Coastal Research and its Economic Justification

By Per Bruun

Abstract

Proper and thorough planning of coastal engineering projects is discussed and the economic justification of research work indicated. Examples are given concerning navigational problems, coastal protection problems, and harbor sediment problems.

This paper is written as a causerie. No attempt has been made to base its reasonings and conclusions on a dollar-and-cents basis, but rather it stresses the importance of common sense, good science, good technology and — most important — good conscience. »All that you do — do with all your might. Anything done half is never done right«.

»We have no time for that sort of thing and furthermore we have no confidence in it«, has been the standard excuse for lack of proper and thorough planning of many coastal engineering projects whether they comprised a navigation problem, a coastal protection problem or a harbor sediment problem. The result was in one case a continuous struggle to keep an inlet free from deposits as a result of inadequate dredging — the use of inadequate equipment at inadequate time intervals. Another result was inadequate coastal protection planning — taking chances in some respects and over-dimensioning in other respects, thereby leaving the arena to engineering philosophy instead of to engineering science.

The question of *why we do coastal research* is, therefore, not difficult to answer: It is necessary to know and understand the coastal phenomena in order that we can:

because if we do not do just that the result we come up with may look as foolish as the above figure.

Coastal research includes a great number of subjects ranging from the emplacement of huge breakwaters on the ocean bottom for the purpose of checking ocean waves and sand drift to the planting of proper vegetation in marsh areas and on dunes for checking sediment transport by water or wind. The employees involved in this research programme are recruited from a great variety of fields in arts and science: geology, geography, soil mechanics, coastal engineering, hydraulic engineering, oceanography, physics, mathematics and meteorology. In order that a coastal set-up shall be a complete and fully effective organization it must include people from all of these fields, which in mutual good understanding »carry the ball« of coastal research.

A discussion on the economic justification of such research requires a discussion of the applied sides of research aspects, but it should never be forgotten that without fundamental research applied research of any importance is impossible.

Man's interference with coastal development is most powerfully manifested in »the jetty« — the huge monsters jutting far out into the ocean as »artificial promontories« built either as vertical impermeable monolithic block jetties or as sloping rubble mound or block jetties which are permeable for water to some extent but will not allow the passage through them of wave motion or littoral drift material.

Jetties are not a new invention. They were built thousand of years ago. The ancient port at Alexandria with the famous lighthouse Pharos had rubble mound jetties. Jetties for the ancient harbor at Tyre which were discovered recently have massive stone breakwaters which in construction showed a notable advance over the work at Pharos as there were two walls of hewn stone, keyed together with metal dowels — the space between the walls being filled with some kind of concrete. The Greek harbor jetties were founded upon beds of tipped impervious material with masonry forming the superstructures. Roman harbor jetties as e. g. found at Ostia were much more substantial than anything previously existing both in design and in construction. One reason was the Roman cement which contributed to stability and lasting qualities. Methods of constructing underwater works were involved and all Roman jetties and breakwaters were built of masonry founded at sea bed level. A structural technique — based on experience — was already highly developed.

Medieval ports using monolithic rock or rubble mound design and mostly having a wharf on the protected side were built in Italy, Great

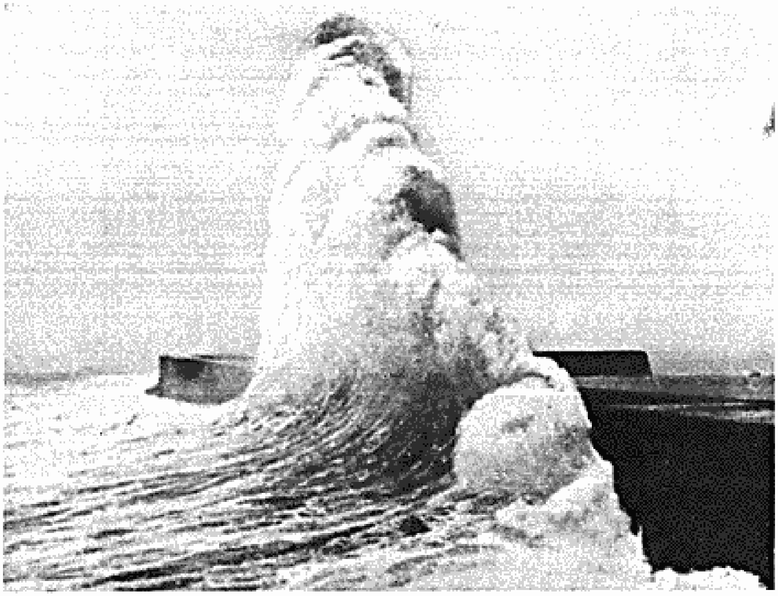

Fig. 1. Typical Storm at Catania Harbor, Algiers (H. F. Cornick).

Britain, France, Holland, and Germany. Realizing through costly experience the forces hidden in wave action, harbors were almost without exception established in protected estuaries, bays and waterways.

With the rapid development of navigation in the 19th century it became necessary to construct harbor jetties out into the open sea in countries such as France, Great Britain, Italy and Spain. The design varied from place to place, but the desire for saving materials usually resulted in attempts being made to build the jetties with as steep slopes as possible — frequently as block constructions founded on rubble mound layers on the bottom. Such jetties were often subject to extremely strong wave action and heavy damages occurred. It is no wonder that attempts at a rational approach to design of jetties based on wave forces started in these countries.

