CHAPTER 82

HEADLAND DEFENSE OF COASTS

Richard Silvester, University of Western Australia
Nedlands, 6009, W.A.

ABSTRACT

Crenulate shaped bays are ubiquitous and constitute the largest proportion of coastline length. The characteristics of stable bays (i.e., no littoral drift) are known, so that realistic encroachment limits can be defined. Allowances for long term changes in direction of persistent swell and annual attack from multidirectional storm waves may have to be made. The exposure of a rock outcrop during an erosive sequence will create a new fixed point on the coast and hence a new bayed system. An existing non-stable bay can be prevented from indenting to its equilibrium shape by the construction of one or more fixed points around its periphery. Research should be conducted to minimise the cost of headlands which might start off as offshore breakwaters, even mobile units.

INTRODUCTION

Observance at the shoreline itself, or better still hydrographic charts of same, will immediately highlight the predominance of bays as coastal features. These sandy stretches are strung between headlands, with outlines that are produced by the incoming persistent waves (generally the swell). The presence of such features, together with other obvious indicators, has been used by the author in 1962 to determine net-sediment movement around the coastlines of the world (1) (2).

A worthwhile analogy appears to be clothes hanging loosely on a clothesline. When the wind arrives normal to the wire, the edges of the fabric assume a symmetric cartenary between the pegged points. No matter what the spacing some curvature will occur. The degree of indentation of the cartenary is dictated by the length of fabric caught between the pegs, as illustrated in Figure 1A. In coastal terms the variable is the volume of sand available to construct the beach. Sometimes when there is a surfeit of sand in a batch supply a spit may be formed which encloses a body of water in the form of a lake or lagoon. This is exemplified in Figure 2A, a feature which exists along many sea margins.

There is no equivalent to the sand spit in the cloth hanging analogy but it can be pursued with advantage a little further. When the wind blows obliquely to the peg line the cartenaries are skewed as depicted in Figure 1B. A large section of the cloth edge is pulled normal to the wind vector, causing the remainder to be stressed into a curve. The indentation as before is dependent upon the tautness of the original pegging. Again the analogy can breakdown, by nature constructing spits to form the crenulate shape that has the characteristics of an equilibrium bay. (See Figure 2B)

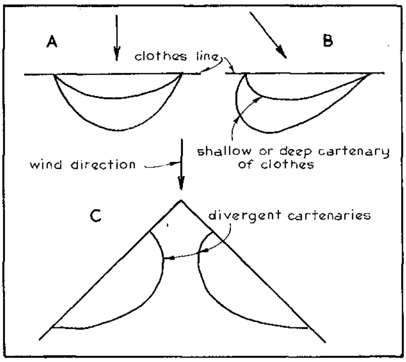
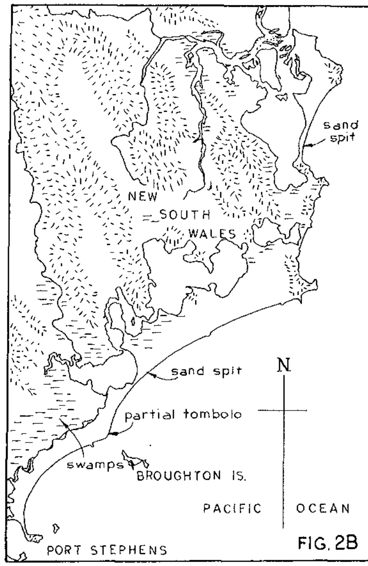


Fig.1. Analogy for crenulate shaped bays of clothes pegged to a line.



