CHAPTER 308

Stabilizing Beaches Downcoast of Harbor Extensions

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Abstract

In geomorphological terms, the sandy shoreline of a bay downcoast of a harbor may be stable or in static equilibrium, or could be in dynamic condition, if sediment is still being supplied from upcoast or from downcoast to form a salient predicted by a static bay shape equation. Should commercial expansion demand a larger port, the general solution is to run a breakwater from the headland or existing structure. This has the potential to create a new static equilibrium beach, often with accretion in the lee which is at the expense of beach erosion downcoast. It is strongly recommended that geomorphic approach be incorporated to stabilize downcoast beaches early in the planning stage of a harbor, or as remedial measures. By creating bay beaches in static equilibrium, the potential beach erosion downcoast of a harbor will be kept to a minimum or may be prevented completely.

Introduction

As Inman (1974) has recalled, man has been interfering with river and coastal environments dated back in 1500 BC when the Minoans constructed wharves in Crete and by 480 BC as the Phoenicians built harbors along the coasts of Lebanon and Israel. Fleming (1992) has also discussed the modern history of harbor developments for fishing ports and major maritime trade. Oliveira et al (1982) has reported disappearances of towns in Portugal, as beaches eroded towards their stable shape.

Despite our current understanding of coastal processes there is a missing link as instanced by the many stories of beach erosion still reported in the technical literatures (for example, Ozaki 1964, Dunham 1965, Inman and Frautschy 1965, Herron and Harris 1966, Jordaan 1970, Sato and Irie 1970, Moni 1972, Lepetit 1976, Tanaka and Sato 1976, Nir 1982, Oliveira et al 1982, Komar 1983, Saxena 1983, Kraus et al 1984, Uda et al 1986, Gonzalez et al 1988, Kuo 1988, Moutzouris 1990).

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The present status of man's abilities in coastal engineering and shore protection has been well summed up by Inman (1974): "In view of man's present extensive intervention in the coastal zone, mostly based on 'brute force' technology, a careful study of the ancients' ability to work with Nature provides valuable insight for today's problems."

In spite of our great knowledge of wave kinematics and sediment movements in marine situations, engineers have not appreciated the macroscopic view of the coast as imposed by Nature. She has transported millions of tonnes of material to sea and back again in a matter of days and also moved it alongshore. More observations are necessary to ascertain the long-term stability of waterlines produced by persistent swell and the aberrations that occur during storm sequences. It is the former which is the concern of this paper.

Many researchers have recognized the effect of harbor construction on sediment transport downcoast, but without adequate quantitative prediction. Herron and Harris (1966) believed that "harbor works are the principal offenders" that have interrupted the balance of natural littoral drift existing over hundreds or thousands of years. Even so, the question of how to predict a stable shoreline in the lee of such structures remains unanswered. It is hoped this situation is overcome with the current submission and other works by Hsu et al (1993) and Silvester and Hsu (1993). In terms of the beach erosion downcoast of harbor extensions, these authors believe it is not so much a need to look back on our achievements but a need to observe natural processes in geomorphological terms and apply them.

Beaches Downcoast of Harbors

In geomorphological terms the stability of a sandy shoreline can assume a bay shape that is *stable* or in *static equilibrium* if the littoral drift is negligible or non-existent, or it can be in *dynamic equilibrium* if drift is still being supplied with sand from upcoast or from within the bay. Whilst this supply is constant the bayed beach can remain in place for decades, but should it decrease the shoreline will recede towards the static equilibrium shape, the final limit to which it will go.

If on a straight sandy length of coast a breakwater or other structure is run out to sea, the immediate result will be interception of littoral drift and the formation of a bay downcoast of the impediment. This will become further indented until sediment bypasses the new structure and dynamic equilibrium is restored. This sudden loss of land instigates the insertion of protective measures such as seawalls or groins, that are usually ineffective since man is fighting with Nature. The walls reflect waves obliquely and so generate short-crested waves (Silvester 1972; Hsu 1990) which expedite the longshore transport. On the other hand, straight groins accelerate drift by forming rip currents during storms that carry vast volumes of material offshore, there to be transmitted downcoast by subsequent swell.

