ZETA BAYS, POCKET BEACHES AND HEADLAND CONTROL

by

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ABSTRACT

The now familiar equilibrium shape of bay sculptured by waves between headlands can indicate to man the direction he could follow in stabilizing shorelines. The characteristics of these crenulate or zeta shapes are known and can be applied in design or defining limits of erosion. Some natural settings are discussed which introduce difficulties in identifying the correct bay shapes for applying these tools. The application of headland control to specific cases of instability is presented. The final requirement is emphasised of aiding Nature to protect the coastline by the formation of the offshore bar and its subsequent return to the beach without concurrent downcoast drift. The method currently receiving widespread support of placing offshore breakwaters in close proximity to each other is discounted as a viable protective alternative.

INTRODUCTION

The occurrence of crenulate or zeta shaped bays between natural headlands when persistent swell approaches the coast obliquely is now observable and well known (1)(2)(3). These may be in dynamic equilibrium with the sediment supply and wave climate or in static equilibrium when no further littoral drift is taking place. (See Figure 1) In either condition the bay will have a curved section of logarithmic spiral form and some indentation dimension (a) that is some fraction of the space (b) between the headlands.

It is seen that the angle of wave crests to the line joining the headlands equals that between the tangential coast and this same alignment. Even when not in static equilibrium this beach extremity is very close to this final angle (β).

In the final stable form certain characteristics of the plan shapes are known from model tests and observations of prototype bays that are in this condition. (2) (4) As can be seen in Figure 2 the ratio of maximum indentation (a) to headland spacing (b) is fixed for a given obliquity of incident wave to headland alignments (β). In the same figure the relationship is shown between the constant (α) for the logarithmic spiral that the curved section of beach assumes.

With the above tools the stability of a bayed coast can be assessed, or the limit of erosion that can take place in the event of no further sediment being supplied, either from upcoast or from within the bay from

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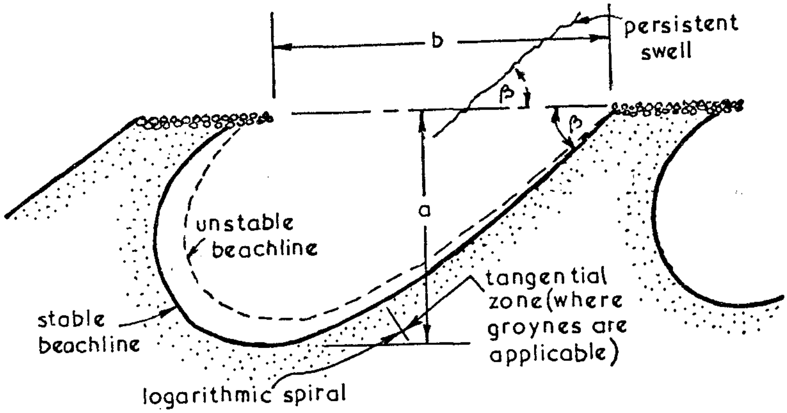
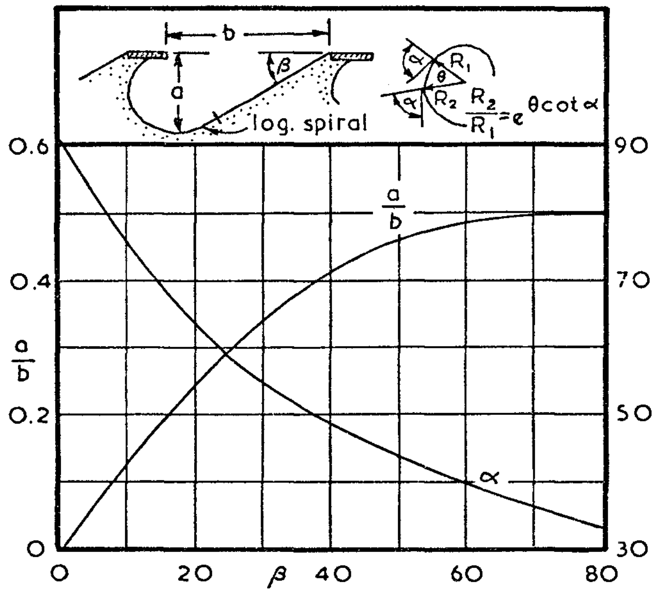


1. Definition sketch for crenulate shaped bay.



2. Parameters relating to bays in static equilibrium

a river. Such yard sticks can also be employed in designing headlands to stabilize an eroding bay or general coastline. In this final equilibrium condition persistent waves will be arriving normal to the complete periphery of the bay. At the tangential downcoast section waves will refract slightly but within the curved zone they suffer both diffraction and refraction before breaking parallel to the beach. Any wave thus breaks simultaneously around the complete bay shoreline.

