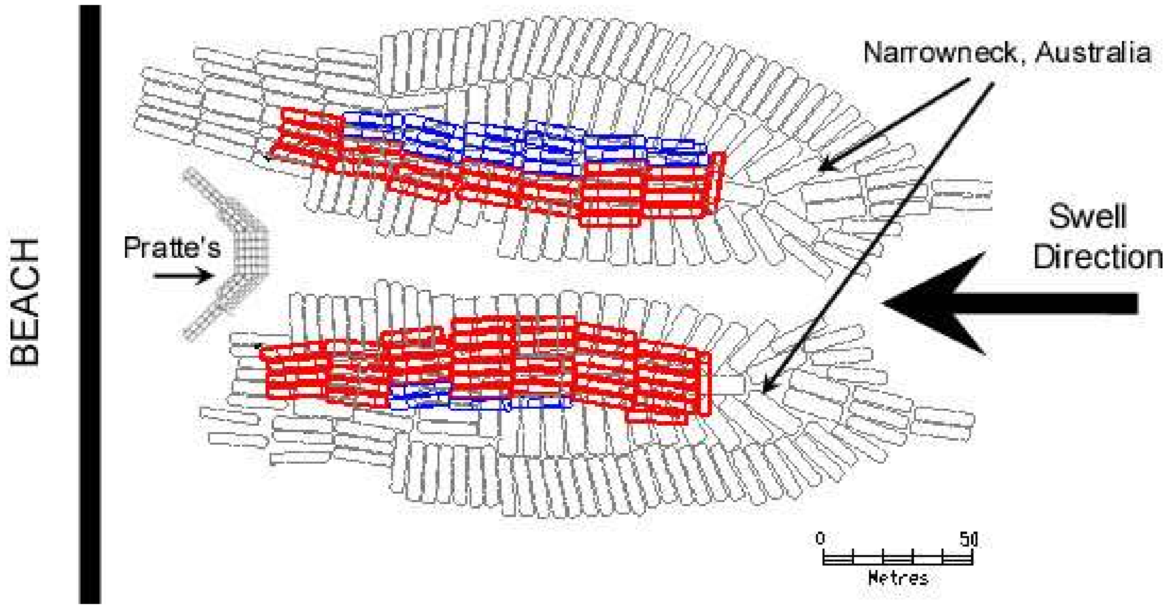


Figure 2. Layout of the geobags for the Gold Coast Reef, as proposed by the Construction Engineer. Pratte's Reef in California is also shown as a comparison of size.
Pratte's Reef proved to be too small and was eventually removed and abandoned.