The first research concentrated on measuring wave forces in the prototype (England, Italy and France), and it became clear that there is a wide difference between wave forces exerted by deep water, shallow water, and breaking waves — the latter giving rise to extremely high shock pressures of explosive character thanks to an air pocket often associated with the breaking phenomena.

A mathematical approach to the problem of wave forces by trocoidal waves on a vertical wall was presented in 1928 by *Sainflou* whose theory was later tested by *Cagli* in full-scale measurements of wave action at Genoa (Italy), and by *Rouville* and *Petry* at Dieppe

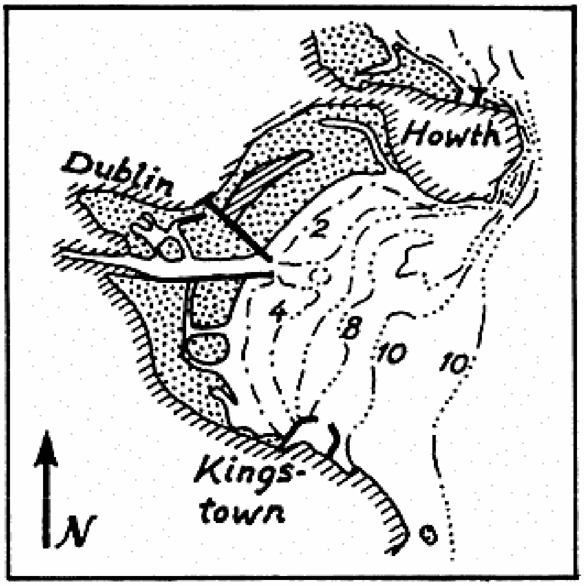

Fig. 2. Harbors at Dublin, Ireland.

(France). Based on these full-scale tests diagrams were developed which proved useful for practical design.

Meanwhile research is still not satisfactory for the shallow area where trocoidal characteristics are changed to solitary and breaking wave characteristics, and where, moreover, the direct influence of wind cannot be neglected. Most harbor jetties are located in this particular area of changing and irregular wave characteristics and most research in prototype and in hydraulic model (*Bagnold, Cagli,* and the *U. S. Corps of Engineers*) therefore has been concentrated on forces by waves which were breaking or about to break. There is considerable scatter in the results of these tests, model tests indicating comparatively much higher shock pressures than prototype tests with irregular wave trains (Dieppe, France). The collapse of or heavy damage to extremely expensive breakwaters such as those at Antofagasta (Chile), Catania (Algiers — Fig. 1), Alderney (England), and Bilboa (Spain), could probably have been avoided if wave mechanics had been explored beforehand and certain precautions taken against too heavy forces by breaking waves. Other jetties, e. g., the Dover Admiralty Pier, has stood even the heaviest wave action. It is indeed surprising that research in this particular and economically well-justified field so far has hardly involved a total expense exceeding the cost of a hundred meter's length of one of the collapsed heavy duty breakwaters. Much research work is awaiting proper action while the USSR recently announced comprehensive research on waves and wave forces to be carried out from a breakwater where rooms for research equipment were built into the breakwater itself.

Regarding the detailed design, costly experience has shown that attempts in only »estimating« the proper size of blocks (whether natural or artificial) and other pertinent factors for the stability of the jetty are often quite costly and difficulties gradually developed in regard to meeting the costs of numerous mishaps. Because of the complexity of this problem all rational approaches must be considered as semi-theoretical in as much as experience coefficients play an important role in their composition (Iribarren, Kaplan, Hudson, Hedar, U. S. Waterways Experiment Station).

Let us, from a purely engineering, wave mechanics and structural field, move into coastal morphology founded by the geographers *(Davis* (9), *Johnson* (17), *v. Richthofen)* and utilized later by the engineers who needed its results in order to understand and predict the natural development of certain coastal areas for which harbors or other coastal developments were planned. The importance of coastal research in practical life is clearly demonstrated in the harbors built at Dublin, Ireland (Fig. 2). Unsuccessful attempts at maintaining desirable depths in the estuary of the Liffey River lead to the construction of the harbor at Howth and later to the development of Kingstown harbor further south. The physical situation is that flood currents with the normal 10 ft. tidal range run north while ebb currents run south. Both currents make turns into the bay part of the river entrance. Prevailing winds are from the south and west, but the biggest waves enter the area from the east.

The bay area is greatly bothered by deposits of river and littoral drift sediments. With the construction of the harbor at Howth less trouble was expected. Meanwhile, it was unfortunate that elementary principles of coastal morphology and littoral drift technology were not considered, and the heavy sand drift from the north along the concave shoreline toward the northwest caused large deposits along the western jetty, eventually covering it completely. The third attempt in establishing a harbor was the construction of the harbor at Kingstown which unlike Howth harbour is located in the bay area on the lee side of the promontory at Howth. Because of this location littoral drift materials from the north do not penetrate into the Kingstown area, and even if the flood currents from the southeast carry considerable amounts of solids these materials are not deposited in the harbor entrance, partly because of an advantageous configuration of same and partly because the slow outgoing ebb-

Fig. 3. Miami Beach, Florida.

currents in the entrance are able to hinder penetration of materials into the harbor itself.