POCKET BEACHES

There are situations where a deep indention occurs and there is insufficient sand to saturate the bay and cause transport around the downcoast headland. These might be termed "pocket beaches", where it is more difficult to identify the control line from which the zeta bay can be tested for its stability. Extra variables entering the problem will be discussed to show how the true crenulate shape can be checked.

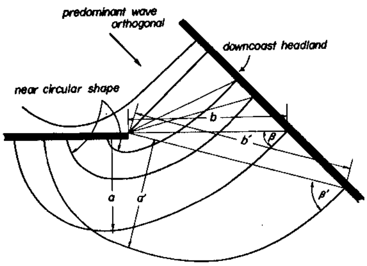
Protruding downcoast headland

Where the downcoast beachline does not reach the extremity of its headland (as pictured in Figure 3) due to lack of sediment, the control point should be the shoreline extremity. The figure shows the direction of the predominant or persistent waves, which determine the ultimate bay shape. The control line runs from the tip of the upcoast headland (on the left of the figure) to the intersection of the beach and the downcoast headland. This provides the measure of (β') from which (a'/b') and the logarithmic spiral constant (α') is determined from Figure 2. Since (b') is known the indentation (a') can be computed and the bay drawn.

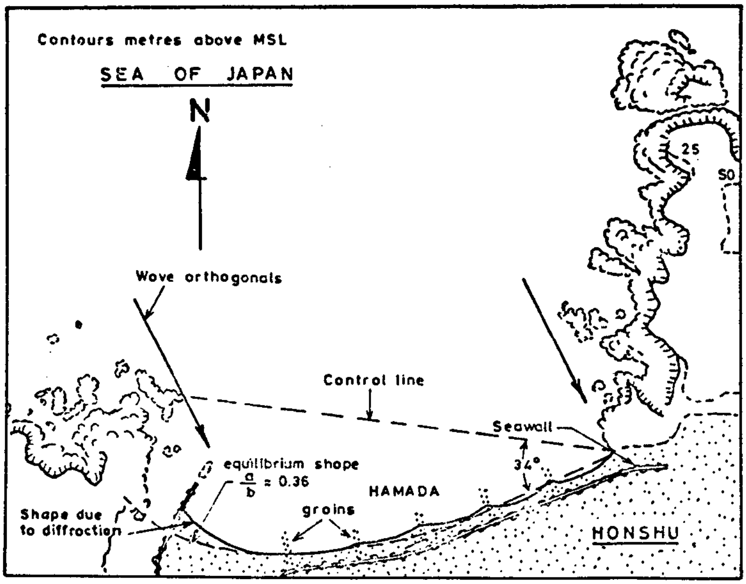
If renourishment by natural or man-made means were effected a new shape would emerge with a new contact point of the beach with the downcoast headland, as exhibited by angle (β) and indentation ratio (a/b). A different value of (α) will also apply. Further addition of sediment will decrease the value of (β) which, as seen in Figure 2, will decrease (a/b) and make the curvature of the beach closer to that of a circular arc. After passing through the stage of a straight beach normal to the wave orthogonal, further accretion would result in a new bay shape which would be dictated by some headland or control point further upcoast.

The set-up as illustrated in Figure 3 would be ideal for further model verification of (a/b) and (α), perhaps with a wave guide parallel to the downcoast headland to prevent reflection from this other headland.

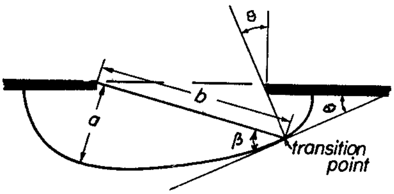
An example of this situation is contained in Figure 4, which is a bay of the Honshu coast facing the Sea of Japan. The wave orthogonals are normal to the tangential downcoast section of the bay. That on the left determines the control point of the upcoast headland whilst the control line intersects the meeting of the beach with the downcoast headland. The value of $\beta = 34^{\circ}$ gives $a/b = 0.36$ from which the equilibrium bay shape can be sketched, as shown dotted. It is seen that at the upcoast end extra accretion has occurred due to wave diffraction around the jetty constructed at a river outlet. Otherwise the existing coast is in static equilibrium or nearly so, which calls into question



3. Bays with no by-passing of downcoast headland.



4. Bay exhibiting downcoast control of beach with headland.



Bay with double curvature due to wave diffraction.

the need for the seawall and groynes constructed along the tangential section of beach. This is a case where sand renourishment might have solved the erosion problem.