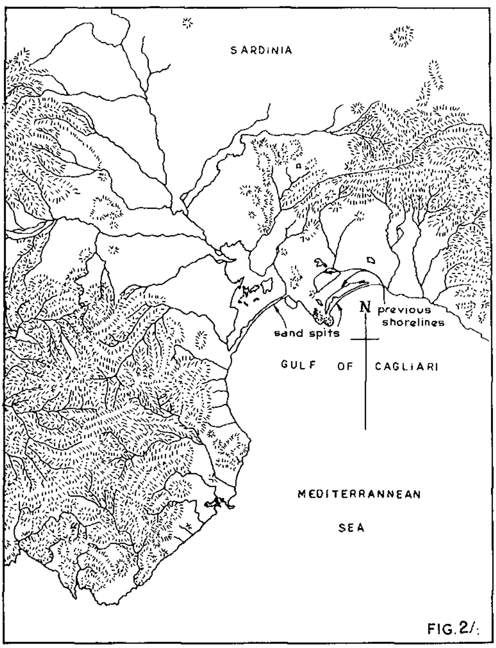


Fig.2 Sand spits formed between headlands enclosing bodies of water. A: with normal wave approach B: with oblique wave approach.

Where a clothesline changes direction, say at right angles as in Figure 1C, the fabrics will be skewed differing amounts and perhaps in differing directions by a given wind. The author has noted this drastic change in two adjacent bays at Point Reyes, California (3) but a further example is illustrated in Figure 3.

The forcing function in the clothesline case is the wind, which produces immediate results on the clothes. The sculpturing strength for shorelines also originates from the wind but is effective per medium of the waves it generates, both locally and far away. As noted by the author elsewhere (4) the generation of waves in the various oceans is reasonably repetitive and hence natural bays exhibit the integrated influence of swell over decades and centuries.

BAY FEATURES

The characteristic of crenulate shaped bays produced by waves arriving obliquely to the alignment of two consecutive headlands has been detailed already (4) (5) but should be recapitulated here. As seen in Figure 4, such a bay comprises a tangential downcoast section and a curved upcoast zone. The resultant shoreline shape is caused by both wave diffraction and refraction (6) in the lee of the upcoast headland. The degree of indentation (termed a in Figure 4) is dictated by a number of variables, namely, the obliquity of the predominant waves (β) to the headland alignment the spacing (b) between the headlands and the supply conditions of sand from upcoast or from river mouths within the bay.

As illustrated in Figure 4 the angle β between the incoming wave crests and the headland alignment is similar to the angle between the tangential coastline and this alignment. This is easier to measure because wave approach from deep water to some representative depth along the seaward extremity of the bay is difficult to determine, even if the predominant 12 second swell is adopted (7) for this purpose. It is the value of β at the fully stable condition that should be used in relationships to be discussed later. However, at the downcoast extremity of the tangent zone this angle is exhibited even in a bay still eroding to its final stable shape. Progressive indentation is achieved by the lengthening of this beach line angled β to the headland alignment.

The spacing (b), within which the bay can form, is related to (a) and (β) by a graph as in Figure 5. This has been derived (6) from model tests and measurements made of natural bays known to be in equilibrium, from their location on a coast and obvious lack of sediment supply. Although the ratio a/b tends to zero as β decreases there will always be a little indentation even with normally approaching swell. This is because a net longshore drift of zero may be made up of an annual drift in each direction of similar magnitude. The other limit of 50^0 for waves arriving parallel to the headland alignment is not likely ever to be realised because of prior refraction across the continental shelf. It could only result in a lake situation where the predominant waves are locally generated and they are of short period. In this case the curved shoreline will be almost circular in character due to diffraction dictating the crest curvature in this shadow zone.

It has been shown (4) (8) that the curved portion of the coast generally follows a logarithmic spiral, the details of which are illustrated in Figure 6. The ratio of successive radii (R_2/R_1) results from the angle (θ)

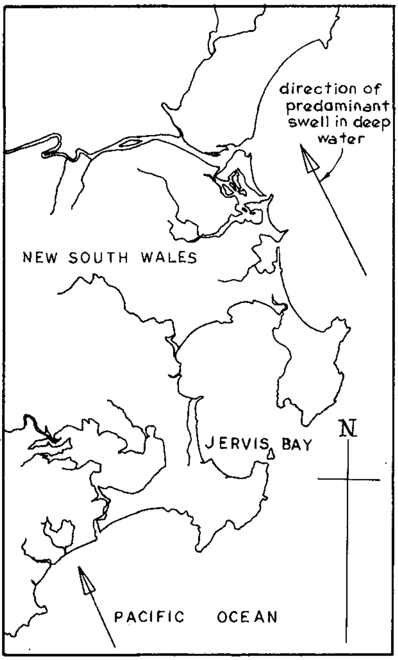


Fig.3. Variable shape and orientation of crenulate shaped bays for a specific approach direction of predominant swells in deep water.