Similar to the eroding beaches on straight coasts, discontinuity or interruption of sediment supply from upcoast has been considered as the main cause of beach erosion downcoast of harbors (Herron and Harris 1966, Komar 1983, Uda et al 1986). This may be attributed to the construction and extension of long breakwaters and dredging of deep access channels.

An additional factor is the potential of salient/bay formation in the lee of the breakwaters, caused by an improper alignment of a new breakwater and the positioning of its tip. This implies that a large volume of sand is needed, often from the beach downcoast, to build up a salient in the form of a bay. In addition to the evolution of shoreline, it also causes change to the bottom topography in the vicinity of the structures (Sato and Irie 1970). The slopes of beach faces downcoast were found to become steeper with armouring units subsided in front of seawalls. (Uda et al 1986; Hsu et al 1994)

Universal Bay Shape Equation

Crenulate-shaped bays are ubiquitous, occurring as they do on oceanic margins, coasts of enclosed seas, lakes, and even river shorelines. They are indicative of Nature's way of balancing the wave energy with the sediment load to be carried. Bays have thus been maintained in the same position for thousands of years inspite of the fierce storms that hit them infrequently. But for the rocky headlands spaced along the coast, vast indentations would have been formed with the downcoast extremity almost normal to the orthogonals of the most persistent swell (Silvester 1976).

Geographers and geologists have published on bay shapes (Halligans 1906) with the first recognition of this as a stable feature by Jennings (1955), unfortunately without full knowledge of the wave action involved. Davies (1958) observed the importance of wave refraction but not diffraction. Langford-Smith and Thom (1969) noted the zeta-shaped beaches of the New South Wales coasts of Australia, without scientific analysis of their profiles. Although the crenulate shaped bays have received the attention of many scientists (Bird 1984, Carter 1988, Davis 1985, Phillips 1985, Shepard 1973, Zenkovich 1967), their stability has only been examined by engineers (Silvester 1960; Le Blond 1979; Silvester et al 1980). This geomorphic feature has existed for some thousands of years (at least since the last still stand of sealevel), but have become more indented during the past century due to the dearth of sediment for many reasons (Silvester and Hsu 1993). In this relatively short period in geologic time rivers have been harnessed, which results in less supply of sediment to the coast for spreading by wave action. This has resulted in bays approaching their static equilibrium condition, causing greatest erosion at the most indented position of the bay with practically no change at either end.

Yasso (1965) suggested the logarithmic spiral for predicting the shape of the crenulate-shaped bays, which Silvester (1974) adopted for many years. But this was found to be inaccurate for the downcoast region where the beach straightens (Hsu and Evans 1989). A polynomial form resulted from data of a multitude of bays examined as follows:

$$R/R_o = C_0 + C_1\,(\beta/\theta) + C_2\,(\beta/\theta)^2 \qquad (1)$$

with the variables R, R_o, β and θ as given in the definition sketch of Figure 1. The values of constants C_0, C_1 and C_2 are available in Hsu and Evans (1989) and Silvester and Hsu (1993), in tabular and graphical form. It is noted that the wave obliquity (β) is measured between the control line (R_o) and the downcoast beach tangent. For a stable or near stable beach this is normal to the orthogonal of the persistent swell which sculptures the shape. The straight crests of these incoming waves at the point of diffraction, at the other end of the control line, are also angled β to it, from which arcs (R) are drawn at angle θ to it. Thus, by knowing R_o and β the value of R is determined for a specific θ, so that the complete periphery of the static equilibrium bay can be drawn. It has been shown that the logarithmic spiral fits only the curved portion of the actual bay, whereas the parabolic formula fits the complete periphery exceedingly well (Hsu and Evans 1989).