These harbors were all built in the 19th century when the field of coastal morphology was in its infancy. It is, therefore, not fair to blame the design engineers for their mistakes which nevertheless were of rather elementary nature. Meanwhile similar mistakes have been made in the 20th century, e. g. in Italy where uncritical use of the Italian engineer *Cornaglia's* »neutral depth« theory for sand transport toward or away from the shore led to a number of great failures e. g. Maurizio Harbor. The Danish version of the same theory, the so-called »Headland-Theory« (Pyntteori) also led to a couple of rather expensive and not very successful experiments at Hirtshals and Hanstholm which are North Sea Coast headlands. Attempts are now being made to correct these mistakes.

Proper research in and knowledge about coastal morphology could have decreased the amount of trouble and saved tax-payers the cost of expensive corrective measures.

Coastal morphology takes into consideration not only the development of planforms (4, 9, 14, 25, 27) but the development of beach and bottom profiles as well (4, 23). In order to evaluate the stability of a beach and its »foundation«, the offshore bottom, knowledge about their reactions to wave and current activity is necessary. These problems have been studied for years by coastal researchers. It is now known that beach and bottom profiles are subject to seasonal fluctuations depending upon the change in wave action from one time to another. It is also realized that their slopes cannot develop beyond a certain maximum steepness, but on the other hand it has been clarified that they are »tough-stable« and do not collapse suddenly like a piece of structural engineering, e. g. a bridge or a piece of aerodynamic engineering such as an airplane (as was claimed in Denmark by a coastal committee in 1942 regarding the stability of the Thyborøn barriers. The claim resulted in inadequately planned protection on one side and the taking of unnecessary risks on the other side. Further unnecessary precautions were taken by overdimensioning other elements, such as the time factor). A »glass of cold research ice water« would have permitted a more thorough and better justified plan from the very beginning. This is now all realized and is being corrected. The author of this article has no desire of keeping the channel open or to close it but find that whatsoever be suggested the project shall be well thought, well reasoned and tested technically as well as economically.

Speaking about sedimentation, the simplest problems are those in rivers and canals which should be mentioned briefly because of their relation to coastal problems. It is no wonder that important developments within this field were the result of research work in India, the United States and the USSR where enormous flood, irrigation and drainage problems call for proper planning, therefore, the assistance of research. China however is the country which has experienced the great flood disasters. Millions of Chinese have through the years lost their lives in floods caused by inadequate river regulation and drainage caused not least by uncontrolled sedimentation in rivers. The Chinese have now become very active in this research where basic knowledge of physics and mathematics is so important and this fits into the Chinese mind.

British engineers in India made the first contributions to the practical sedimentation technology introducing the so-called »regimen theories« as a basis for design of drainage canals (Sir *Claude Inglis*). Engineers in India and *Thomas Blench* in the United States later followed up behind this line while the USSR and Germany took more interest in the physical aspect of channel stability. *Meyer-Peter's* work in Switzerland, *Shield's* work in Germany and *Kalinske's* work in the U. S. A. further developed this field which went into its purely physical and final development stages by the work of *Einstein* and *Chien* in the U. S. A. (13) The results were: better

Fig. 4. Palm Beach Inlet, Florida. North to the right.

planning, fewer mishaps and, therefore, huge savings. One of the bad examples of planning which ignores sedimentation laws was the construction of a huge hydraulic power plant in the Congo. Shortly after its completion the plant choked up with sediment deposits and the project had to be re-worked (by model experiments).

Let us from this introduction return to sediment problems on seashores where they are mainly concentrated around harbor and coastal protection works.

Sedimentation problems on seashores and their relation to man-made structures can most effectively and conveniently be explained by the terminologies »Source and Drain«.

A *source of materials* is a coastal zone, submerged or emerged, which delivers materials to other coastal areas. A source might be an area where erosion takes place, a shoal in the sea e. g. located on the downdrift side of a (newly) jetty-improved inlet, the shallow area in front of an inlet which has been closed, a river which transports sand material to the coastal zone, or sand drift from dunes to the beach. Artificial nourishment of any kind to a beach is also a source.

A drain of materials is a coastal zone where materials are deposited. Natural drains include marine forelands of any kind such as spits, recurved spits, tombolos, cuspate forelands, angular forelands, etc. The drains may also be a bay, an inlet or a shoal. Artifical drains include man-made constructions such as jetties, groins, dredged sand traps, inadequately designed and inadequately constructed harbors etc.

In practical coastal engineering and littoral drift technology the following rules are valid.

(1) a coastal protection should be built in such a way that it functions as a drain. It should, therefore, have a source but not a drain on the updrift side. If there is a drain the coastal protection in question cannot be expected to work satisfactorily unless materials are supplied artificially to the shore in question.

(2) a harbor (or an improved inlet) on a littoral drift coast should not act as a drain. It is, therefore, desirable that it has no source area or only a limited source area on the updrift side or on either side of it. It is best if it has a drain on the updrift side or on both sides.

Without making themselves fully clear on the importance of »sources« and »drains«, geographers, geologists and engineers have, with great eagerness, studied these phenomena for decades; the geographers concentrating on the coastal morphology aspects (17, 25, 27); the geologists most often on the mineralogical aspects and the engineers on the total amount of nuisance caused by inadequate understanding, therefore, lack of respect for nature's source and drain rules and regulations (1, 4, 7, 24).