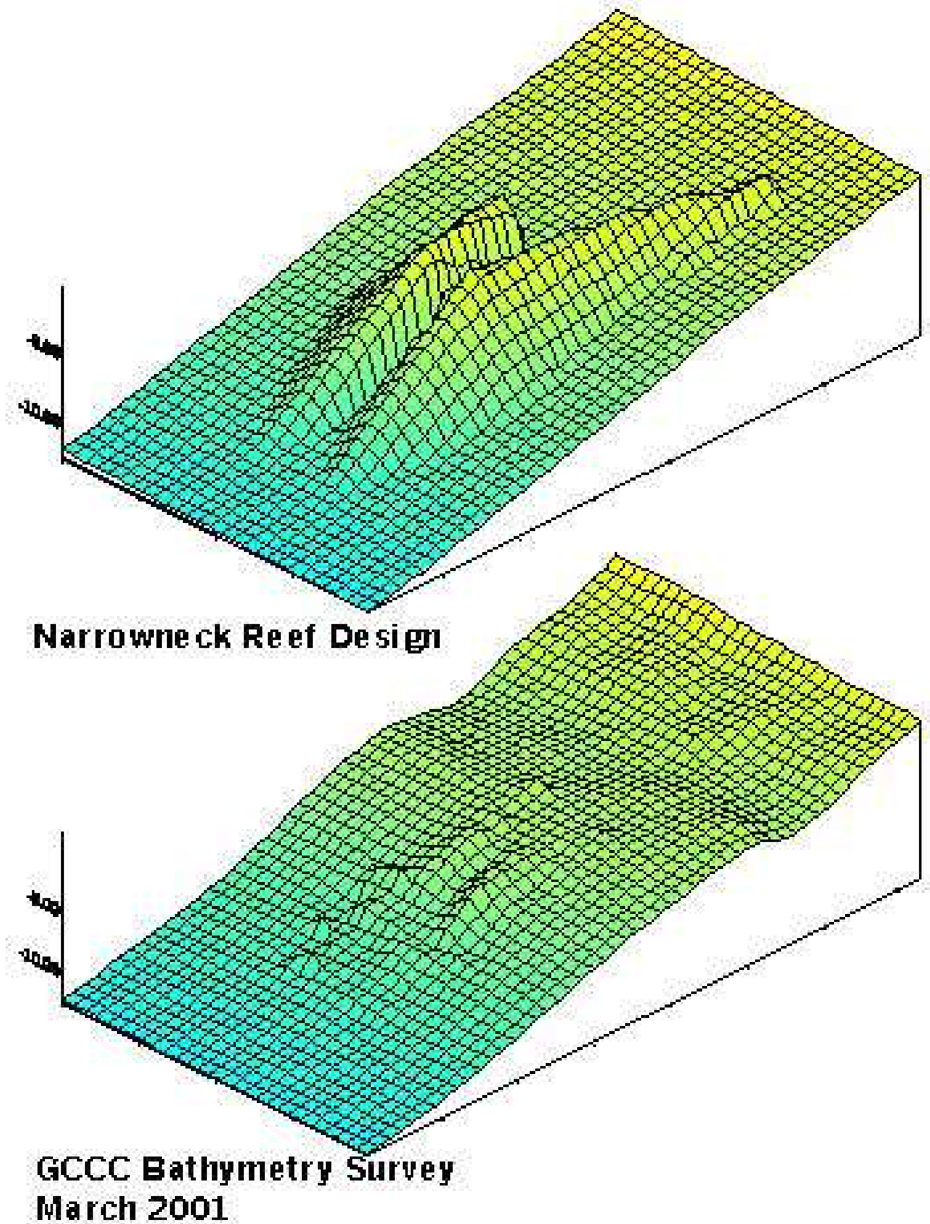


Figure 3. The computer design for the reef (upper panel) and a reef survey at the end of the main construction phase after December 2000 (lower panel). In the light of this survey, 45 additional geobags were placed to bring the reef shape more into alignment with the design but the built shape remains substantially at odds with the computer design. The last of the extra 45 geobags was placed in August 2004.

Expectations for the reef prior to construction

In one of the scientific papers it is noted that:

"The Gold Coast region is known to experience up to 500,000 m^3yr^{-1} *of net longshore transport. Any structure in this 'river of sand' could have serious impacts downstream. It was necessary to trap some sand, but not all. The City was able to sustain a downstream re-nourishment program of around 80,000* m^3yr^{-1}*, which meant that the structure should allow free passage of more than 80% of the total littoral drift, while still providing a coastal control for the widened beach profile upstream and a 'reef' for surfing."*

In this context, the specific sedimentation criteria for the reef were:

- Provide a coastal control point to assist the maintenance of the widened beaches at Surfers Paradice
- After the "long term" equilibrium is established, no more than approximately 80,000 m^3yr^{-1} of re-nourishment should be needed on the downstream (northern) side of the reef
- Prior to a dynamic equilibrium becoming established, beach adjustment should cause minimal impact on adjacent beaches.

Thus, the reef was designed to "leak" sand and was never meant to totally eliminate maintenance dredging at Surfer's Paradise. Indeed, with some 500,000 m^3yr^{-1} heading north, the reef should allow at least 420,000 m^3yr^{-1} to pass by at all times. As such, beach erosion at Surfers was anticipated to continue occurring but the reef was meant to slow the losses.