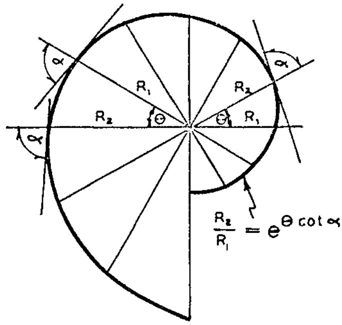


Fig.6. Definition sketch of logarithmic spiral.

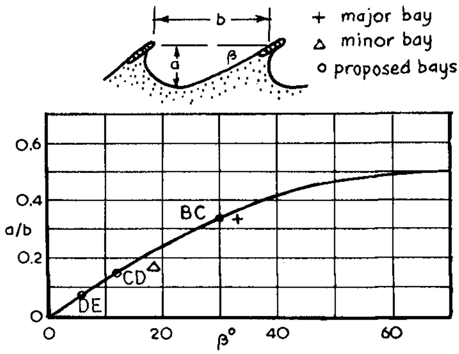


Fig.5. Indentation ratio a/b versus wave approach angle β.

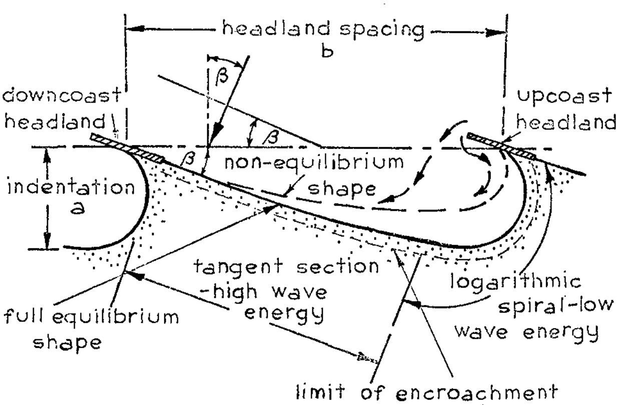


Fig.4 Definition sketch of crenulate shaped bay.

between them and the constant angle (α) between the radius and the tangent. The degree of curvature is given by α whence a logarithmic spiral can be drawn once θ has been chosen. A series of such sprials have been provided by the author (4). It should be noted that the size of the bay or of the plan being examined is of little consequence as the same value of α or R_2/R_1 will result, only a different section of the curve will be utilised. For equilibrium conditions the curve relating β to α is given in Figure 7. Whilst a bay is receeding to this stable shape, values of α vary in a consistent manner with angle β as shown elsewhere (3) (4).

When in equilibrium a bay suffers no littoral drift since the predominant waves are arriving normal to the beach at all points around the periphery. This does not preclude the possibility of batches of sediment arriving sporadically from upcoast. This will mainly be transmitted across the bay to the intersection of the tangent curved zones as proven by tracer tests in Australia (9). Because of the almost normal approach of the waves the longshore component of their energy is slight, so requiring the offshore zone to accrete to the stage where the waves can handle the load to be transmitted.

The offshore shoaling lessens the demand for material to construct the bar during storm sequences. This reduces the berm width which is indicative of the active beach which goes to sea and back again in the course of each two or three years. The good protection so afforded makes little or no demand on the sand dunes being constructed by wind blown sand which therefore grow to much greater height along the tangential section of the bay than along the curved zone.

USE OF CHARACTERISTICS

Whilst the evaluation of a/b and α for a measured β may indicate a bay to be in a non-stable condition, this is not the case if the present sand supply to the bay equals the rate of removal by the waves. If an embayment is not fully receded the plotted point will fall below the curve in Figure 5 and above the curve in Figure 7. By using the a/b and α values on the curves an equilibrium shape can be drawn for this bay which indicates the limit of erosion if and when all sediment supply is stopped. It is on this basis that more realistic encroachment lines may be determined than setting back fixed distances along the whole periphery of a bay.