Let us consider a few of these cases. Fig. 3 is an aerial photograph of Miami Beach, Florida, which is provided with a great number of wooden or steel groins. There is, however, very little beach left and statistics indicate that only approximately 15 per cent of the visitors to this famous beach and seaside resort ever swim in the ocean. The 85% prefer to stay on the dry side of the shoreline or else enjoy swimming in the numerous swimming pools which have now been built. The natural conclusion seems to be that Miami *Beach* is not a very attractive beach for ocean bathing, and the reasons for this apparently are a too little and not a very attractive beach, steep offshore bottom, dangerous currents at the vertical wall groins and too much loose shell material (up to 50%) in the beach sand.

Using coastal engineering terminologies the reasons could also be expressed as a result of lack of any source of material for the groin system in question. It has probably cost several millions of dollars

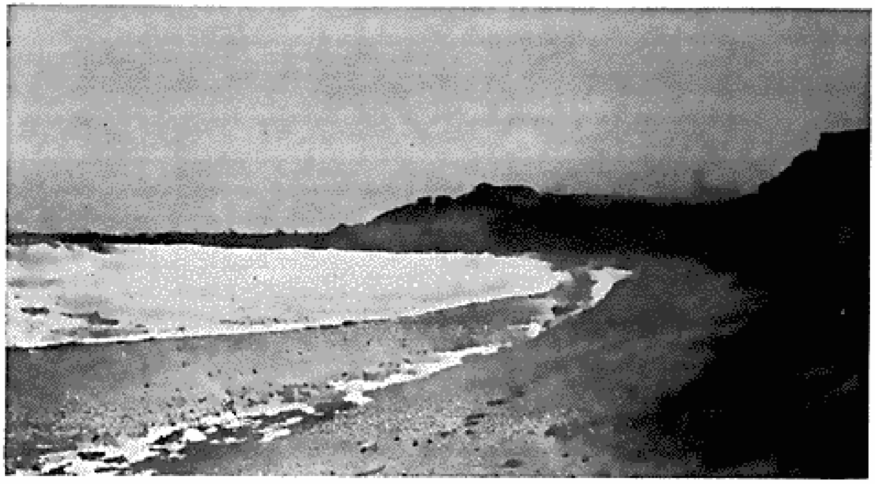

Fig. 5. Leeside Erosion on the Southside of a Group of Groins at Bovbjaerg, North Sea Coast, Denmark.

to build up coastal protection at Miami Beach mainly based on groins and vertical sea walls, and the outcome as described is that only little beach is left. If a source of suitable material for beach nourishment had been located in the bay and this material had been dumped on the beach we would still have had and could still maintain a beach at Miami Beach instead of great amounts of coastal protection junk.

Another example, Fig. 4, is an aerial photograph of Palm Beach, Florida, after the inlet was dredged and the jetties which were built in 1918-1925 had blocked the southward littoral drift almost completely. The consequence was heavy erosion on the southside of the inlet. Through a number of years attempts were made to combat this erosion by construction of a great number of groins, but being without any source of material the groins failed. Modern development in the coastal protection field was later responsible for artificial nourishment from the bay and finally (1958) a by-passing sand plant was put in operation on the north side of the inlet and is supposed to pump 200.000-250.000 cu. yd. of sand fill across the inlet per year. Further south it is the intention to nourish the beach from dredging operations in the bay. It would probably have been better if groins had never been built.

It is a well-known fact that groups of groins function as drains and for this reason will always have adverse effects on the downdrift shore. If groins were not drains they would not work at all (24). It may, nevertheless, not be fully recognized that groins will usually cause considerably more erosion than accretion! A good example of such tremendous disadvantage to the overall picture is illustrated by Fig. 5 showing the last groin in a group of 130-250 meter long groins on the Danish North Sea coast at Bovbjerg. The groins in question have stabilized the beach where they were built, but on the leeside (southside) they have caused erosion of the shoreline of up to 10 meters per year in farmland. It is now the intention to build more groins on the 2 kilometer non-protected downdrift shore extending to the next group of groins which consist of only five partly abandoned shorter structures. Meanwhile the result will only be an extension and activation of the erosion problem further south.

This again points with adequate clearness to the fact that artificial nourishment of beaches is to be much preferred as shore protection because it is entirely free of skirmishing »boundary conditions«. Meanwhile in order to utilize artificial nourishment it will be necessary to develop better and more suitable dredging equipment as e. g. nuclear powered submarine dredges such as suggested by the author in an article in the »Shore and Beach« (American Shore and Beach Preservation Association) in June 1959.

Harbors are not supposed to work as drains for littoral drift materials. They are supposed to work contrarily. They can, however, be built in such a way that they present marvelous »olympic gold medal drains« because of not being designed correctly. The harbor of Madras, India, (Fig. 6) presents a very instructive case (7). Its breakwaters extend outward about 1000 meters from the original low-water shoreline (1876). Up to 1913, a large triangular area of sand about 260 acres (105 hectares) in extent had accumulated on the southside of the harbor; on the northside considerable shoreline recession had taken place. The old entrance to the harbor was centrally situated between the breakwaters facing east and the sand drifting northward found slack water between the pier heads in which to settle with the result that before the entrance was closed it was shallowing up at the rate of about 1 ft. per year. In 1902 a northeast entrance project was started including a 400 meter long sheltering arm completed in 1911. The result of this closing of the old entrance and extension of the eastern arm was continued deposits along the whole eastern jetty face which would have become more and more pronounced if it had not been checked by comprehensive dredging operations. Another advantageous result of the described »remodeling« was that the harbor became smooth enough for working cargo into and out of lighters alongside the ships and piers in practically all kinds of weather. Later another sheltering arm was built at the southern corner of the harbour, where accumulating sand is checked by a suction-dredge (mounted on the arm) which pumps the spoil into hopper barges moored inside the harbor. All the expensive nuisance described above could have been avoided with proper planning, but the hydraulic model technique was unknown when the harbor was first built in the 1870—1880 period.