Double curvature of bays

It has already been shown in Figure 4 that deviations from the logarithmic spiral curve can take place if a secondary headland, in this case a jetty causes local wave diffraction. Another example at the downcoast end of a bay is illustrated in Figure 5, where waves sculpture an almost circular beach which is asymptotic to the end of the log-spiral section. Any such change in curvature should indicate this extra control condition. As noted in the figure, the wave orthogonal must be normal to the tangent at the transition, from which β is obtained. The control line from which (b) is measured then provides the indentation (a) by which the static equilibrium shape can be assessed.

An example of this problem is given in Figure 6 which is a bay on the Shikoku coast of Japan facing the Pacific Ocean. The increased curvature at the western end of this pocket beach indicates diffraction by the protruding downcoast headland. The wave orthogonal must be normal to the transition tangent giving the control line shown. The resulting equilibrium bay can be drawn and compared to the existing shoreline for testing its stability. It is seen that the bay can be continued into the upcoast headland complex even though it cannot exist there.

Multiple upcoast headlands

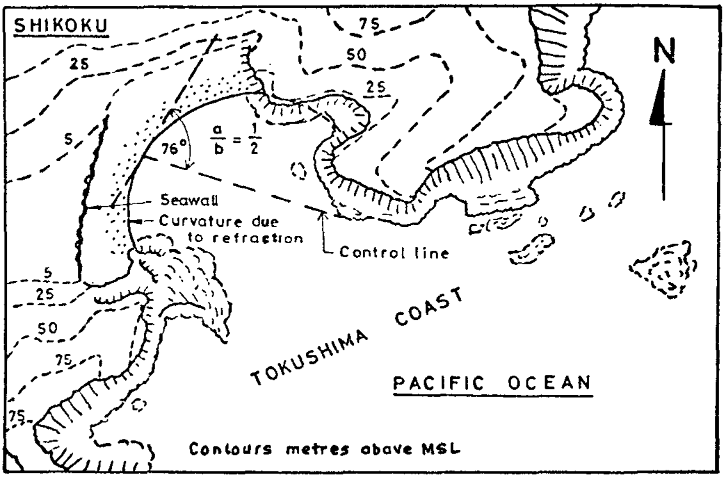
Figure 7 shows the complication of more than one headland in the upcoast region. It is necessary to determine which one controls the shape of the bay. The orthogonal of the persistent waves is normal to the tangential downcoast beach. This same orthogonal applies to the upcoast region as illustrated. In the absence of headland B point A becomes the control point and AC the control line by which β' is measured. This gives the indentation and curvature for the equilibrium beach from these controls. If this orthogonal intercepts the tip of headland B if it exists the new control line BC gives a new β value and completely different bay shape. It is obvious that the presence of headland C, even with A effecting control of the bay will cause greater curvature within its lee due to secondary diffraction.

In Figure 8 a bay on the Japanese coast is shown where the control point for the upcoast zone must be determined. It is another case of double curvature at the downcoast end so that a transition point must be determined to assess the line of the wave orthogonal. Once this is done the same alignment of wave approach indicates the protruding headland as the upcoast control point. The resulting equilibrium bay is much further inland than the existing coast indicating a great potentiality for erosion. This is displayed by the extensive seawalls shown, which have been provided to protect the road and rail links on the coast, a necessary feature around most of the Japanese coastline. A method of stabilizing this bay is indicated by headlands but will be discussed later.