At the time, Dr Black said, "The level of precision required was testimony to the confidence in the designer and the computer models. If the reef was too imposing , a shore attached tombolo would substantially block the passage of sand. On the contrary if the reef was too ineffective, then no benefit would be noted. In either case, the project would be considered a failure. This led to the requirement for a large amount of data collection and technical computer and physical modelling".

Sediment transport mathematical and physical modelling was undertaken during the design phase. The physical modelling was undertaken to confirm the mathematical modelling of the reef designer and permission to proceed with construction came from the Gold Coast City Council only after the physical modelling confirmation.

From the mathematical modelling, the following excerpts (in italics) are relevant:

"Patterns of sedimentation are highly variable between wave scenario cases and for high and low tide. However, sedimentation is consistently largest in the paddling channel, the outer rim of the reef and on the inner flanks of the two headland arms."

"The submerged reef remains relatively transparent to interruption of natural littoral drift. This occurs because of (a) high penetration of waves in the lee of the reef …and (b) the submerged nature of the reef …"

"The tendency for scour in the gap between the northern arm and the beach can be explained by flow convergence through the gap causing currents to locally accelerate."

The patterns of sedimentation are shown in Figure 4 for the common south-east swell condition. The blue and purple colours depict a substantial build up of sand to the south of the reef at the shoreline.

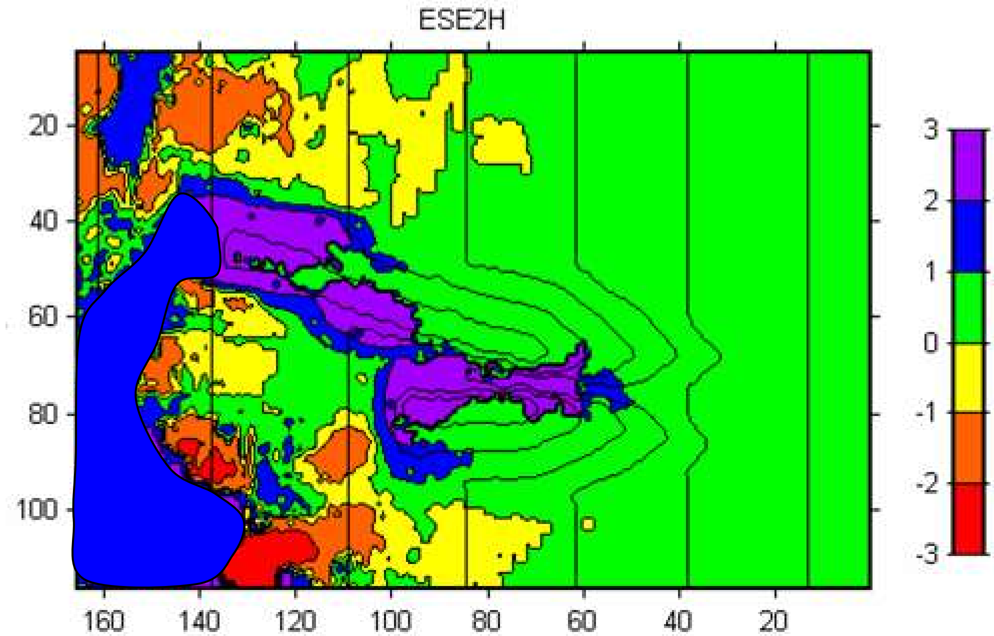


Figure 4. Predicted patterns of sedimentation at the reef during the common south-east swell condition. The blue and purple colours shows a substantial build up of sand, including to the south of the reef at the shoreline.

The following excerpts in italics are taken from the physical modelling report:

"A qualitative sediment-tracer methodology was employed to investigate shoreline adjustment trends in the lee of the reef. It was confirmed that due to the relative transparency of the reef to the incident wave field, moderate beach widening by the formation of a shoreline salient could be anticipated. No indication that over-widening of the beach to form a shore-attached tombolo was observed."

