A NEW LOOK AT BEACH EROSION CONTROL

By *Richard* SILVESTER*

ABSTRACT

Many methods used previously to reduce or prevent erosion have not worked effectively. It is now necessary, due to rising costs of construction, to examine old methods and see if Nature has indicated some direction in which to go. Limitations of groins, seawalls and beach reclamation are described. The most effective natural method of controlling beach erosion by the formation of an offshore bar is described. The need for normal return of this material to the beach is met by the zeta shaped bays sculptured between headlands by persistent swell waves. Man can copy Nature by installing offshore breakwaters in order to form stable bays along an eroding coast. The indentation of these is limited and is predictable from the obliquity of the waves or the angle between the downcoast shoreline and the headland alignment. This method has been used successfully in Singapore in spite of the extreme obliquity of the incident swell.

INTRODUCTION

There have been many criticisms in the technical literature of coastal structures that have not worked satisfactorily. It is common observation that groynes have not prevented erosion and that seawalls have promoted worse erosion. The only progress made in recent years is the construction equipment for building bigger and more impressive groins and seawalls, often on top of the ruins of the previous structures. However, in describing these new installations in articles, no explanation is given for the failure of the previous construction nor any reason for the new feature working any better.

A more recent procedure to overcome erosion is spread sand along it or to reclaim the beach by dredging sand from nearby rivers or from offshore. There are references to large sums of money being spent in this manner, in the order of US$1.0m at one time and generally similar amounts 2 years later. It is normally accepted that 30~50% will be lost in the first year, with a continual recharge of 20% required. Bigger dredgers are being constructed that can operate in the open sea. To keep them busy beach renourishment is a fast developing source of income.

DISADVANTAGES OF THESE METHODS

The probable chronological order of coastal defense structures was seawalls, groins and reclamation. The first obvious solution was to fight Nature by breaking waves or reflecting them seawards. The second recognised the need to store sand for Nature to work on. The third is a paliative to natural forces by giving more material to transmit downcoast.

Seawalls

In 1956 the author was told by an eminent oceanographer that seawalls were the answer to coast erosion because the reflected waves were sent out to sea, never to be seen again. Little

*Department of Civil Engineering, The University of Western Australia. Visiting Research Fellow (1979), Disaster Prevention Research Institute, Kyoto University.

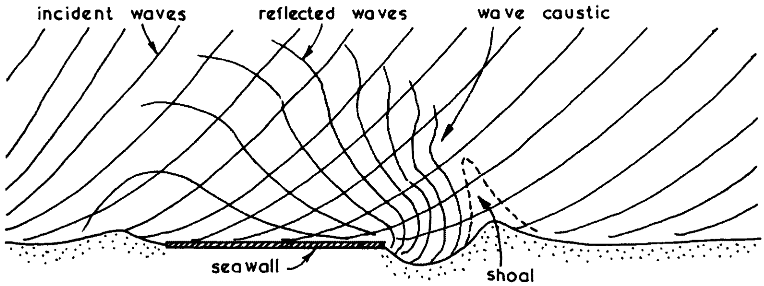

Fig. 1. Wave action and resultant scour near a seawall.

did he realize, as many engineers today with him, that in propagating obliquely seawards these waves apply a second batch of energy to the seabed in the vicinity of the seawall[1]. The incident and reflected waves are not just two progressive waves acting on the sedimentary bed, but they interact to form a short-crested system with very complex water-particle motions. Much macro-turbulence is generated which accelerates downcoast transport of sediment.

Consider a promenade wall constructed on a beach as in Fig. 1. The incident waves are refracted before they strike the wall at an angle. The reflected waves refract as they pass seawards, being concentrated some distance offshore in a wave caustic. Diamond shaped or short-crested waves form whose water particle motions are double the speed for each train singly and include, on some alignments parallel to the wall, vortex type action. The result is swift removal of sediment in front of the wall end even downcoast of it, where the diffracting reflected walls continue the short-crested system. As illustrated in Fig. 1 erosion takes place downcoast of the wall but is complemented by a shoal where incident waves alone cannot cope with the excessive sand load. The sight of a degraded shoreline between the wall and the possible protuberance a few hundred metres alongshore prompts an unwary engineer to continue the wall to this "stable" feature. This expands the problem and deflects the erosion downcoast for the same procedure to be followed.