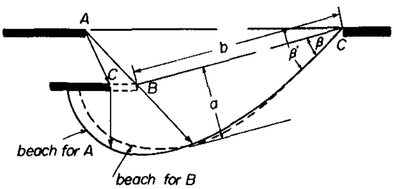
Orientation of headlands

It is convenient for considering bay characteristics to align headlands with the line joining the tips, about which waves diffract as in Figure 1. Natural conditions are never so easy and hence alignments as in Figure 9 must be accounted for. The original situation is presented by alignments A and E where the control line and spacing (b) fixes indentation (a) once (β) has been measured. If other headland orientations still have the same (b) the same plan form results. However, with alternatives B, C and D for the upcoast structure part of the bay will not exist. Even so the drawing of the remainder of the bay may help the determination of (a) within the hypothetical section in order that it, with portion of the logarithmic spiral, can be assessed.

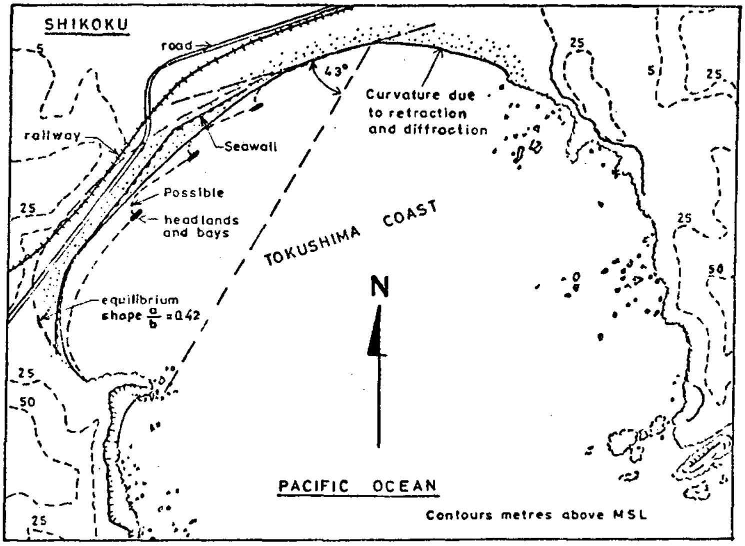
Similarly the orientation of the downcoast headland at G or F has no influence on the equilibrium bay formed by the control line as pertains to E. It is only when this structure protrudes into the bay, as with alternative H shown dotted in Figure 9, that a new control point is established. As seen a new (b') is operative as well as a different (β), from which a new (a) is derived and, of course, a changed log-spiral for the curved section of bay.



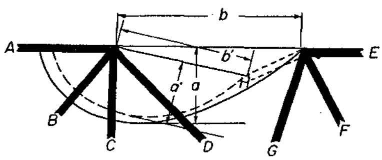
6. Example of bay with double curvature.



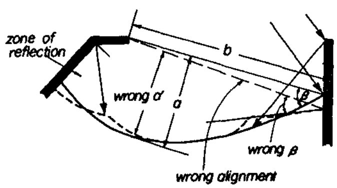
7. Bays formed by different upcoast headland control



8. Example of defining control by upcoast headland.



9. Effect of headland orientation on bay formation.



10. Influence of wave reflection on smooth beach line.

It is interesting to compare alternatives of breakwaters running parallel to the coast, as with A and E in Figure 9, to groynes running normal to it, as with C and between G and F. With the former a complete bay exists for a given spacing (b) between structures whereas only a fraction of it can result from the latter or groyne solution. Not only is a longer beachline possible with the breakwaters A and E, but material is prevented from being dispersed seawards during storm events. Any longshore drift during these sequences is forced into the deeply indented zone with perhaps deposition offshore. With the groyne alternative a rip current will form along the face of C in the figure and much material is thrown out to sea, possibly to return to the beach much further downcoast(5) .

Influence of wave reflection

The crenulate shaped bays resulting from persistent waves from one direction will produce a uniformly curved beach of log-spiral form. Any deviation from this should indicate some secondary influence on the waves or the sediment motion. One of these could be a rocky shoal offshore which refracts the waves to produce a slight protuberance of the beach with possibly adjacent denudation. These aberations should be smoothed out when determining indentation (a) or the log-spiral (α) value.