When so determining building lines, due allowance should be made for annual give-and-take by storm waves. These waves can arrive from almost any seaward direction. The erosive effects of arrival from three major obliquities are illustrated in Figure 8, where the width of lost beach varies according to this angle. The presentation does not take into account the likely offshore slope variation around the bay. The tangential stretch should have a milder bed slope than the curved zone, which infers that less material is demanded to construct the protective offshore bar during storm sequences.

A point to note about Figure 8 is that a rip current will form in the vicinity of the greatest indentation. This means that longshore drift brought from both directions towards this zone will quickly construct a shoal and the seaward current will also aid the dissipation of storm waves.

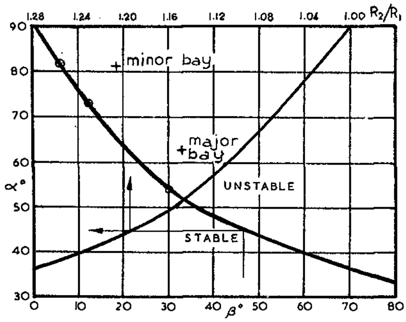


Fig.7. Logarithmic spiral constants (α and $R_2/R.$) versus wave approach angle β.

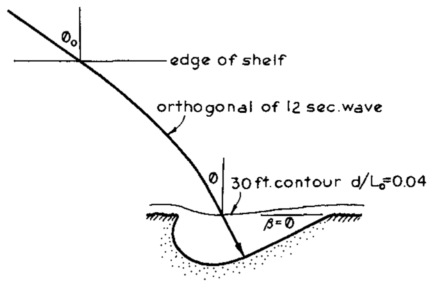
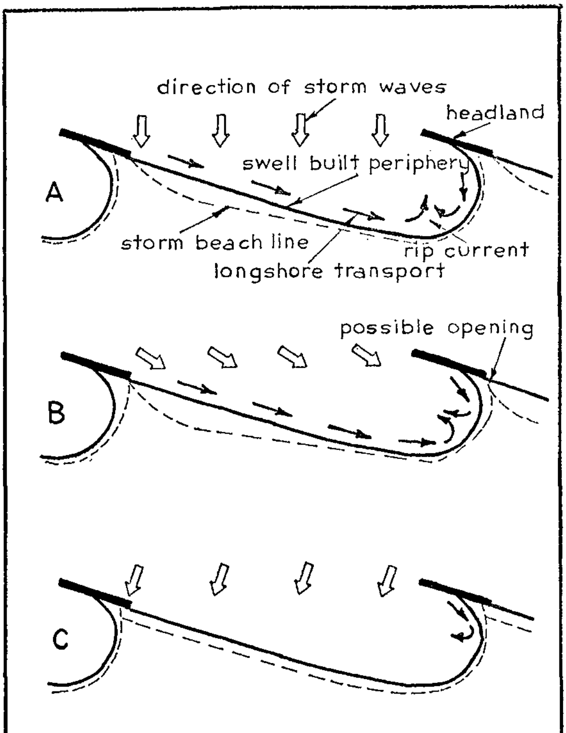


Fig.9. Typical wave orthogonal across the continental shelf.



Influence on crenulate shaped bay by storm waves arriving from different directions.

Fig.8.

This most landward region is therefore better protected than other sections of coast closer to the headlands.

In Figure 4 it is seen that for a non-stable bay the greatest future retreat of the shoreline will take place near the intersection of the curved and tangential zones. But even the whole curved section must erode to accomodate enlargement of the bay. The portion least affected by future progression to an equilibrium shape will be the tangential strip adjacent to the downcoast headland. This reaches its final alignment long before the remainder of the bay. Only a drastic change in the long-term approach angle of the swell or predominant wave system could cause erosion of any significance in this region. With this observation must be considered the added volume of sand offshore due to the milder bed slope, as already discussed.