It was predicted that there would be a *"uniform widening of the beach by approximately 30 to 40 m in the lee of the reef"*. The predicted shape of the beach from the physical model is shown in Figure 5.

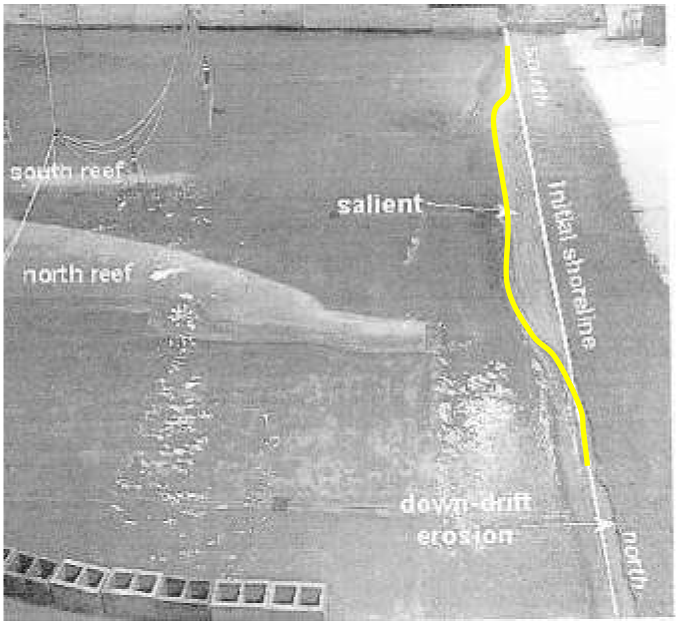


Figure 5. Predicted shape of the salient at the beach from the physical model.

"Further testing was undertaken to examine the adjustment of the shoreline in the vicinity of the reef to both oblique and erosive (storm) wave conditions. In the first case, there was a general northward shift of the salient, but, due to a strong northward current, the channel between the shoreline and the northern inshore tip of the reef was observed to remain open. In the second case, the relative transparency of the reef to larger (storm) wave conditions was apparent, and a significant reduction in salient size resulted."

"In accordance with the findings of the numerical model investigations, it was observed that sedimentation occurred within the central channel of the reef, and particularly along the inner flank of the northern arm. Sedimentation was also evident within the lagoon area formed in the lee of the reef. No sedimentation was observed along the reef crest, and of particular significance, sedimentation did not occur within the gap between the northern arm of the reef and the nourished shoreline. As predicted by the numerical modelling, it was apparent that scour due to convergence of the wave-driven longshore current was maintaining a 'channel' between the reef and shoreline."

"Following the completion of the extensive hydrodynamic and sediment tracer test programs, it was concluded that the proposed reef shape satisfied these criteria, and more generally confirming that submerged offshore structures can be designed for coastal protection and surfing."

"Once re-alignment of the shoreline in the lee of the structure had reached near-equilibrium, sediment bypassing of the reef was observed to return to approximately the updrift rate of longshore transport."

In summary, the key expectations from the mathematical and physical modelling were that:

- A salient some 30-40 m wide would form
- The salient would not be permanent, particularly during storms.
- No tombolo would form
- The “paddling channel” between the two arms would fill with sand
- Sand by-passing would occur with no serious downstream impacts
- The patterns of sand bars would be variable as the wave conditions changed

Measured Outcomes around the Narrowneck Reef

Video monitoring of the shoreline around the reef was commissioned by the Gold Coast City Council. A succession of 6-monthly monitoring reports has been produced titled “Analysis of shoreline variability, seasonality and erosion/accretion trends. Technical Reports of the Water Research Laboratory, University of New South Wales”. These can be found on the website:

http://www.wrl.unsw.edu.au/coastalimaging/public/goldcst/index.php?page=goldcstMonitoringReports.html

Here, the most recent report by Blacka et al. (Technical Report 2008/27, November 2008) is considered because it contains the longest record of data around the reef.