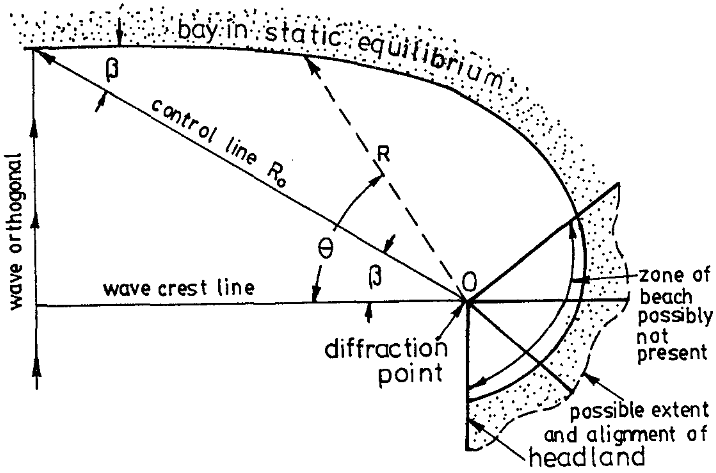

Figure 1. Definition sketch of a new empirical equation for static bay shape.

Besides the shaping of bays in the lee of headlands, equation (1) can be applied to salients behind offshore breakwaters (Hsu and Silvester 1990), as seen in Figure 2. These accretions are not triangular but assume the parabolic curve either side of the apex, as dictated by the diffracting and refracting waves and the associated longshore current circulation. This added land is at the expense of beaches beyond the extremities of the breakwater, if beach nourishment is not carried out.

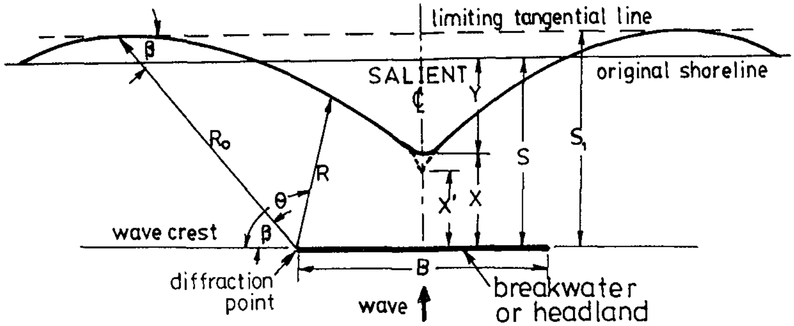

Figure 2. Definition sketch of a salient formed in lee of an offshore breakwater, with normal wave approach, based on the static bay shape equation (1).

Influence of Upcoast Headland Conditions

A natural headland is depicted in Figure 3 a & b as A and the downcoast limit as B in which control line AB ($= R_{01}$) angled to the downcoast tangent by wave obliquity β_1. When breakwater AC is built the new diffraction point C gives a new control line CB and new angle β_2, which results in a changed static equilibrium or stable shape. This natural reshaping will take place inspite of any modest attempts with groins or seawalls to prevent its fruition.

Looking first at Figure 3a, the existing bay may be in dynamic equilibrium, with littoral drift still passing through, as seen by the full line in the figure. The dotted curve denotes the stable shape for control line *AB*, to which the beach would erode if all sand supply around point *A* should cease. Now, when the breakwater *AC* is inserted its length and orientation could be so chosen that diffraction at point *C* and control line *CB*, with the static bay for *CB* being the same as the dynamic for *AB*. This can be achieved close enough for erosion at all points around the periphery to be negligible. If, however, sand were finally to bypass point *C* the resulting beach may become dynamic once more with a beachline seawards of this stable shape. But it should be designed for the static condition in case this additional drift ceases in the future.