Groynes

Groynes are generally built at right angles to the shore, out to the limit of the breaking waves. The reason is to intercept the littoral drift within the surf zone and hence construct a beach to the tip of the groyne. Until recently it was not fully appreciated that significant sand movement occurs beyond the breaker line. There the waves are more angled to the shore than when breaking and mass transport of water due to wave propagation is maximum at the bed where sediment is continually disturbed each wave cycle[2]. Thus, beyond the groyne extremities, bed erosion can continue due to the difference in supply and removal which caused the original problem. Seaward of the groynes the bed will deepen and steepen, so allowing waves to attack at larger angles.

But even the sand accreted between the groins is not permanent, for when storm waves arrive, from many directions, a strong littoral current is generated towards the upcoast groyne (See Fig. 2). This is deflected seawards as a rip current and carries sediment to larger depths. If and when swell returns this material it is displaced further downcoast than if the groynes were

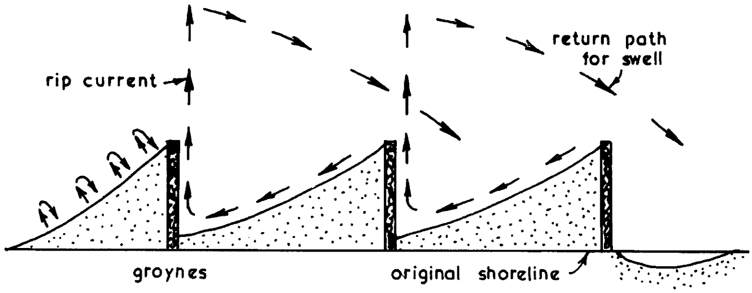

Fig. 2. Path of sediment during storms waves and subsequent swell within a groyne field.

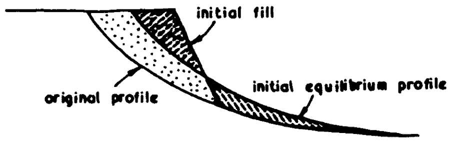

Fig. 3. Sand renourishment perched on natural beach slope.

not present. Thus a field of groynes can promote longshore drift and therefore worsens the problem it was installed to solve.

Renourishment

This consists of dredging sand and by pipeline or other means spreading it in the nearshore zone. The water carrying the material flows away leaving the sand to slump at its angle of repose in a saturated condition. As seen in Fig. 3, this can be much steeper than the natural bed slope so that the new deposite is perched on the original profile. Waves soon construct a new profile which is much the same as the original displaced seawards of it. But the waves are still arriving obliquely and during this unstable condition will quickly move material downcoast.

Summary

To protect an eroding shoreline, of the three existing alternatives seawalls are not worth

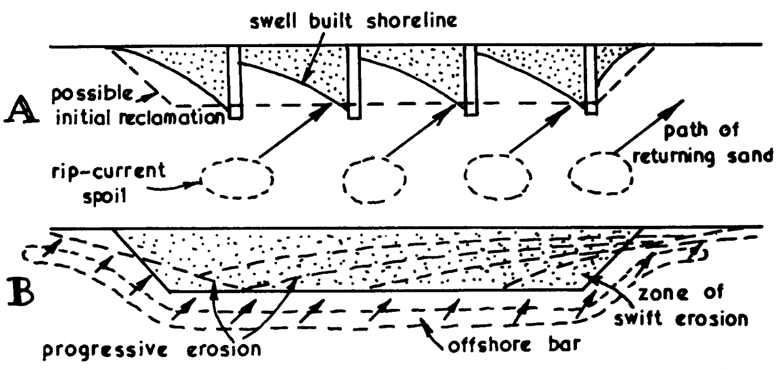

Fig. 4. Developments following A: Renourishment plus groynes, and B: Renourishment alone.

considering, which leaves only groynes and renourishment to be compared[3].

Even if filling is carried out in conjunction with groyne construction, as depicted in Fig. 4, the first storm season will effect its removal offshore and downcoast. During the refilling process by natural means the shoreline downcoast will be badly eroded.

Reclamation over a limited length of beach will have the downcoast extremity quickly removed, since the waves are greatly angled to it. But even whilst the bulk of the reclaimed area is being eroded the water line will be more angled to the persistent swell than the original shoreline, and hence longshore drift is at a greater rate.