It is worth working an example on the deep-water changes in direction necessary to effect a given change in approach angle β to the headland alignment. Figure 9 shows a wave orthogonal traversing the continental shelf to arrive at the line joining the headlands at its deepest point. If a wave period of 12 seconds is assumed (7) and the operative depth as 30 ft., the relevant $d/L_o = 0.04$ as illustrated. Table I shows that for increments of 5^o in deepwater obliquity (ϕ_o) the variation in $\phi = \beta$ at $d/L_o = 0.04$ is around 2^o. If a β change of 5^o were considered significant, this implies a ϕ_o variation of 12.5^o

TABLE I - Variations in ϕ at $d/L_o = 0.04$ for 5^o increments in ϕ_o at $d/L_o = 0.5$

ϕ_o^o	20		25		30		35		40		45		50
ϕ^o	9.6		11.7		14.0		16.		18.		19.9		21.7
$\Delta\phi^o$		2.1		2.3		2.1		1.9		1.9		1.8	

If the storm source for this persistent swell were 1500 nautical miles distant this implies a lateral change in position of 300 NMs or 6^o latitude. Whilst seasonal changes of this order can occur in storm location, it would take a dramatic change in climatic pattern to effect such a shift in the long term. It is difficult to verify such changes by swell observation and any 7 to 10 year cycle of bay erosion due to this source would possibly be overshadowed by more local changes perpetuated by man.

COASTAL DEFENSE

It has been illustrated above that there is a limit to which a bay will erode when all sources of sand are intercepted by whatever means, natural or man-made. If during the course of this recession a rock outcrop is exposed it will become a new fixed point in the coastal system. Such a case is exhibited in Figure 10 which is a bay on the border of South and Western Australia, where a predominant South West swell is known to exist. It is seen that the reef in the curved section of the bay has prevented the removal of material in its vicinity. It has, in fact, created two bays where one would have existed otherwise. Take the reef away and the shoreline would receed to the line indicated in Figure 11 as "major bay profile". This figure is a tracing of Figure 10, in which reefs have been identified by breaking waves.

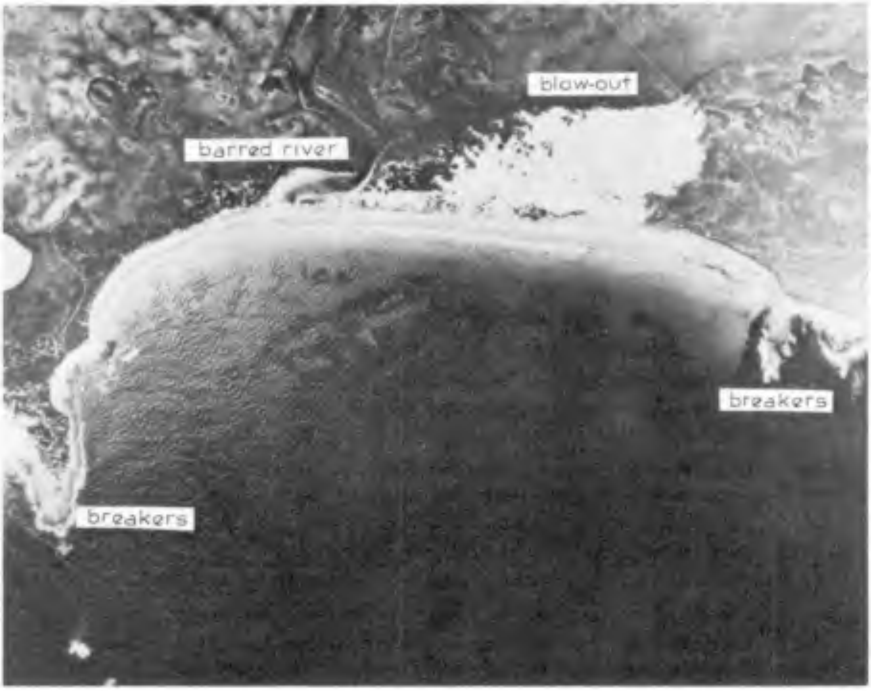


Fig.10. Natural bay showing the influence of intermediate reef serving as a headland.