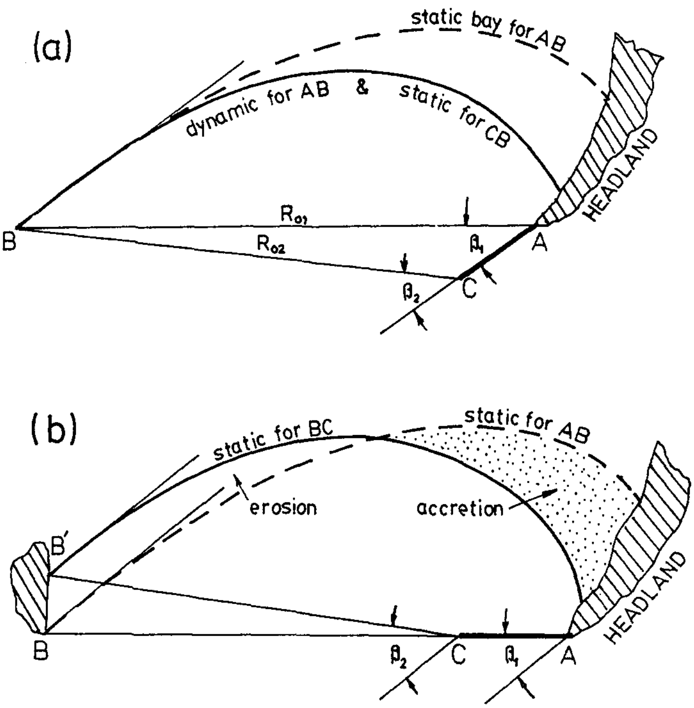

Figure 3. Effect of positioning a breakwater tip (a) in a dynamic bay, and (b) in a static bay, for harbor planning and beach erosion control.

Now turning to Figure 3b, the dotted curve represents the static equilibrium shape for control line *AB* which is the existing beach. When breakwater *AC* is added the new control line *CB* creates a new static beach which involves massive accretion in the lee of headland *A*. The material for this has to be supplied from the region of *B* because the beach was originally stable. This causes a new downcoast tangent to operate that determines a new β_2 for equation (1). The situation would detract from the calm water area serving as an anchorage but could be attractive for tourism purposes.

It must be remembered that the stable waterline being predicted applies to swell conditions or calm weather. When storm waves arrive, the beach berms will be removed offshore to form a bar, which take some days to be returned. In the case of static equilibrium the same waterline will result, but all infrastructure should be kept landward of the receded storm limit.

Case Studies of Stabilization

Conventional defense solutions, such as seawalls, groins and offshore breakwaters, have been used to stabilize eroding beaches downcoast of harbors without much success. Sand bypassing and nourishment schemes have also been tried, with some degree of success in the short term. However, the geomorphological approach, involving the construction of stable bay beaches, will be attempted in this paper. This may be regarded as a permanent solution.

Like the medical profession, which prefers to make sick people better by the administration of drugs or surgery, coastal engineers have concentrated on rectifying problems rather than preventing them. Some of these are due to their own mismanagement. Many medicos are now working holistically in looking at the whole person (body, mind and emotions) to find causes rather than remedies as such. In approaching a coastal situation from a geomorphological viewpoint the final trends can be examined which point to a permanent rather than a temporary solution.

As will be seen in many of the cases to be presented, the macroscopic view of the whole coastline gives a better picture of a problem, than looking at a limited section of it. Erosion can be predicted long before it is likely to take place and hence means can be devised to prevent it. In some of the Japanese harbors the breakwater extensions are mammoth, with lengths in terms of kilometers. The incentive may be large current expenditure to generate a larger budget next year. These structures certainly produce many subsidiary problems such as siltation and erosion which demand more money.

1. Durban harbor, South Africa

The erosion of beaches north of Durban harbor on the Indian Ocean of South Africa has been presented by Jordaan (1970). This involved siltation at the port entrance, which is continually dredged and dumped out to sea or along the eroding beaches. The suggested solutions entailed Y or L shaped groins plus two offshore sand breakwaters, each 300 m in length and spaced apart the same amount, and 600 m from the beach. Whether any of these have been implemented does not affect the this exercise to apply the principle of static bay shape.

Using the tip of the outer breakwater as the diffraction point (*A*) the resulting stable bay *A* is shown in Figure 4. This indicates substantial erosion even if minor attempts are made to prevent it. The need is for a new diffraction point to the north in order that a beachline seaward of the present can be established. Such a point (*B*) can be provided by an island breakwater *BD* from which bay *B* is formed. The space between structure *BD* and the existing inner breakwater will permit some wave action to round-off this waterline to the existing (old) breakwater as shown. The beach between it and the main port structure will be reoriented as indicated by the dotted line.

The accretion anticipated for bay beach *B* could be supplied from dredging of the entrance channel that appears to be continuous. Otherwise the siltation would come from beaches to the north. It is expected that the groins will be removed and their stone etc used in the new breakwater *BD*. The offshore sand mounds (if built) could also be removed and perhaps utilized as fill for the beach *B*.