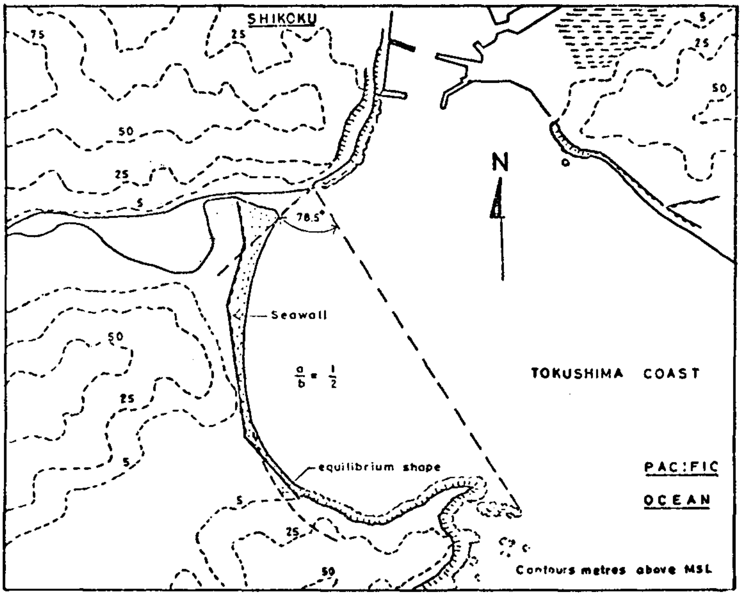
Another source of shoreline deviation would be reflection from headlands, two types of which are depicted in Figure 10. At the downcoast end orthogonals are drawn which show the extent of the reflected waves. The short-crested system so produced by these and incident waves is very conducive to sediment transport parallel to the wall, or headland in this case.(6)(7) Outside the bounding orthogonal of the reflected wave accretion will occur so that the shoreline shown dotted in the figure results. Using the intersection of this waterline with the headland as the control point is erroneous (as illustrated) as it should be derived from the smooth curve of this tangential or log-spiral curve.

The upcoast headland is also shaped to give the possibility of reflection. The incident orthogonals from the headland extremity will have varying angles of reflection but the bounding orthogonal is as shown. Here again material will be scoured and produce a shoreline as dotted in Figure 10. The deviation in the correct log-spiral curvature may cause a wrong assessment of indentation (a') instead of (a).

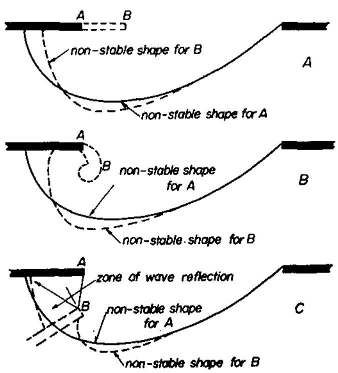
Figure 11 does not provide an example of reflected wave influence but it does indicate the need to extrapolate a bayed shoreline across a river mouth to the downcoast headland control point. It can be seen from the (β) measured and the (a/b) derived that the bay is in equilibrium except for a short length at the southern end where excess material is apparent. This is unlikely to be stable, as indicated by the presence of the seawall very close to this margin.

Changing control points

Figure 12 gives three examples of alterations in control points, those in A and C are man-induced whilst B could be a natural phenomenon.



11. Extrapolation of bay across river mouth to determine control line.



12. Examples of natural or man-made features that influence bay shape.

It is unfortunately a common practice to extend an upcoast headland in order to provide calmer water for the construction of a port in its lee. As seen in A of Figure 12, a control point is shifted from point A to point B, about which the persistent waves must now diffract. This results in accretion in the port location, probably before construction is commenced. In the case of the bay being close to equilibrium this siltation is at the expense of the adjacent beach.

The sand spit illustrated in B of Figure 12 will also produce a new control point B which will cause accretion in the lee of the breakwater, perhaps by denuding the adjoining beach by littoral drift being held within the spit.

In diagram C of the figure the reshaping of the coastline by the intrusion of a large structure, such as an airport runway, is illustrated. Between A and B reflection of waves can re-orient the beach as shown dotted. Downcoast of the new feature accretion will occur adjacent to it with concomitant erosion a little distance away, particularly if there is no sediment input into the bay.

HEADLAND CONTROL

Bays which are not in equilibrium can be stabilized by the installation of headlands within them. This results in smaller bays being sculptured by the persistent swell or predominant wave system. This is depicted in Figure 13 where the existing unstable shoreline is shown, together with the static equilibrium shape which would ensue in the event of all sediment supply being stopped (an eventuality quite possible in these days of dredging substantial channels to ports). To prevent the obvious loss of valuable land, which could be highly developed for commercial or recreational purposes, the suggested headlands could be located to give no net loss or complete gain of land area.