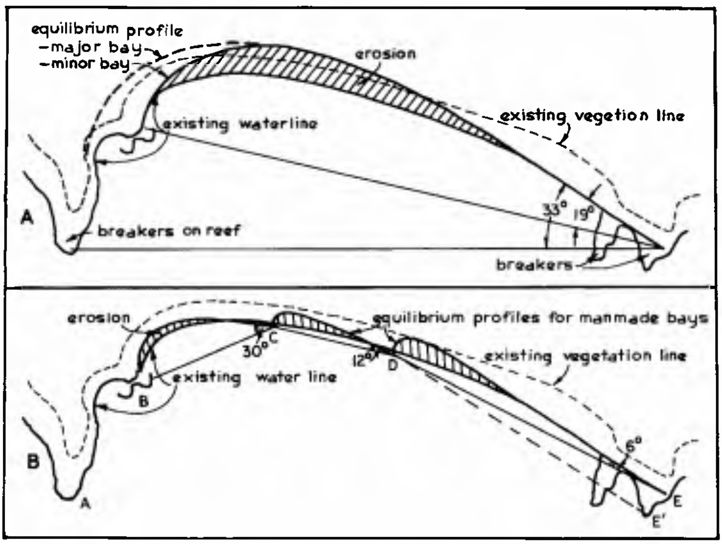


Fig.11. Tracing of features in Fig.10. showing characteristics A: of major and minor bays and B: of proposed bays from headland construction.

It can be gathered from Figures 5 and 7 that this major bay or its larger minor bay have not reached equilibrium due to the deviation of their points from the curves. The relevant values for stability produce the two logarithmic spiral curves shown in Figure 11A. The possible retreat from the present water line indicates an erosion area which is hatched. It is seen that this encompasses even the existing vegetation line which is where the primary dune is located. Whilst the natural reef in the figure is at present retaining quite a modest piece of real estate, it will have saved substantially more as full equilibrium is reached.

There is a lesson to be learnt from this example, namely that reefs or headlands occurring naturally or synthetically within a large eroding bay can prevent its recession to an equilibrium limit. To illustrate this point two further fixed points have been suggested at C and D in Figure 11B. They have been located just seaward of the present waterline. The appropriate headland alignment lines have been drawn and the approach angle β determined from the normal orthogonal to the equilibrium coastline in that region. Hence for bay BC with $\beta = 30^{\circ}$ a limiting indentation ratio of 0.33 was used (see Figure 5). In bay CD for $\beta = 12^{\circ}$ the a/b value is 0.15, whilst accepting E as the continued downcoast fixed pointthe angle $\beta = 6^{\circ}$ for bay DE results in a/b = 0.08.

It can be observed that with these headlands set close to the present shoreline progressive erosion to an equilibrium state entails some loss of the present beach zone. However it is much less than would occur under natural conditions, as illustrated by the zone of hatching in Figure 11A. If no beach loss between DE were to be permitted the better solution would be to construct a headland at E. The resultant shoreline is shown dotted. This probably implies a reclamation since the volume of material now available from bays BC and CD for natural accretion appears insufficient. Of course a headland or groyne in this case, at E can be constructed to any point between E and E^1 or may be progressively built to catch any sediment that is still passing through the bay system. In so intercepting this drift the influence on the next downcoast bay must be taken into account.

If the suggested erosion within bays BC and CD were deemed undesirable the new headlands at C and D could be located further seaward. This could be carried out to provide equal erosion and accretion areas or even net gain in beach volume (10). This might demand more sand than is available from external sources, in which case supply from the adjoining dunes may be necessary.

This proposal of utilising sand dunes in a stabilization programme is submitted as a squeak from the proverbial mouse who is addressing the environmental lions. When ever such a valuable piece of real estate is wanted for some commercial or even recreational use there is a tumult of opposition from lay persons, and even some engineers, to retain the dunes for safety of the coast. It has already been noted that where the bay is most stable, along the tangential section, the dunes are highest. This is one of nature's anomolies, that she has not engineered the coast efficiently.

The retention of dunes for some future unknown erosion event is equivalent to using factors of safety. The point to be made is that as progress is made in stabilizing coasts by natural and scientific means, such as through adding headlands, there is less need for such factors of ignorance. The necessary reserve of sand for present and future storm activity can be stored in the form of new beach area where in the meantime it is useful. This is equivalent to commercial enterprisees keeping their reserve funds in use rather than stacking them in a vault for the rainy day. As long as they are liquid enough to serve the day to day fluctuations in demand their employment in commercial activities is to the benefit of all.