Thus, all three solutions of walls, groynes and renourishment are seen to be inefficient and uneconomical. They may serve as temporary measures, much like the pill given by the doctor to relieve pain or hide the symptoms of a real illness. In the present case the disease is too much longshore energy for the load to be carried.

NATURE'S DEFENSE MECHANISM

Two distinct wave conditions exist on the coast, that of swell where waves have spread out after leaving the generation area, and that of storm waves which are still building up when they arrive at the coast[4]. Swell has a small height but long period, whereas storm waves have large height and a great mixture of short and long periods. Consider now their separate effects on a beach.

Swell waves have a strong sweeping action on the seabed which grows as the waves steepen and then break. In the resultant turbulence of the surf zone sand-laden water is swashed up the beach face (See Fig. 5). Because there is reasonable time between each wave the uprush percolates readily through the beach face and berm down to the water table and back to the sea. This causes the backwash to be minimal and unable to carry sediment down the face. The suspended sand is thus stranded on the beach, and hence accretion occurs under swell conditions.

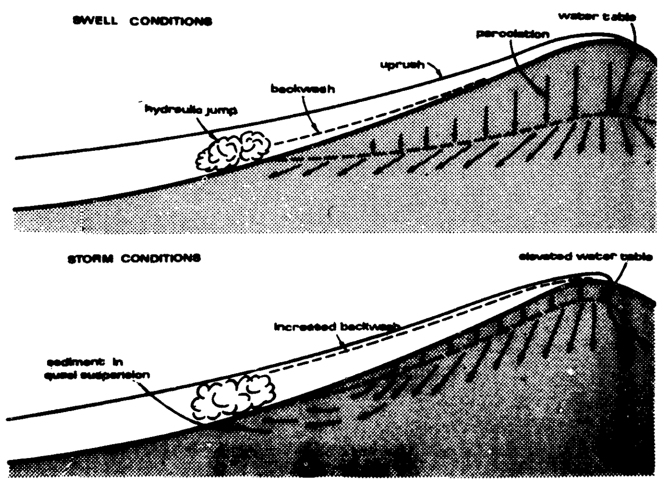

Fig. 5. Water motions at a beach during swell and storm wave conditions.

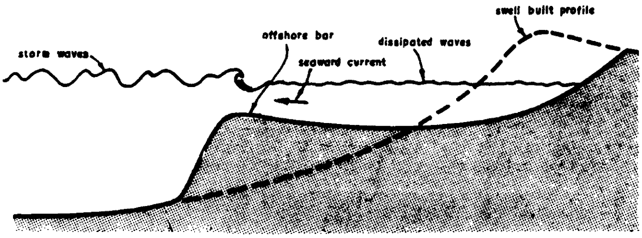

Fig. 6. Formation of an offshore bar during storm conditions.

This continues until the swell cannot sweep any more material into the surf zone due to the increasing slope of the bed.

When storm waves arrive there is a crest almost every second breaking on the beach, which is soon saturated. The water-table becomes coincident with the beach face and the backwash equals the uprush. The hydraulic jump (See Fig. 5) at the waterline also enlarges, occuring in the region where groundwater is flowing upwards in its path to the sea. This "quick-sand" condition aids in the suspension of material and it is little wonder that the beach is eroded well back in a matter of minutes.

The sand-laden water travels seaward beneath the incoming surface current caused by wind stress. As this seaward current slows down in the offshore region its sedimentary load is deposited and forms an offshore bar (See Fig. 6). This continues to grow until the depth over it is sufficiently small to break all incoming storm waves, aided by the outward current from the surf zone water returning to the sea. At this stage of wave dissipation erosion of the beach stops.

Swell following the storm sequence quickly removes the top of the bar and replaces it on the beach. This may only take hours, whereas the complete return of the bar to the beach may take weeks or even months. During this unstable transition period the littoral drift is excessive, as large volumes of material are transmitted downcoast by the oblique swell. It is possible for 95% of all longshore drift to take place during the few weeks after a storm and 5% during the remainder of the year. For similar oblique swell conditions a coast with more storm events will experience greater annual littoral drift. Since storm waves generally arrive from many directions during the course of a cyclone and their duration being so short compared to the persistent swell arriving from one oblique direction, it can be considered that eroded material is moved