To help overcome the necessity for dredging at the port entrance the outer breakwater could be extended as shown (*AC*) which would reflect waves obliquely. The short-crested system so established would transmit material across the slightly diverted navigation channel and create a shoal near the tip *B*. It would finally finds its way to the beaches. This new structure would prevent swell entering the gap between breakwater *B* and the existing structure so that beach *B* would extend to the tip of the old breakwater.

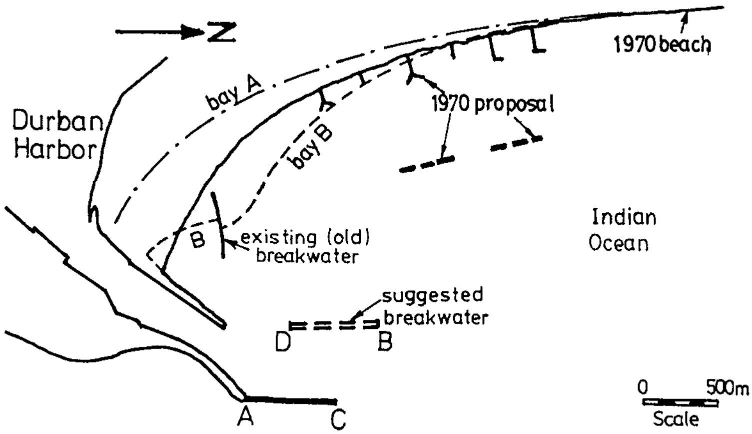

Figure 4. Durban harbor, South Africa

2. Esperance port, Western Australia

Esperance Bay is part of a continuous chain of embayments facing the Southern Ocean in the south of Western Australia. The curved shoreline, in geomorphological terms, was in dynamic equilibrium, implying its stability was maintained by the uninterrupted supply of littoral drift. However, the construction of a breakwater and dredging of an entrance channel for the Port of Esperance between 1962-65, with breakwater extension in 1973-75, has cut off the littoral drift. This has forced the shoreline to recede back to a potential static equilibrium, which is destined by Nature. This limit is landwards of the existing shoreline (see Figure 5). A total of 573,000 m^3 of dredged material was placed onto the beach.

The engineering solutions taken to combat with the eroding beach at Esperance has been a low-cost rock groin field with beach renourishment, which has been an ongoing task ever since 1969. Between 1977 and 1995, sand renourishment at an average rate of 23,100 m^3/year has been placed on sections of beaches suffering the worst erosion. Two headlands in the shape of a walking sticks with fronting beaches are proposed to achieve the overall stability with one-off beach nourishment to form a bay, rather than a field of short groins or offshore breakwaters with continual renourishment.

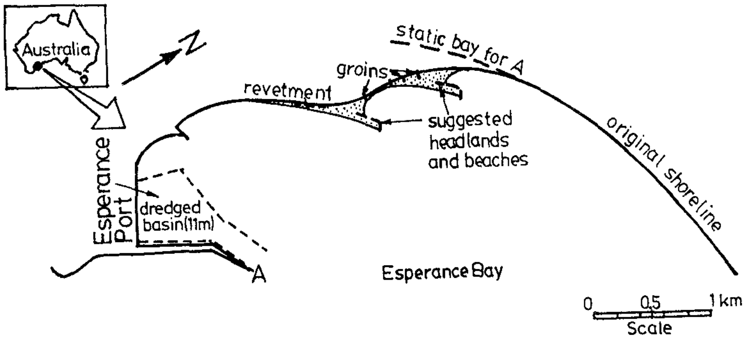

Figure 5. Esperance Bay, Western Australia

3. Hua-Lien harbor, Taiwan

Hua-Lien harbor is located on the Pacific Ocean coast of Taiwan at latitude 24°N. Two breakwaters (*AB* and *CD*) were constructed in 1987, as noted in Figure 6 (Hsu et al 1994). Prior to this extension, erosion of the coast south of the harbor entrance had been experienced, resulting in lengthy seawalls protected by concrete armour units which have steepened the offshore area. The stable beach for breakwater *CD* is shown dotted (bay for *D* in the figure) which is landward of the majority of the protected area, except at the northern tip where accretion would inhibit the discharge of the stream in the lee of breakwater *AB*.