In the process of levelling sand dunes in order to construct wider beach zones the problem of wind blown sand must be overcome. This calls for a big "think tank" involving coastal engineers, geomorphologists, soil scientists and botanists. *The costs of vegetating these areas, plus the investment in the associated headlands, must be balanced against the long term gain in land area and the greater protection of facilities through a stable coastline. To this must be added the value of previously duned area which is now put to use for residential, commercial or recreational purposes. Another saving is the continual cost in trying to maintain these massifs of sand in their natural state.*

The structures involved in this stabilization programme are necessarily large and may not be undertaken simultaneously. This situation calls for an overall plan which is then implemented in stages. For this purpose it is wise to start construction at the downcoast end of an eroding coast in order quickly to retain sediment within the system to be treated. This is assuming that further downcoast the lack of sand nourishment will have no political or financial repercussions.

The lengths of coast involved in a headland-control system will generally be greater than where groynes or seawalls are attempted. This may call for co-operation between a number of local councils and even between adjacent State Legislatures. Such sharing of costs and profits has been forthcoming for rivers and other waterways and hence its extension to the seacoast should not prove too difficult. In this regard it is to be remembered that littoral drift is a "river of sand" extending hundreds or even thousands of miles, over widths varying from a few hundred yards to many miles. This inter-dependence applies equaly to pollution as it does to sediment supply.

If a long enough section of shoreline can be treated at once, or the downcoast zones can be discarded, the ultimate goal should be to stop all littoral drift, at least close to the coast if not further out on the continental shelf. The bulk of coastal engineering problems emanate from longshore sediment transport. It causes erosion in one area, siltation in another, and during transmission from the former to the latter constructs bars across river and harbour mouths or blocks dredged channels. Even with stabilized bays, with no net drift, there will be annual longshore and lateral movement to be controlled, but this will be predictable soon after the major equilibrium shape has evolved.

HEADLANDS

Offshore breakwaters have been advocated by the writer as a starting point for headlands. These can cause accretion on their lee side without becoming attached to the mainland. This occurs frequently in nature as illustrated in Figures 2B and 12, which is a sandy protuberance known as Quinns Rock on the Western Australian coast near Perth. The offshore reef is a half mile in longshore dimension and a mile from the mainland. The displacement of the apex northwards from the centre line of the reef is due to the persistent swell arriving from the Southwest. The diffraction of such waves is exhibited in the figure. Inspite of the lack of local controls at the beach itself such triangular features are exceedingly stable, since they have been produced and are maintained by a wave system that alters very little decade after decade.

Man-made islands or offshore breakwaters are more likely to be closer to shore and smaller in dimension. If a sand spit or tombolo is to be formed, which then acts like a groyne and subsequently as a headland, the further offshore the structure the larger should be its longshore length (11). This seaward location implies deeper water and hence massive mounds of rock. This tendency can cause the whole proposition to become uneconomical, especially when considered in concert with a mammoth reclamation task to prevent downcoast erosion. The prizes of area won from the sea or saved from the sea are gained long after the investment has been made. The larger the outlay the more convincing must be the argument that the rewards are actually obtainable.

Because of the expensive nature of marine structures, especially those for dissipating wave energy, much thought must be given to minimizing their cost. This hydrodynamic requirement only demands reef-type structures which trigger the waves, particularly the persistent swell. The sporadic storm waves will readily break over such a shoal. Any contact with the mainland through a tombolo may quickly be broken in these circumstances, but will just as quickly be remade when subsequent swell arrives. This low profile structure not only saves in volume of material but is also more aesthetic in that a synthetic mound is not imposed on the sea panorama.