No offshore sub-tidal surveys of the depths around the reef have been provided for scrutiny by the Gold Coast City Council. This is unfortunate as much could be learned from such surveys, but the video is a powerful monitoring tool for the shoreline changes.

The Results

The report of Blacka et al. notes that on the downdrift (northern) side “*the beach width immediately north of the Narrowneck Reef was approximately the same as was recorded at the commencement of monitoring nine years earlier in August 1999”*.

That is, no downdrift impacts have been observed.

At the reef itself on the updrift (southern) side, they note that “*at the completion of the current monitoring period the beach is approximately 15 to 20 m wider than at the initiation of monitoring nine years earlier in August 1999*”.

That is, the beaches have widened due to the reef.

Figure 6 shows the wider beach on the south side of the reef. There is also a new depositional sand dune immediately south of the reef.

The shape of the beach is very similar to the shape predicted by the physical modelling prior to the initiation of the reef project (Compare Figure 5 with Figure 6).

The models were correct.

Many fishing boats are using the reef as a source for their catches (Figure 6).

The reef is enhancing the fishing and eco-system.

A plan perspective is shown in Figure 7. The new sand dune can be seen and the beach is wider to the south than to the north.

The sand dune which protects the beach has grown substantially.

Evidence of the salient in the lee of the reef is shown in Figure 8 which shows beach widths for February 08 to July 08 (top panel) and for the period since the beginning of records (bottom panel). The reef is at 1000 m in the coordinate system and the beach is characterised by a salient of about 30 m amplitude immediately south of the reef.

While the technical report of WRL says that the baseline is arbitrary, Figure 7 shows the baseline to be a smooth curve against which the salient stands out. Beach observers confirm that the beach is wider to the south and near the reef than to the north.

…40–50 m additional beach width had been achieved at Narrowneck since 1999 due to nourishment plus the reef, relative to the unnourished beaches to the north and south. This compared to an additional 20–30 m of additional beach along the entire 2 km of nourished shoreline. Approximately 20 m of additional beach width can be attributed to the offshore reef structure, at the Gold Coast site

Independent scientist
Dr Ian Turner, in the prestigious
Journal of Waterway, Port, Coastal, and Ocean Engineering,
Vol. 132, No. 3, May 1, 2006. ASCE

Thus, several broad conclusions can be taken from the monitoring:

- There are no upstream or downstream adverse impacts
- The beach at the reef and to the south is wider in July 2008 than after the nourishment. This is opposite to the long pre-reef history of the beach which has exhibited constant erosion and needed regular re-nourishment.
- There is a salient of about 20-30 m width at the reef. The salient is reflected by a new dune that is becoming overgrown with dune grasses immediately south of the reef. The amplitude, length and shape of the salient is close to predictions made by the physical modelling prior to reef construction. The salient amplitude is about 10 m less than predicted, which can be explained by the fact that the constructed reef is deeper than the computer design.

Figure 6: Narrowneck Beach showing the wider beach on the south side of the reef including a new depositional sand dune immediately south of the reef. Notably, offshore of the reef, many fishing boats are using the reef as a source for their catches. The blue line shows the high tide line.