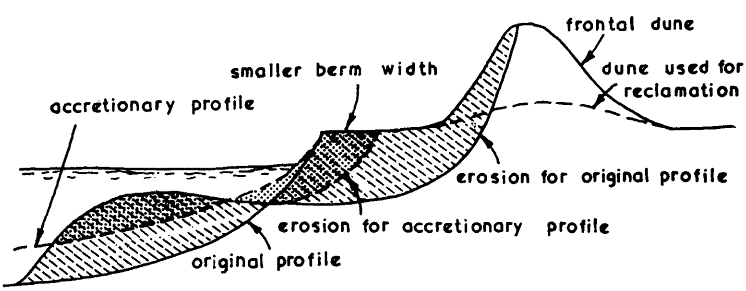

Fig. 7. Comparative erosion volumes to construct the offshore bar for a mild or steep seabed profile.

directly offshore, or that longshore transport is negligible. On the other hand, when the oblique swell waves return offshore bar material they do so downcoast. It is thus the persistent swell waves that dictate the nett movement along the coast.

Another point to note at this stage is that the more normal the waves to the coast the more difficult is it for the waves to transport sediment alongshore. Sitting takes place until the offshore is shallow enough for the waves to carry the load available. As depicted in Fig. 7, such a mild offshore slope consumes less beach material to construct a bar that stops erosion. Thus the beach berm, which is the active part of the shoreline that goes to sea annually, is much narrower.

Sculpturing of coast by waves

Now consider a coast with headlands or fixed points with movable sandy coast between (See Fig. 8). Commencing with a straight beach and waves angled at 45° to the headland alignment, with no input of sediment, the model shoreline is allowed to erode. It is seen that an ultimate indentation is reached[5]. The bay to the right is not so eroded because at the cessation of testing material was still passing through from upcoast.

Other results are typified in Fig. 9, where the true curved nature of the beach was observed, which has been shown to be a logarithmic spiral, which is illustrated in the figure[6]. The final equilibrium shape could be checked by several criteria, namely:

(a) no further recession of the waterline
(b) no further sand collected in the downcoast trap
(c) any single wave breaking simultaneously around the bay
(d) dye streaks not moving alongshore.

These indicated no further littoral drift and hence a stable shoreline.

Bays of differing degrees of indentation, depending on approach angles of predominant swell to headland alignments plus sand supply conditions, are the most prolific physiographic feature on coastlines of the world. This is Nature's way of effecting balance between the longshore energy available and the load to be carried.

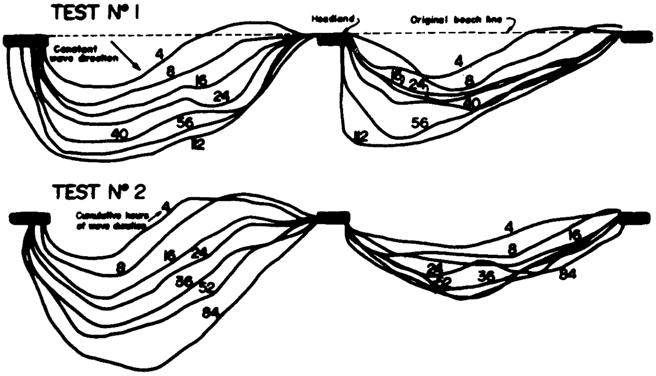

Fig. 8. Bay development with oblique swell and no sediment supply.