But even a mound rising to a foot or two below low water can become expensive if set initially in a deeper zone, where its length is around one wave length in order for a tombolo to form. One solution to this problem is to create a horizontal platform which will break the predominant waves. If such a submerged platform breakwater were buoyant it could be relatively mobile. After accreting sand at a point on the coast, and perhaps upcoast from it, the structure could be towed seawards to continue the action (10). When a suitably indented bay were formed a rubble mound headland could be constructed on the beach. This need not be of a high profile, only sufficient to be at mean sea level after subsidence has occurred. The mobile platform could then be hauled to a new site.

Research has been carried out for some years at the University of Western Australia on submerged platform breakwaters (12). This concept is more economical than the surface floating structure because to attenuate the same swell wave it need be only a fraction of the width. An example will illustrate this: To reduce the energy of a 10 second wave in 15 ft., depth of water a floating breakwater must be at least one wave length or 105 ft., in width. A similar platform, either impervious or perforated, moored at a level 5 ft., below the water surface will require a width of only 30ft., since it need be only half the length of this 10 second wave in 5 ft., of water. The submerged platform can be slung from floats or if buoyant held down with weights. Research is being aimed at minimizing the mooring forces and coping with stresses imposed by maximum waves at the site.

In respect to the final wave tripper to be built on the accreted beach apex, it would appear that the cheapest material to use is sand at the site. The cartage of rubble stone is costly at any time, but especially when roads must be provided in remote locations to the breakwater site. To provide vehicular access the structure must be constructed to a meter or two above high water mark and be of such a width to carry such large trucks. The seaward and landward forces as well as the top must be protected by armour units of such a weight as to withstand the fiercest storm waves. A degree of interlocking, plus dissipation of wave energy within large voids, are desirable characteristics sought when designing concrete units for this purpose.

A more economical approach has been reported in the literature for groyne and seawall construction of sand confined in a flexible sheath. Plain sand or cemented material has been employed in this large scale "sand-bag" approach. Perforated polyethylene tubes are available up to about 7 ft., in diameter. Sand is flushed in whilst the water percolates through the skin. Use of these sausages singly or in heaps as headlands or reefs provides a new outlook for coastal engineers.

When cement additives are used the sausages become a solid rock mass immediately. This obviates the problem of splitting or cutting of the polymer during construction, or later through human vandalism. Research is needed into the most effective mixtures to achieve the minimum strength required in such massifs. Lime may be found a better proposition than cement in this saline situation. Means of pumping beach sand into tubes whilst adding chemicals at a fixed rate needs investigation.

There is little question that coastal defense structures need a new outlook since conservatism has proved very costly in the decades gone by.

REFERENCES

1. Silvester R. "Sediment movement around the coastlines of the world" Proc. Conf. Inst. Civil Engrs. (London) 1962, 289-315.

2. Silvester R. "Sediment movement - long term net movement" Encyclopaedia of Earth Sciences, Reinhold Publ. Corp. (Ed. R.W. Fairbridge) 1968, 985-988.

3. Silvester R. "Development of crenulate shaped bays to equilibrium " Proc. ASCE 96 (WW2), 1970, 275-287.

4. Silvester R. Coastal Engineering Vol II Elsevier Publ. Co. 1974.

5. Silvester R. and S.K. Ho "Use of Crenulate shaped bays to stabilize coasts" Proc. 13th Conf. Coastal Eng. 2, 1972,1347-1365.

6. Ho. S.K. "Crenulate shaped bays" M. Eng. Thesis No. 346. Asian Inst. Tech., Bangkok, 1971

7. Silvester R. "Design waves for littoral drift models" Proc. ASCE 89(WW3), 1963, 37-47.

8. Yasso W.E. "Plan geometry of headland - bay beaches" J. Geol. 73, 1965, 702-714.

9. Hughs E.P.C. "The investigation and design for Portland Harbour, Victoria" J. Instn. Engrs. Aust. 29, 1957,55-68.

10. Silvester R. "Stabilization of sedimentary coastlines" Nature (London) 188, 1960 467-469.

11. Silvester R. "Offshore breakwaters" Trans. ASCE 124, 1959, 356-365.

12. Silvester R. "Submerged platform breakwaters" Proc. 1st Aust. Conf. Coastal Eng., 1973, 182-189.

Fig.12. Coastal protuberance crested by an offshore reef at Quinns Rock, Western Australia.