One solution to these two problems is to extend the breakwater from *CD* to *DE*. The new diffraction point at *E* will produce the waterline shown as salient for *DE*, which is seaward of the current shoreline protected by the seawall. The remainder of the beaches will be stabilized, so not requiring other protection such as groins or seawalls. An offshore breakwater *FG* may be constructed which will intercept material in the lee of the main breakwater *DE* to form the secondary curve in the form of a salient to ensure that the stream outlet will not silt up.

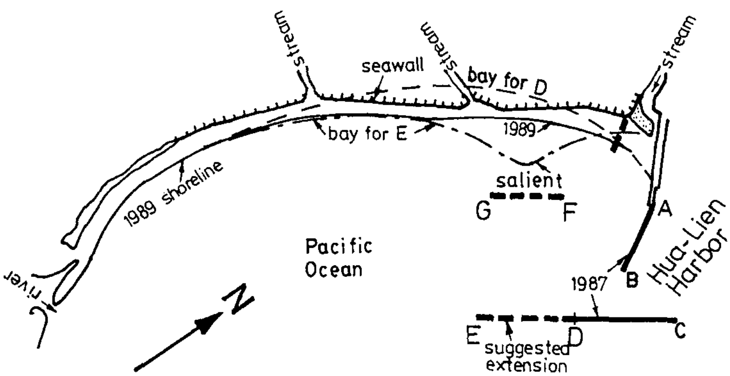

Figure 6. Hua-Lien harbor, Taiwan

4. Ohtsu harbor, Japan

The fishing harbor at Ohtsu on the east coast of Honshu, Japan (see Figure 7 for location), as seen in Figure 8, had a small breakwater complex initially in 1977. It was added to point *A* in 1984, as noted in the figure. The island structure created a new diffraction point *A* that caused accretion west of the groin at Edokomi river and between that and the Satone river outlet. The static equilibrium bay shape for point *A* is seen to match this erosion some distance from the port. To overcome this a revetment was built which suffered undermining and collapsed in places during 1983.

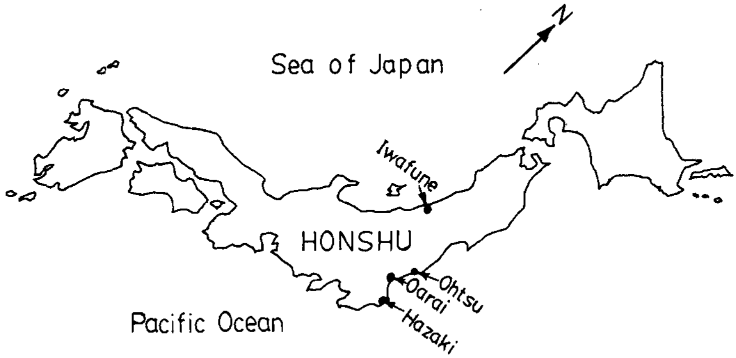

Figure 7. Map of Japan, showing locations of harbors discussed.

Offshore, in the region of the island breakwater, accretion was measured between 1977 and 1984. This was probably due to the oblique reflection of waves from this 600 m long structure that transmitted scoured material to this area. Uda et al (1986) believed these measurements were erroneous soundings. They were aware that the island breakwater had caused the beach accretion but stated: "the current induced the sand movement toward the lee of the breakwater". These authors believe it is the wave direction of approach due to diffraction that generates the new waterline orientation.

Two alternatives are shown in Figure 8 to rectify this problem, namely, either to extend from *A* to *B* or to provide a separate structure *CD*. The new diffraction points *B* and *D* result in stable beaches as shown, which indicate substantial accretion adjacent to the Edokomi river groin but less erosion further west. The additional material required for beach stability could be provided from dredging the outlets of these two rivers, to give the stable beach shown between the two groins. To deal with the slight erosion to the west an offshore breakwater could be constructed from the revetment that should be removed.

5. Oarai harbor, Japan

Oarai harbor on the Honshu coast of Japan (see Figure 7) has had many researchers analyze it (Sato and Irie 1970, Mizumura 1982, Kraus et al 1984 and Uda et al 1986). It was a small port comprising two breakwaters at 45° to the coast which was silted up quickly between 1911 and 1916. By 1976 a new breakwater was built to point *A*, in Figure 9, for which the predictable bay shape (not shown) matched the existing beach at the time (Hsu et al 1993; Silvester and Hsu 1993). In

1981 it was extended to point *B*, and to point *D* by 1985, of which the stable bays for *B* and *D* are shown. This involves massive accretion, which had partially been achieved by 1988. The sediment needed was at the expense of erosion downcoast.