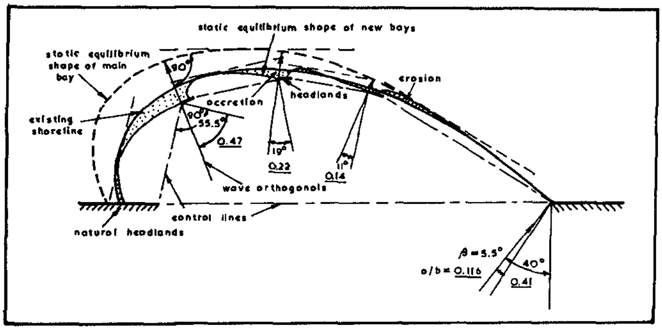
In determining (β) for each segment or bay it should be recognised that the persistent wave orthogonals at each headland location must be normal to the tangent at that section of the static equilibrium bay. The angle between the orthogonal and the normal to the control line joining adjacent breakwaters is (β) which gives indentation (a) from the value of (a/b) derived from Figure 2. Values are indicated in the figure. The bay can be sketched in by starting with the tangential section parallel to the static equilibrium section of coast and making the indentation line tangential to the curved section of the new bay. In the case of bay erosion the newly formed bays will be oriented in the same direction as the main bay, with the tangential sections to the right, for example, in Figure 13.

Another situation may arise where a bay is still building out to its static equilibrium limit. This possibility is displayed in Figure 14 where a deep indentation between two mountain structures has been virtually cut-off buy a sand spit supplied from a source which is indicated is at the recognised downcoast zone of the bay being formed. The sediment still filling the bay will travel in the direction shown, towards the curved section of the coast. With the control points and (b) known, the angle (β) can define (a) and the log-spiral (α) so that the equilibrium bay can be drawn. Whilst material is available for filling the coast will remain dynamically stable, with siltation continuing in the curved section of the bay. If however the supply is insufficient for the wave energy arriving, erosion will take place at the tangential downcoast end which is normally the most stable section.

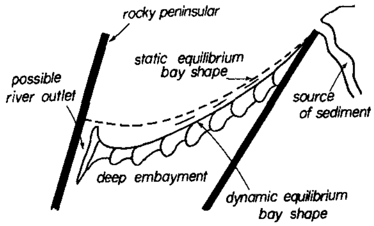
An example of this is given in Figure 15 which is a bay in Honshu facing the Sea of Japan. The Hino river in its natural state has over geologic time supplied an abundance of material to form the sandy spit reaching the Shimane Peninsular. However, the static equilibrium bay is far seaward of the existing shoreline, indicating the need for much more sediment before stability is reached. Since the river has been harnessed by dams upstream the discharge of sand has diminished substantially resulting in erosion near the Kaika coast.

A method of stabilizing this coast by headlands is suggested in Figure 14, in which the indentations of each bay is determined from the angle between the wave othogonals (normal to the static equilibrium line) and the normal to the control line of each bay (as detailed in Figure 13). It can be seen in this rather unique case that the stabilizing bays are oriented in the opposite direction to that of the major bay, due to this silting situation.

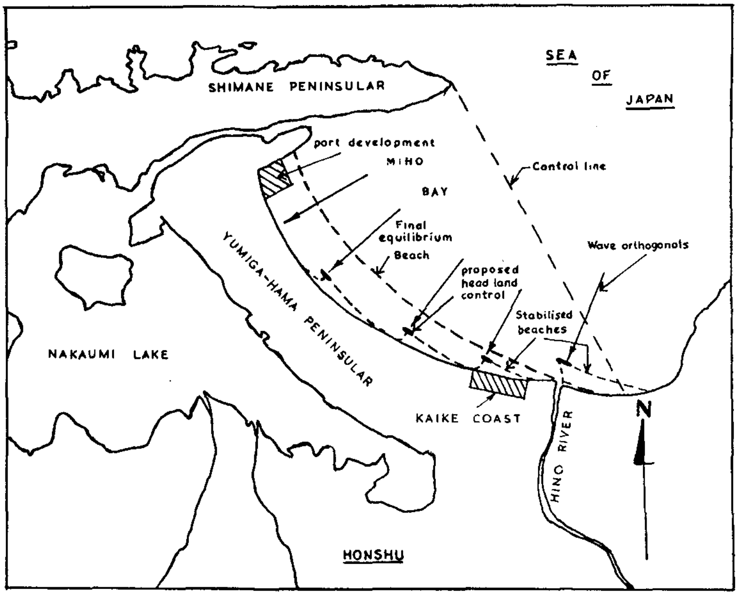
The solution proposed by Toyoshima (8), as in many other locations in Japan (9), is the installation of offshore breakwaters parallel to the coast but spaced very close together. The openings were, in fact, one quarter the length of the individual structures placed echelon fashion. This was after attempts at stabilisation by groynes and seawalls had failed. Figure 16 shows three of these breakwaters behind which tombolos have formed. However, also apparent are defensive blocks found necessary, in line with the openings between breakwaters. This indicates too close a spacing of the structures from the beachline desired. Although it was concluded that tombolo growth occurred during storm conditions, it would be during these events that a strong rip current would be generated through the openings as overtopping water and storm wave water entering the circular bays must return to the sea through these limited spaces. Toyoshima (9) suggests that counter-measures will always be necessary in this exposed zone.