The same is true for Zeebrügge harbor in Belgium which was completed in 1907. It has the configuration of a big northward curved »nail« (Fig. 7). 5-6 ft./sec. (1.5-2 m.) and heavy silt laden flood currents from the southwest carried 3—4 million cu. meters of silt per year into the harbor to be deposited on the leeside of the jetty in a big eddy current. Attempts were made to flush this material away by a 400 m. wide »clair-voie« (opening) at the land end of this jetty, but the result was an increase rather than a decrease in the deposits. The opening was, therefore, closed and after World War II hydraulic model experiments were carried out partly in Holland and partly in Belgium to solve this problem. Fig. 7 is a photograph of a floodtide situation demonstrating the current pattern. By constructing a large semi-circular breakwater to fill out the eddy area, deposits in the harbor will decrease about 50% which, in turn, will present a tremendous saving in maintenance costs of the harbor. The remainder of the material bypasses the harbor with the tidal currents.

In somewhat similar model experiments with the Karlsruhe river harbor in Germany special jetty configuration se-

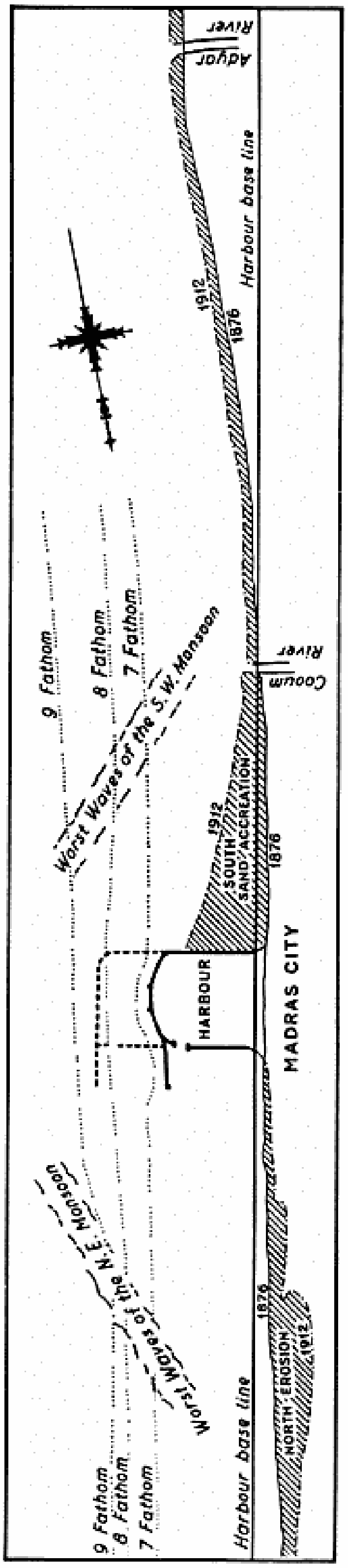

Fig. 6. The Harbor of Madras, India (H. F. Cornick).

cured by-passing of heavy bed-load transport in the river flow.

The harbor at Abidjan, Ivory Coast, Africa, presents a similar problem which was properly solved by model experiments in the Netherlands. A cut was made to connect the ocean with a lagoon to accommodate vessels of 27 ft. draft (Fig. 8). Sand coming from the west is deposited by the flood current at »M«; the ebb current, which is strongly concentrated at that point transports it in the direction of »P«, where part of it settles in a deep hole in the sea bottom.

In this case, as well as in many other cases of research, man was successful in making nature his servant and this is so much better than making nature an opponent or enemy. This philosophy is true for artificial »man made« harbors with jetties, breakwaters, wharfs, etc. as well as for natural harbors which man has tried to improve in different ways. This last mentioned subject has been given much thought by coastal morphologists, whether they were geographers, geologists or engineers, and deserves special mention because of its relationship to one of the most interesting subjects in coastal research.

The ancient Egyptian, Phoenician, Greek, Roman and Viking naval fleets were based in estuaries, bays, fiords and lagoons and we find similar installations today at such places. Now, as thousands of years ago, the tidal estuary, river or inlet is a cultural factor of immense importance.

It is customary to talk about »nature's delicate balance« which man cannot touch without bringing about adverse effects. The fact is that everything in nature is in a process of development and man by interfering with this development can influence the natural process in one way or another and the accompanying effects will usually be adverse in certain ways, but advantageous in other respects.

Inlets have always been »problem children« and this is particularly true for those inlets which have resulted from breakthroughs on littoral drift shores — and this is the greater part of them (3).