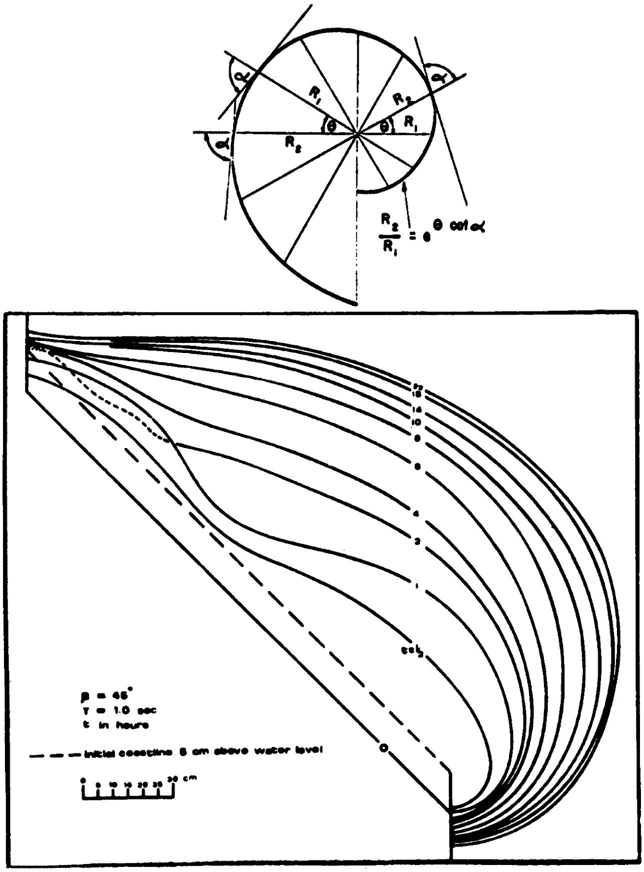

Fig. 9. Bay development showing wave cleanly the logarithmic spiral shape as defined in the sketch.

Nett littoral drift

The existence of such bays on a map or hydrographic chart indicates the direction of nett sediment movement, since in the model studies cited sand departed each bay at the tangential or non curved section of coast. The author has studied coastlines of the world and produced maps of nett movement for continental margins and for the world as a whole[7] (See Fig. 10). Arrows in the figure only indicate in macroscale the direction of movement if any mobile material is available.

It is seen that longshore drift, as determined from zeta bay orientations, matches the January and July wind patterns which generate the waves. Movement in general is towards the equator in both hemispheres, particularly on western margins of continents. These two observations are understandable when it is realised that the major wave generation zones are in latitudes 40°

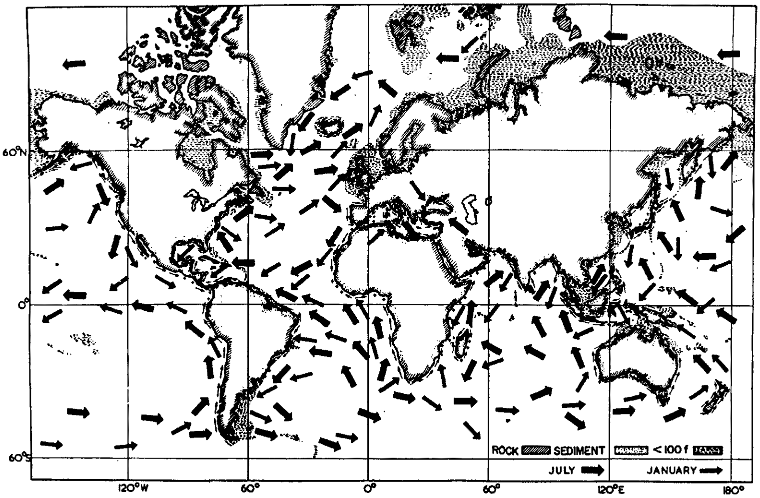

Fig. 10. Nett sediment movement around coastlines of the world. Plus signs indicate no nett drift.

to 60° N & S and the storm centres travel from west to east. The waves spread across the oceans towards the equator in easterly directions. Eastern margins of continents have predominant waves generated by local storms and therefore exhibit greater variation in directions of nett sediment movement.

The author has made a detailed study of the sources of sediment and its transport around the islands of Japan[8]. This has been included in a text book on COASTAL ENGINEERING[4] as a prime example of how to study sinks and sources for littoral drift. The material must come from somewhere (mainly the river systems) and must reach a destination, there to be stored as land above high water or as an offshore shoal.

Whilst sand moves along the coast it creates many problems of bar formation across river and harbour mouths, and concerns people who wish to fix waterlines. One characteristic of littoral drift that has not been recognised sufficiently in the past is its large fluctuation, as already discussed[3].

HOW TO COPY NATURE

Let it be reiterated that: *The construction of an offshore bar with material taken from the beach by storm waves is the most effective protection that can be conceived.* Man could not provide a structure equal in magnitude and efficiency, especially one that is dismantled after its purpose has been fulfilled. If man could economically construct such a mound as a permanent feature, the oblique swell waves would reflect from it and hence scour the bed seawards of it and so create a greater longshore drift.