In order to achieve a stable shape more in keeping with the 1988 shoreline, or even the current profile, two extensions to *E* or *F* are suggested, together with their resulting beachlines. It is seen that *F* matches the 1988 shoreline at the groin-type structure, even though it is landward of it towards the south. It is envisaged that the two small groins would be removed, which would permit the sand to find its way back to renourish beaches to the south that have been eroded. The extension of *AB* to *F* infers that breakwater *CD* would be removed as it is no longer needed for wave attenuation.

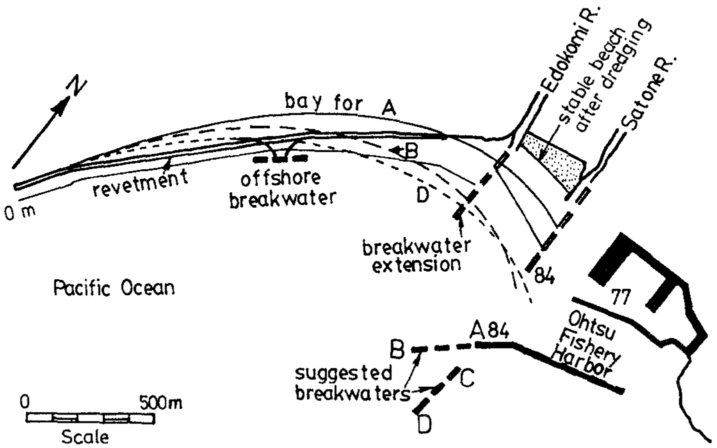

Figure 8. Ohtsu harbor, Japan

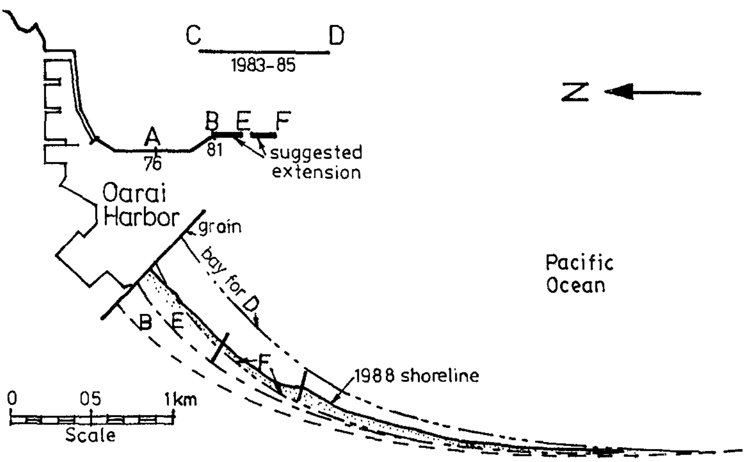

Figure 9. Oarai harbor, Japan

6. Hazaki harbor, Japan

Hazaki fishing harbor is located at the outlet of the Tone river in Honshu, Japan (see Figure 7 for location). As seen in Figure 10, a breakwater was commenced in 1974 and extended in 1976 with another started nearer the mouth. Additions were made to both in 1978 and to the SE one in 1981. By this time erosion had commenced some 600 m from the NE breakwater with accretion adjacent to it. In 1983 a shore parallel section 350 m in length was inserted to calm waters in the harbor, which became silted very quickly. Uda et al (1986) believed this was due to sediment discharge from the Tone river but the actual mechanism was not discussed. These authors believe it was due to waves being reflected obliquely from this shore parallel arm. These transported sand along it, depositing it at the entrance, which subsequently was moved into the harbor. The leg added in 1984 (see Figure 10) did little to prevent this as the mass-transport current of the short-crested wave system would have still formed a shoal at the entrance.

An extension of this leg to point *A* in the figure would achieve two important objectives. Firstly, continued oblique reflection will transmit sediment from the Tone river in a NW direction to form a shoal beyond the scoured area in proximity to its tip where an access channel can be maintained. This shoal will continually be fed to the downcoast beach. Secondly, the new diffraction point *A* will create a stable bay shape, as indicated in the figure, which will require no further structures to keep it in place. The accretion already there will thus remain for all time.