13. Headland stabilization of an eroding bay.



14. Situation of a bay still filling to non-littoral drift state.



15. Example of bay accreting to equilibrium and method of stabilizing by headlands.

The sand finding its way behind the breakwaters will be that scoured by the reflected and incident waves seaward of these structures. Tbe result of this can best be expressed in the conclusion of Toyoshima(8): "The most important problem is subsidence of the breakwaters".

The writer's concept of coast stabilization by headlands does not countenance offshore breakwaters placed so close together. It envisages a spacing in the order of ten times the length of each structure, in order that a zeta shape of coast can be sculptured. The alternative suggested by Toyoshima virtually constitutes a continuous wall being constructed offshore at great cost. The excessive reflection by oblique waves accelerates the transport of sediment that results in scouring of the bed and a resulting maintenance problem. The spacing of headlands from the existing shoreline can be such as to exchange some beach zone for accretion elsewhere or beach agradation at all points. A renourishment scheme accompanied by headland installation will provide stable bays very quickly with no erosive effects downcoast of the system.

The suggested plan in Figure 8, to stabilize a highly developed coastal plain, contemplates (at first look) three headlands which would have cost much less than the seawalls finally constructed, even when nourishment of the bays is considered. It is worthy of note that such headlands only need to break the waves under the worst storm conditions. Even natural reefs have achieved the same results of maintaining sandy prominences leeward of such submerged features.

NATURE'S DEFENSE MECHANISM

The essence of the problem is to maintain a supply of sand for offshore bar construction by storm waves without the waterline continually receding. This implies that the bar material is brought back to the beach by subsequent swell exactly from whence it came. This is the case for bays in static equilibrium since persistence waves around their periphery arrive normally. Even with littoral drift occurring in a dynamic equilibrium situation, fluctuations in sediment supply will not be accompanied by such large beach recessions as for a long straight coast controlled by headlands at much greater spacing. The limiting indentation for no sand supply at all is predictable.

Man can do no better than observe natural processes and emulate them in his marine structures or operations, or by helping Nature to be more efficient. In this way he is copying natural scientists who try to enhance the productivity of Nature.

REFERENCES

(1) Silvester R. "Stabilization of sedimentary coastlines" Nature (London) Vol. 188 (4749), 1960, 467-469.

(2) Silvester R. "Development of crenulate shaped bays to equilibrium" Proc. ASCE J. Waterways and Harbors Divn. 96 (WW2), 1970, 275-287.

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

(4) Silvester R. "Headland defense of coasts" Proc. 15th Conf. Coastal Eng. 2, 1976, 1394-1406.

(5) Silvester R. "A new look at beach erosion control" Disaster Prevention Res. Inst., Kyoto Univ. Annual Rep. 22A, 1979, 19-31.

(6) Silvester R. "Wave reflection at seawalls and breakwaters" Proc. Instn. Civil Engrs. 51, 1972, 123-131.

(7) Silvester R. "Sediment transmission across entrances by natural means" Proc. 16th Congress IAHR, 1, 1975, 145-156.

(8) Toyoshima O. "Changes of sea bed due to detached breakwaters" Proc. 15th Conf. Coastal Eng., 2, 1976, 1572-1589.

(9) Toyoshima O. "Design of a detached breakwater system" Proc. 14th Conf. Coastal Eng. 2, 1974. 1419-1431.

16. Offshore breakwaters closely spaced at Kaika coast in Figure 15.