Lack of understanding of inlet-physics led to misuse of inlets, particularly when they were loaded with more navigation responsibility than they were able to carry on their sand and water shoulders. The result was an endless succession of failures. There is hardly an inlet on the United States barrier east coast (or on the Danish North Sea coast) which has not caused all kinds of trouble including irregular shoaling or deepening, uncontrollable meandering, erosion or accretion, unprovoked movements, or even sudden »disappearances«, furthermore, headaches, backaches and ulcertrouble. This is true whether the name of the inlet is Ponce De Leon, Great Egg,

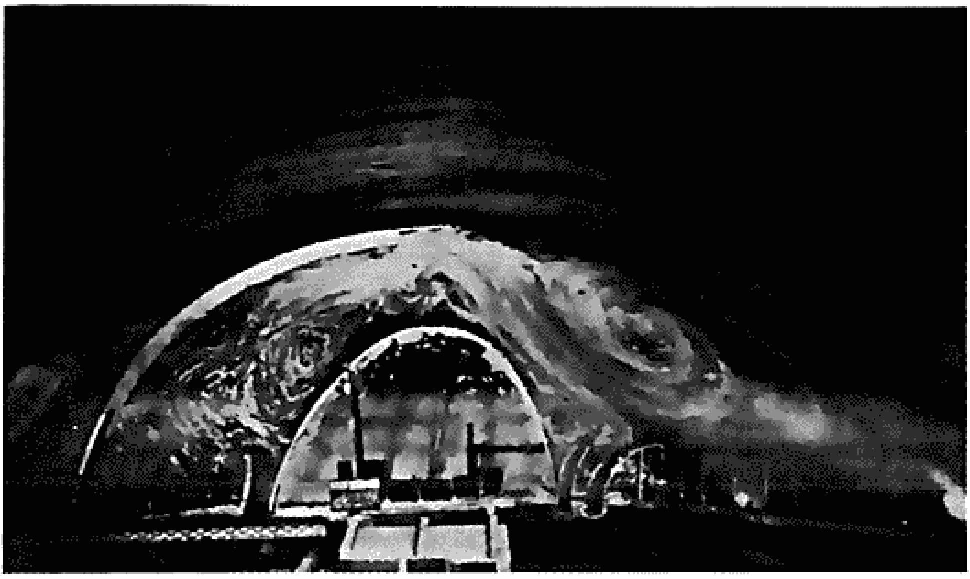

Fig. 7. Model Experiment with Zeebrugge Harbor, Belgium (Waterbouwkundig Laboratorium, Antwerp).

Man-Killer (Matanzas) or Thyborøn. The reason why they were »problems« was that they were not »understood«, and for a long time their various »doctors« were representatives from all branches of life including butchers and lawyers (but not coastal researchers who were able to handle the problem from a physical point of view). *Brown* (3) and *O'Brien* (22) were responsible for the first real progress which later was followed up by the work of others on an entirely physical basis (2, 5, 6, 8, 12). It is now known that an inlet in alluvial material is not only a »difficult hole in something else« but that it — as everything else in nature — depicts a balance between the acting forces. Based on analysis of many inlets (5) it seems possible to express the stability of an inlet »Stab« as:

$$\text{»Stab«} = F\left(t_s, \frac{O}{M} \cdot \frac{Qm}{M}\right)$$

where t_s is the so-called »stability shear stress« between flow and bottom. ($t_s = \frac{PgV^2}{C^2}$, where p = density of water; g = acceleration of gravity; V = mean velocity of flow; and C = Chezy's friction coefficient). O = the so-called »tidal prism« which is the total amount of water flowing through the inlet in one half tidal cycle, usually referring to spring tide, flood or ebb conditions; and M = the amount of littoral drift material brought to the inlet entrance per year. Regarding Qm, see below.

Considering first the t_s, a great number of analyses of inlets have

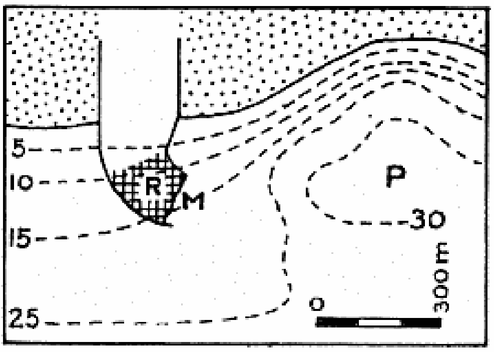

Fig. 8. Abidjan Harbor, Ivory Coast, Africa.

shown that the cross-sectional area of the inlet gorge, which is the smallest cross-section in the inlet channel, can be considered explicitly as a function of different factors such as maximum flow, configuration and shape of the cross-section flow characteristics, shear stress between flow and bottom, soil conditions, suspended load and littoral characteristics, wave action, freshwater head flow, and finally the »time history« of the inlet channel. These factors are interrelated and further analyses have shown that the shear stress t is the most practical and useful parameter (5). The question of inlet stability has therefore become a »structural design problem« in which detailed computations of flow (12) must be compared with »the allowable« or »the ultimate strength« of the bottom (»the determining shear stress«, t_s) which in turn depends upon the factors mentioned above. t_s for »average conditions« is about 0.39 kg/m^2; for heavy littoral drift conditions, 0.47 kg/m^2; and for light littoral drift conditions, about 0.32 kg/m^2. It is hopeless to endeavor to maintain an inlet with free flow over an alluvial material bottom with lesser values of t_s.