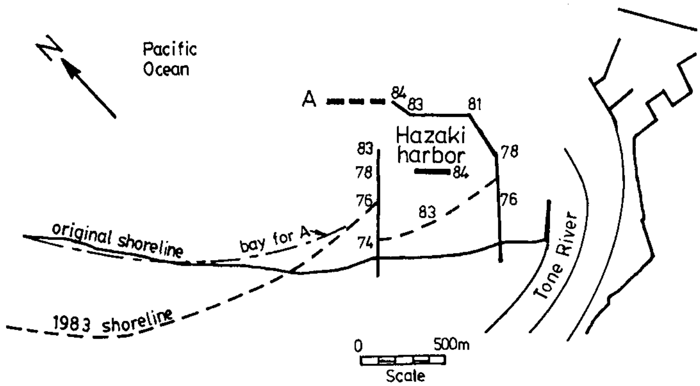

Figure 10. Hazaki harbor, Japan

7. Iwafune harbor, Japan

The shoreline evolution at Iwafune harbor (see Figure 7 for location) has been discussed by Hsu et al (1993) and Silvester and Hsu (1993). As seen in Figure 11 a large triangular land mass had been accreted up to 1988, from having attained to a stable bay shape for *A* in 1965. The static bay for diffraction point *A* matched extremely well the waterline at that time. The extensions of the main breakwater from *A* to *B* and then to *C* (by means of a detached structure) relocated the diffraction points for the incoming swell waves. The resulting bay shapes are shown which predict much more siltation if sand is available from the southern beaches. To overcome the present erosion many groins and an offshore breakwater system have been installed with little effect. The reason for this is that littoral drift still occurs offshore, just after each storm, as the storm bar is being moved back to the beach.

To prevent the transposition of further material from southern beaches it is recommended that two offshore breakwaters be installed (see Figure 11), with concomitant groin removal. The outer structure would have stable bay *C* pass through its southern tip, with the tombolo curved bay stretching to the tip of the inner breakwater. its curved tombolo would be tangential to the 1988 or present shoreline. The fill required in the lee of and south of each new breakwater could be transported by truck or pipeline from the large triangular landmass, in order to reduce siltation at the harbor mouth.

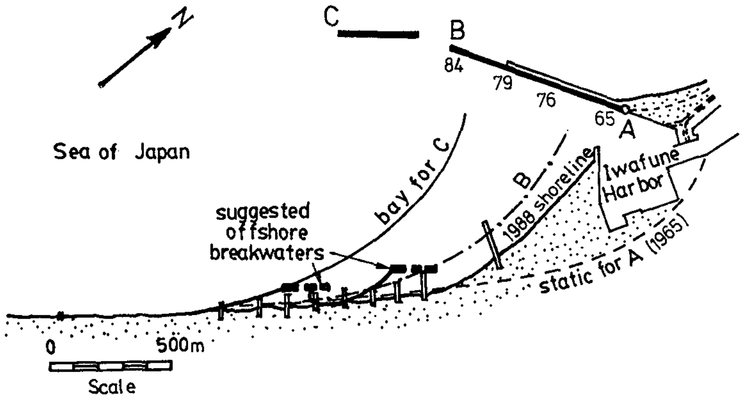

Figure 11. Iwafune harbor, Japan.

Conclusion

1. Bay beaches form downcoast of headlands or man-make structures that can be in dynamic equilibrium (continued littoral drift) or static equilibrium (zero littoral drift).
2. Should the diffraction point for persistent swell waves be altered, the bay as in (1) above will change, which may involve siltation in the lee of the structure and/or erosion downcoast.
3. A bay initially in dynamic equilibrium can be stabilized by a judicious selection of breakwater location, which then does not require any other defense measures.
4. Many major ports have suffered siltation as noted in (2) above after extension of breakwaters, together with erosion of downcoast beaches.
5. There is a dire need for coastal engineers to emulate Nature, who has maintained crenulate-shaped bays for aeons, by taking a geomorphic approach to their problems, both at the planning stage and in remedial measures later.

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