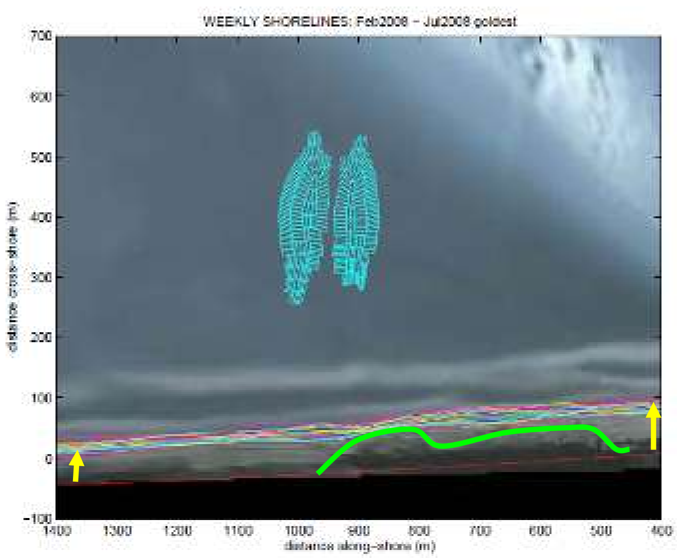
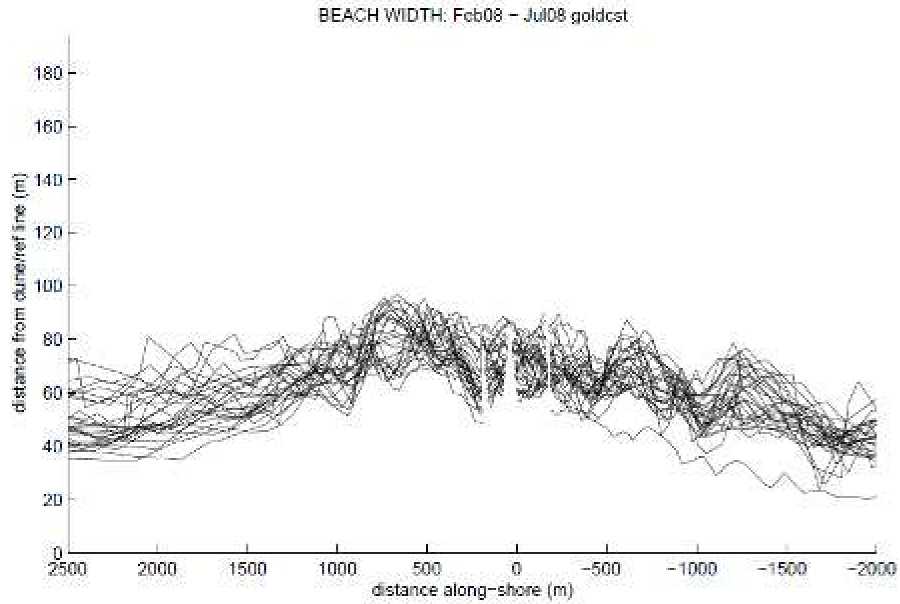


Figure 7: Vertical perspective from the video monitoring showing the reef located at 900-1000 m in their coordinate system. The wider sand dune immediately south of the reef is shown by the Green Line. The shoreline positions are in various colours with the baseline used to determine beach width shown as a red line.