The need, therefore, is to retain sufficient sand in reserve for bar construction without the waterline receding when the supply of sediment from upcoast reduces, either temporarily or permanently. For this constant waterline to be maintained the persistent swell should arrive

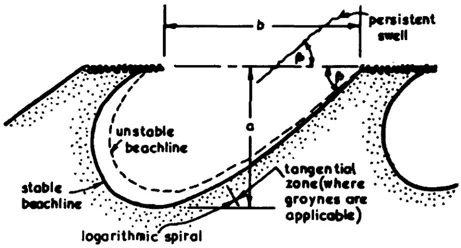

Fig. 11. A zeta bay in unstable and stable condition.

normal to the coast. In this way the material removed offshore returns directly back from whence it came, with no accompanying littoral drift.

This ideal condition has been seen to exist in the zeta bays formed between headlands with oblique swell. It has been shown that for an equilibrium shaped bay the waves both diffract and refract into the bay, arriving normal to and breaking simultaneously around the perighery. In the event of sand still being removed, or passing through the bay, the unstable bay is not so indented, as illustrated in Fig. 11. The logarithmic spiral and tangential sections should be noted in this figure, together with the approach angle β of the crests to the headland alignment, which equals the angle between the downcoast beach tangent and this alignment.

Characteristics of zeta bays

In the progressive and final development of bays by oblique waves on beaches between headlands two parameters are useful. One is the curvature of the shoreline as specified by R_2/R_1 or α in the logarithmic spiral (See Fig. 9). This has been shown to vary with duration for a beach eroded from a straight shoreline parallel to the headland alignment, but reaches a limiting value when the bay reaches equilibrium[9]. In Fig. 12 this equilibrium indicator is seen to form a falling curve with increasing angle β.

Also shown in this figure is the second parameter of indentation (a) divided by the spacing between headlands (b). As for α, this curve was derived both from model tests and prototype bays judged to be in equilibrium due to no supply of sand being available from upcoast or from

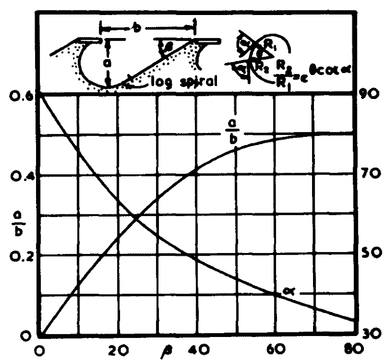

Fig. 12. Values of α and a/b for bays in stable condition for a range of obliquities β.

within the bay from a river[10].

If values of α, a/b and β are plotted from any bay on a map or chart, its stability can be gauged. Points for an unstable bay will fall above the α curve and below the a/b line. As further erosion occurs towards equilibrium the resulting plots will approach these lines but never go beyond them. For a nonstable bay the limiting erodable state can be found, since in reaching it the value of β (angle of tangential beach to headland alignment) will remain sensibly the same. Such equilibrium curved waterlines should be utilised in the establishment of encroachment lines, rather than fixed distances back from a changeble beach face. Allowance, of course must still be made for beach removal during storms, but with the normal return of bar material back to its original position the waterline should retain a steady position in the final stable condition[11].

Application of headland control

The headlands implied in such a coastal defense measure are offshore breakwaters parallel to the existing shoreline or parallel to the crests of diffracting waves in the depth where the structure is to be located. To create reasonably indented bays of large magnitude such island breakwaters would have to be large and located in deep water. This would normally be uneconomical but it is well to remember the role of reefs in maintaining sandy headlands.

To obviate this expense it is worth considering movable breakwaters as in Fig. 13, whose progressive movement seawards is associated with natural filling from upcoast[4]. Two alternatives present themselves, one of equalising loss and gain of coastal land area, and secondly of accumulating beach seawards of the present shoreline. In the latter case confirmation of adequate upcoast supply would be necessary. Also the consequences of no supply to the area downcoast of the headland system would have to be considered. This may solve an added problem of silting at the mouth of a river so located. The ultimate aim is to obtain a shoreline which is stable but it is seen that in the process much valuable land can be gained from the sea.