Meanwhile satisfactory $\frac{O}{M}$ and $\frac{Qm}{M}$ ratios are as important as an adequate t_s. Consideration of a great many inlets (5) have revealed that those having a $\frac{O}{M}$ ratio in excess of 300 have a higher degree of stability while inlets with $\frac{O}{M}$ ratios < 100 have a more predominant transfer of sand on (shallow) bars across the inlet and less significant tidal currents, for which reason they are rather unstable and usually characterized by narrow, frequently shifting channel(s) through shoals. It is not possible to say where the transition $\frac{O}{M}$ ratio between stable and unstable inlet channels lies because the littoral drift irregularity, in quantity as well as in direction, most likely will make it impossible to establish such fixed ratio. Meanwhile, numerous mishaps could have been avoided if such (in fact) rather elementary problem had been investigated and taken into consideration properly before actual construction work commenced, but regardless of where you go in the world the philosophy seems to have been that »everybody shall have his private inlet exactly where he (not nature) pleases« (28).

The question of an adequate $\frac{O}{M}$ ratio automatically brings to light the fact that littoral drift material — even with the most advantageous t_s and $\frac{O}{M}$ — cannot pile up infinitely on either side of the inlet's seashore or on sea and/or bay shoals. It is necessary to get rid of this material by passing the material across the inlet channel either by natural or artificial means.

If nature itself in numerous cases did not by-pass sand across inlets, passes, and channels on seashores a number of »marine forelands«, including barriers, spits and entire peninsulas would not exist. A typical example of nature's strategy is found in Florida which was built up of sand washed down by rivers and streams from the Appalachian Highland and carried southward, crossing estuaries and tidal inlets, for final deposition in the huge barrier and ridge systems which we call Florida. In fact northern Florida seems to be the world's largest recurved spit system (25, 28).

The two main principles in by-passing or sand by natural action are:

By-passing on an offshore bar, and
By-passing by tidal flow action.

Most cases present a combination of these two methods.

A submerged bar in front of an inlet or harbor entrance on a littoral drift coast will often function as a »bridge« upon which sand material is carried across the inlet or entrance (6). Every channel dredged through the bar will, therefore, be subject to deposits.

By-passing by tidal flow action takes place when littoral deposits are spoiled out of the inlet by ebb currents in the downdrift direction. Both bar and tidal flow by-passing include cases of irregular transfer of large amounts of materials in migrating sand humps or by change in the location of channels.

Research (6) has revealed that one can distinguish between inlets or entrances with predominant bar by-passing and inlets with predominant tidal flow by-passing by considering the ratio $\frac{M}{Qm} = r$ between the magnitude of littoral drift (M in cu. yd. per year) and the quantity of flow through the inlet or entrance (Qm in cu. yd. per sec. under spring tide conditions).

If this ratio is >200-300 bar by-passing is predominant; a ratio <10-20 indicates that conditions for predominant tidal flow by-passing exist. Meanwhile, whether or not such by-passing actually takes place depends on whether or not it is possible to use the tidal flow for transferring material in the downdrift direction. This depends, among other things, upon the inlet configuration. Inlets exist which, due to strong tidal currents, jet material so far out into the ocean that it is lost forever to the shore. Characteristic examples of this situation are Ft. Pierce Inlet and Bakers Haulover Inlet in Florida where inlet ebb currents up to 7-8 ft./sec. may occur, particularly at the Haulover Inlet (28). Similar current velocities may exist in Thyborøn channel after a storm when the tide is running out shooting material out into the North Sea.

By-passing problems can be solved by careful planning including model experiments as e. g. carried out for the harbors at Abidjan, Lagos, the Volta River and many others. Failures and heavy maintenance costs have in this way been avoided. Establishment of sand traps including devices for artificial (mechanical) by-passing is an example of man's »cut-through« of the problems when other solutions were not convincing or possible as e. g. at Palm Beach Inlet, Florida (Fig. 4).

The sediment transport field is still in a state of rapid development with the radioactive tracing technique being the newest invention. Two different types of radioactive labeling are now in use: the direct labeling and the artificial labeling. The direct labeling can be realized either by neutron activation of sediment constituents (as with the phosphorus — 32 St. Peter quartz sandstone from Kentucky) or by absorption into or the depositing on the sediment's surface of a radioisotope as e. g. radioactive gold Au 198 (used in California), and radioactive silver Ag 110 (used in Portugal). The artificial labeling is employed by the solution of a radioisotope in melted glass which when ground and property screened is supposed to reproduce the properties of the sediment. The best traces seem to be the isotope Scandium (Sc) 46 which has been used in rivers (the Thames) as well as in the sea (off the Norfolk coast). The Russian luminophore method uses fluorescing materials.