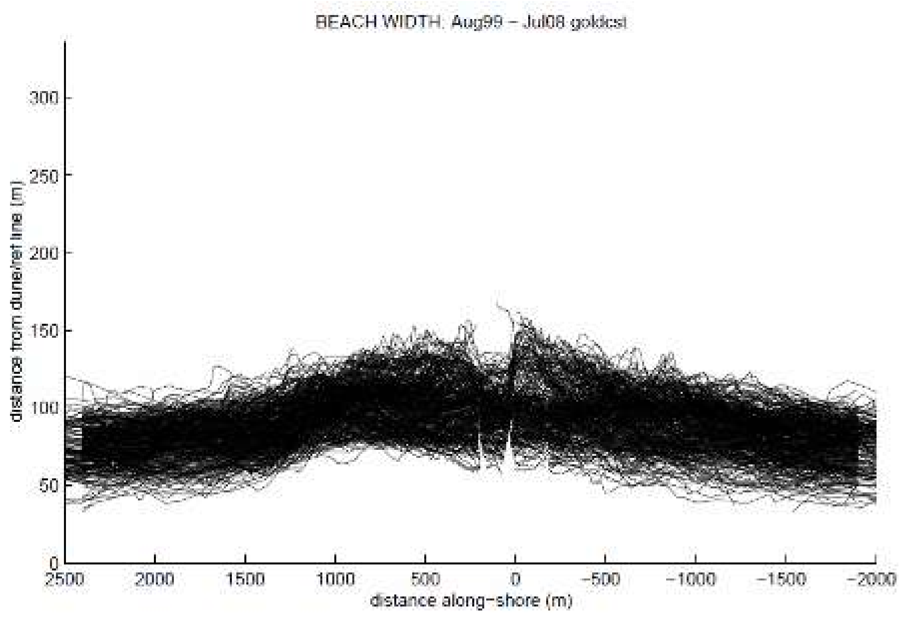


Figure 8. Beach widths for February 08 to July 08 (top panel) and for the period since the beginning of records (bottom panel). The reef is at 1000 m in this coordinate system. The beach is about 30 m wider immediately south of the reef.

Gold Coast City Council Perspective

The Gold Coast City Council's perspective reflects their satisfaction with the project. The technical engineering expert from the Council, Mr John McGrath provided the following summary of the beach changes at Narrowneck in late 2008:

- *Prior to reef construction, the Gold Coast beaches had been nourished on average every ten years since the 1970's. The last nourishment was done in 1987 (prior to 1999 project).*

- *The average rate of beach recession was ~5 meters per year prior to the reef project. (Current rates are -1.5 to -3.6 according to WRL 2008). The current reduced beach recession is caused by a combination of over nourishment and reef stabilization.*

- *The beach in the lee of the reef was purposely over-nourished in 1999-2000 (more so than the other sections of the project) with the understanding that the erosion rates would be higher at that location as the beach system moved towards dynamic equilibrium. In other words were higher erosion rates expected behind the reef and they expect that to continue until a dynamic equilibrium had been achieved.*

- *The south reach experienced accretion for the first 6 years as the salient moved towards equilibrium (WRL 2008 Table 7.1.).*

- *Now that the south reach has achieved relative equilibrium the excess sediment is moving northward resulting in the slightly erosional trend of the last two years (-1.5m/yr).*

- *The erosion trend is expected to equalize along the project shoreline once the entire system has reached equilibrium.*

- *The reef has significantly stabilized the nourishment project and reduced the total rate of beach recession rate along the entire project.*

- *It is not anticipated that any nourishment projects will be required in the area until 2030. In other words, the reef has extended the re-nourishment cycle well beyond the 10 year cycle that was experienced before the reef."*

“The reef has significantly stabilized the nourishment project and reduced the total rate of beach recession rate along the entire project.”

John McGrath, Gold Coast City Engineer

Discussion

The Consultant's Brief issued by the Gold Coast City Council at the time of reef design asked that 80% of all sediment coming up the coast should pass by the reef. Thus, the goal was to design a leaky system.

There is no doubt that the reef is widening the beach and slowing erosion, strictly in accordance with the design requirements. The reef was designed to widen the beach at the hotspot at Narrowneck, which it has done well. Interestingly, the shape of the salient is similar to the laboratory predictions when the reef was first signed off. The accumulation to the south of the reef was similarly predicted by the numerical modelling. The total accumulation is less than expected due to the fact that the constructed reef is 1-7 m deeper than designed.

This single reef, which was designed to leak sand to the north, cannot control all sediment movement and erosion along the entire system of Surfers Paradise beaches. In the long term, the salient changes the beach orientation south of the reef and thereby reduces sand losses. Consequently, re-nourishment requirements along Surfers Paradise beaches have been substantially reduced by the reef.

One of the key benefits of submerged reef technology is that designs can be changed to suit local requirements by allowing a required amount of wave energy to pass over the reef and by training the waves onto pre-selected orientations to create a salient and reduce longshore drift respectively.

Modelling

The physical and mathematical models were in good agreement when the reef was approved for construction in the late 90’s. The 10-year anniversary assessment confirms that the modelling done before construction has been proven correct.

The mathematical models of ASR Ltd have been calibrated and confirmed many times. Recently, the same models were used to simulate the conditions at the Mt Maunganui Reef in New Zealand. Once again, the model was able to simulate the growth and changes which occurred in the measured sand bars around that reef. The results were published after peer review in the esteemed scientific journal “Shore and Beach”.