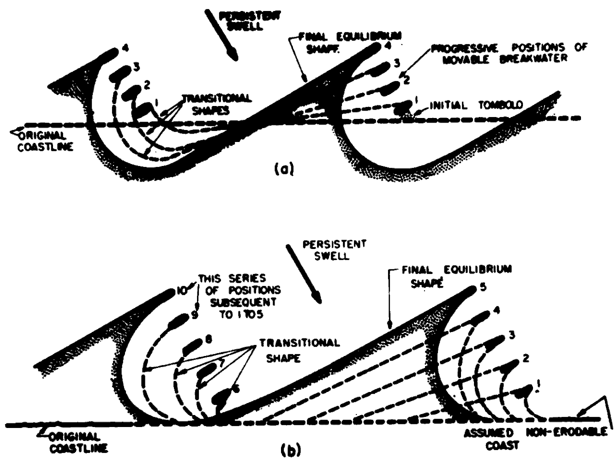

Fig. 13. Progressive development of bays by mobile headlands, to permit equal erosion and accretion, or total land acquisition seawards of the existing shoreline.

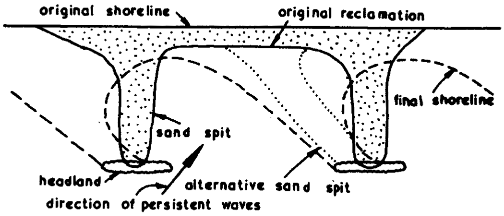

Fig. 14. Use of sand spit formation to construct headlands well seawards of an existing beach.

The sale of this real estate can help pay the cost of headland structures. It could also accomodate costs of concurrent reclamation which could provide immediate bays ready for development.

The use of sand filling could also overcome the problem of moving headlands seawards. As seen in Fig. 14 the construction of sand spits could permit headlands to be built in the dry. Such a method of deposition was found economical in filling a groyne field since pipes running along a busy beach was considered undersirable. The man-made tombolo will quickly be reshaped, with accretion on the upcoast and side curved bay in the leeward area. As noted in the figure, a spit angled more to the predicted final shoreline would erode less during the construction period. The more natural looking the material and mode of placement of the headland the readier will these control measure be accepted. It is only required that waves break on this structure during the highest tide and storm surge and therefore a breakwater many metres above HWM is not required.

This headland concept has been used to protect the reclaimed shoreline in Singapore[10]. This section of coast suffers extremely oblique swell from the South China Sea, which would have eroded the newly deposited material very quickly. The proposed revetment wall along the length would have caused scouring from the oblique reflection and created a large maintenance problem, as well as silt the harbour into the bargain.

Two types of headland were employed. This first was gabions which were placed on the waterline at low tide in a 4 m range. Later, rip-rap structures were formed by excavating two V shaped trenches after over filling. The waves eroded the excess material leaving the stone facing as the headland. Bays were quickly sculptured and in doing so the waves sorted the clay material and deposited it offshore, leaving the coarse sand to form beautiful cream coloured beaches.

Photo. 1 is reprinted from the cover of the 1975 Annual Report of the Housing and Development Board of Singapore. It is seen that whilst sediment is still passing along to fill downcoast bays the shoreline is even seaward of some headlands. The authority was advised against placing recreational facilities on this protruded area beacuse it will later be eroded, as supply from upcoast reduces to zero.

The benefits of headland control in this case were:

(a) littoral drift was stopped completely
(b) silting of the harbour was prevented
(c) aesthetic and functional beaches were formed instead of a seawall requiring continual maintenance
(d) the headlands cost 30~50% of the proposed wall

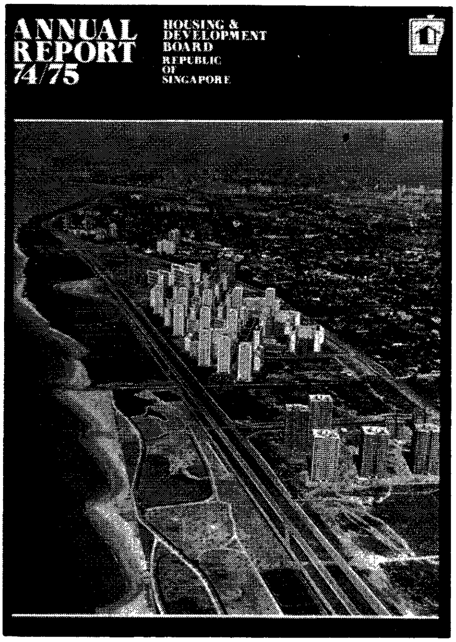

Photo. 1. Headland control of reclaimed land at Shingapore.

(e) sea spray and overtopping are less than for the alternative wall.

Although the waves arrived almost parallel to the coast, by the time they were refracted into the depths of the headlands, their obliquity was around 30°, resulting in $a/b=0.25$ (See Fig. 12). This determined the location of headlands offshore to support a designed building line.