Black, K. and Mead, S. 2008. Sand bank responses to a multi-purpose reef on an exposed sandy coast. Shore and Beach.

Other examples of the successful prediction capability of the models have been published in quality scientific journals. One example involved Dr Ranasinge who has been outspoken in relation to reefs in New South Wales, Australia.

Ranasinge, R., Symonds, G., Black, K. and Holman, R. (2004) Morphodynamics of intermediate beaches: a video imaging and numerical modelling study. Coastal Engineering. 51(7): 629-655.

Submerged structures

In the esteemed journal "Coastal Engineering", Ranansinghe and Turner noted that 7 out of 10 submerged structures have been a failure as a coastal protection device. Very positively, Narrowneck Reef was classified by them as one of the 3 that was successfully accreting.

Ranasinghe, R.I. and Turner, I. (2006) Shoreline response to submerged structures: a review. Coastal Engineering 53: 65-79.

Referring to the Ranasinghe and Turner assessment, the following quote from Black and Mead is extracted from their "Shore and Beach" paper:

Ranasinghe and Turner (2006) concluded that 70% of submerged structures constructed for beach protection to date have resulted in net erosion of the shoreline in their lee. However, nearly all of the "reefs" considered by Ranasinghe and Turner (2006) are more like narrow submerged breakwater walls constructed over long lengths of the beach (e.g. Lido di Ostia, Italy (Tomassicchio, 1996a,b); Vero Beach, Florida (Stauble et al., 2000), while others have groynes joining the reef to the shore and the structure is more like a "box" (e.g. Lido di Dante, Italy (Lamberti and Mancinelli, 1996); Delaware Bay, USA (Douglass and Weggel, 1987; Niigata, Japan (Funakoshi et al. 1994)).

Thus, while all submerged structures can be considered to be "reefs", 9 of the 10 considered by Ranasinghe and Turner (2006) and Ranasinghe et al. (2006) are actually very simple shore-parallel submerged continuous or segmented breakwaters with or without linking submerged groynes. The multi-purpose Narrowneck Reef designed by Black and Mead (2001a) for Australia's Gold Coast was in the successful accreting 30% and was the only structure with complex form.

Just because they are offshore and underwater, not all offshore structures can be considered to be multi-purpose artificial soft reefs.

Simple narrow-crested offshore structures are unlikely to stop erosion.

Reefs of more complex form as designed by ASR have been shown to be successful.

Hindsight

When balancing the coastal protection and surfing, there were some very strict and precise requirements for the Narrowneck Reef. It is important to go back and see if the modelling was correct. The 10-year anniversary of the reef construction is a good time to do that.

Dr Black says, "*I was asked once if I would have built the same reef now. In hindsight, the right arm, rather than two arms, may have been sufficient to protect the coast using ASR's wave rotation system to oppose the longshore currents.*

Especially noting the problems confronted by the engineers with accurate construction, I may have done just one arm to allow more budget to be put into better completing the all-important right arm. However, I am very satisfied that the coastal protection outcomes are so close to the design expectations".

ASR has completed the R&D needed to overcome the construction problems confronted by the Gold Coast engineers, and we now have working examples of these methods in New Zealand and Britain.

Surfing

"The reef provides improved surfing conditions for a wide range of surf craft. Records show that waves break on the reef for wave heights over 0.7 - 2.0m, depending on the tide. This is an average of ~50% of the time. While waves tend to be more spilling than plunging in average conditions, particularly at higher tides, larger swells, lower tides and offshore winds have the potential to produce hollow, plunging breakers.

Bar formations around the salient also provide favourable conditions on the shore-break and the reef break often merges with the adjacent bar break to extend ride lengths. GPS data shows that recorded rides averaged 150-200m, but reached up to 260-270m on both the north and south reefs. Ride times averaged 30 seconds, but reached up to 60 seconds."

Professor Roger Tomlinson
International Conference on Coastal Engineering, Hamburg, 2008.