CONCLUSIONS

1. Coastal defense solutions, of groynes, seawalls and renourishment, may serve temporary erosion needs, but are not effective in the long term and can exacerbate the problem.

2. Nature provides the best mechanism for defending the coast by constructing an offshore bar during attack and dismantling if soon afterwards.

3. Nature also tries to balance transporting energy with the load available by sculpturing embayments between fixed points on the coast.

4. The direction of nett littoral drift on a macroscale is dictated by the persistent swell which arrives from repetitive fetches in the ocean storm centres concentrated in the 40° to 60° latitudes in both hemispheres.

5. Zeta bays have a maximum indentation which is predictable and can therefore serve to establish encroachment lines.

6. Man can emulate Nature by constructing zeta shaped bays, controlled at their extremities by headlands, which may take only the form of reefs.

7. Construction of stable bays can be aided greatly by a reclamation programme in which

sand spits are initially built, on which hadlands can be constructed.

8. Application of headland control in defense of a shoreline in Singapore has provided many benefits besides that of economy.

ACKNOWLEDGMENTS

The author was Visiting Research Fellow at the Disaster Prevention Research Institute, Kyoto University during the pieparation of this paper, which was presented at the 1978 Annual Meeting of the Institute. He thanks Professor Y. Tsuchiya, Director of Coastal Studies, for his support.

REFERENCES

1) Silvester, R.: Wave reflection at seawalls and breakwaters, Proc. Instn. Civil Engrs. 51, 1972, pp. 123–131.
2) Silvester, R.: Sediment movement beyond the breaker zone, Trans. Instn. Engrs. Aust. CE 12, 1970, pp. 63–71.
3) Silvester, R.: Some facts and fancies on beach erosion, Proc. 16th Conf. Coastal Eng., 1978 (In Press).
4) Silvester, R.: Coastal Engineering, Vol. II, Elsevier Publ. Co., Amsterdam, 1974.
5) Silvester, R.: Stabilization of sedimentary coastlines, Nature (London), 188, (No. 4749), 1960, pp. 467–469.
6) Silvester, R.: Development of crenulate shaped bays to equilibrium, Proc. ASCE. J. Waterways and Harbour Divn. 96(WW2), 1970, pp. 275–287.
7) Silvester, R.: Sediment movement around the coastlines of the world, Proc. Conf. Instn. Civil Engrs., 1962, pp. 289–315.
8) Silvester, R.: Sediment transport and accretion around the coastlines of Japan, Proc. 10th Conf. Coastal Eng. (Vol. I), 1967, pp. 469–488.
9) Ho Siew-Koon: Crenulate shaped bays, M. Eng. Thesis No. 346, Asian Institute of Technology, Bangkok, 1971.
10) Silvester, R and Ho, S. K.: Use of crenulate shaped bays to stabilize coasts, Proc. 13th Conf. Coastal Eng., 1972, pp. 1347–1365.
11) Silvester, R.: Headland defense of coasts, Proc. 15th Conf. Coastal Eng., 1976, pp. 1394–1406.
12) Dette, H. H.: Effectiveness of beach deposit nourishment, Proc. Coastal Sediments '77, ASCE, 1977, pp. 211–227.

海岸侵食制御の最近の動向

リチャード・シルベスタ

要　旨

従来，海岸侵食の防止軽減に対して種々の工法が用いられてきたが，一般にあまり効果的でないことがわかってきた。建設費の増加に伴って，現在自然が与える示唆を見出して，それらの工法を試すことが必要である。

本論文では，まず突堤，護岸や海浜造成の限界を明らかにしたのち，砂州を形成させて海岸侵食を制御する最も効果的な自然の方策について述べる。いわゆる headlands 間にうねり状の波によって形成されるζ状の海浜では，漂砂は汀線に直角方向のみに存在し，その海浜は安定している。適当な沖防波堤を設置して，このような自然海浜を模倣すれば，侵食性海岸に安定な湾状の海浜を形成させて，その侵食を制御することができる。この場合，かような海浜の湾入の程度には限界があって，波の入射角が漂砂の下手側の汀線と headlands を結ぶ線となす角によって予測することができる。波の入射角が非常に大きいにもかかわらず，この方法はすでにシンガポールにおいて用いられ成功している。