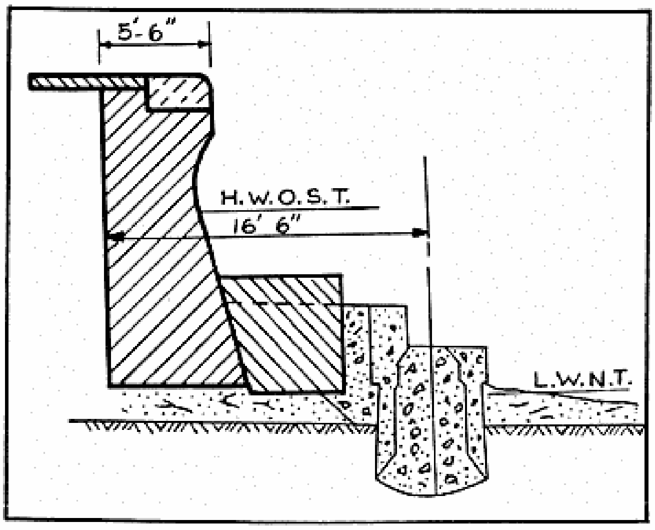

Fig. 9. Sea Wall at Bray, Ireland.

The Sc-tracing technique was developed particularly in Great Britain (10, 11, 15). An example of the use of Sc 46 is the now classic Thames River experiment carried out in 1954 and 1955 by the Hydraulics Research Establishment, Wallingford. The isotope Scandium 46 was selected as a suitable gamma-ray source, with a convenient half-life of 85 days. The Thames experiment was arranged with the object of demonstrating with certainty whether or not landward transport of silt takes place in the Thames Estuary. The tracer material had a density similar to that of Thames mud, and consisted of soda glass containing about 1.5 per cent of scandium oxide. Material corresponding to 30 curies was injected in the main shipping channel abreast of the entrance to the tidal basin of Tilbury Docks at the upper end of Gravesend Reach, 26 miles below London Bridge. No dredging of the shoal area at the lower end of Gravesend Reach during the period of 18 days immediately preceding injection was carried out, so that the radioactive material would not be unduly attracted there. Immediately prior to the time of the test a systematic blank survey was made of background readings on Geiger counters on the bed of the estuary between 8 and 38 miles below London Bridge. The scandium glass was mixed with natural mud and released from containers on the river bottom after which detection started. One of the surprising results obtained during the next three weeks of tracing was that in the tidal basin at Tilbury Docks (12 miles above the injection point) where siltation necessitates considerable dredging, the activity gradually increased to 3 times the background value during the first fortnight. From the total number of observations it became quite clear that silt can move toward the head of the estuary in these reaches when it is known that close to the bed there is a net landward movement of water. This, in turn, indicates that dredged material should be pumped ashore behind the high water line. This change of practice compared to the present dumping in the outer part of the estuary practice would not be expected to have an immediate effect on the river because regime is a delicate balance between accretion and erosion, and as material was removed, it would be partly replaced by material eroded from the mud flats and by fine silt from the coast washed into the estuary on flood tides, some of which would deposit in the estuary instead of being washed seaward on the ebb as hitherto. Gradually, however, the balance would change until eventually a considerable improvement would occur, with a corresponding reduction in the amount of dredging required. The economic importance of this would be enormous.

Similar techniques are now under development for the seashore, the USSR, Great Britain, and Portugal having the lead so far.

The conclusion of the abovementioned on sediment transport in streams as well as in the sea is not an unusual one; it is much better to have nature as your friend than as your enemy.

Typical examples of a somewhat different method of making nature a real enemy are presented in the numerous vertical coastal protection sea walls built everywhere in the world whether they are heavy gravity walls of English type or steel sheet-pilings such as e. g. the Florida shores are cluttered with — many of which are turned over or are in other ways worn out because of misunderstood use and inadequate design (28). Fig. 9 shows a gravity wall at Bray, Ireland. It was built in 1884-86 with cross-section as shown by heavy full lines. Meanwhile its vertical face contributed to an increase of erosion at the same time as oversplashed water and inadequate drainage aggravated its stability. It, therefore, became necessarry to put a sheet-piling apron in front of the wall, but its vertical face had the same adverse effect as the original wall. Finally it was necessary to put one more (caisson) apron in front of the other apron and all of this became very expensive. Today Florida continues the same mistakes made in Ireland 70 years ago. Fig. 10 shows a photograph of Jacksonville Beach in Florida, and it clearly demonstrates what happens when an equal amount of misunderstanding of the problem and lack of proper planning made up the prevailing background for the design. Some miles of similar seawall collapsed in that way in

Fig. 10. Jacksonville Beach.

Florida, and more will collapse in the near future because Florida has been due for a serious hurricane flood for several years now.

The statistical approach to storm flood tide analysis was »born« in Holland. In 1939 *Wemelsfelder* published a statistical analysis of high tide data from the Dutch coast. His method when adjusted to and interpreted in agreement with the local situation allows estimation of the frequency of high tides and also, using great care, extrapolation outside the zone of present experience. Such frequency analysis now in progress in Florida and elsewhere where storm tides are common are of great importance, e. g., for the determination of the insurance values of real estate in coastal areas. In Florida, despite the lack of adequate data, the available information clearly shows that the possibilities of flooding are high and, unfortunately, very much under estimated. At many coastal communities and developments even the most elementary considerations with respect to safety of life and damage to property have been disregarded and the inhabitants are living on »borrowed time«. Those who »developed« the coastal areas in question are not easy to find but may occasionally appear behind the so-called »free press« when they believe that this will help them force their dollarbased desires and inadequate projects through.

The above examples all consider »wet parts« of the coastal research fields. Other parts are only half wet or perhaps all dry. A company built a rubble mound breakwater pier somewhere in the United States. This pier was supposed to carry pipelines for fuel oil.

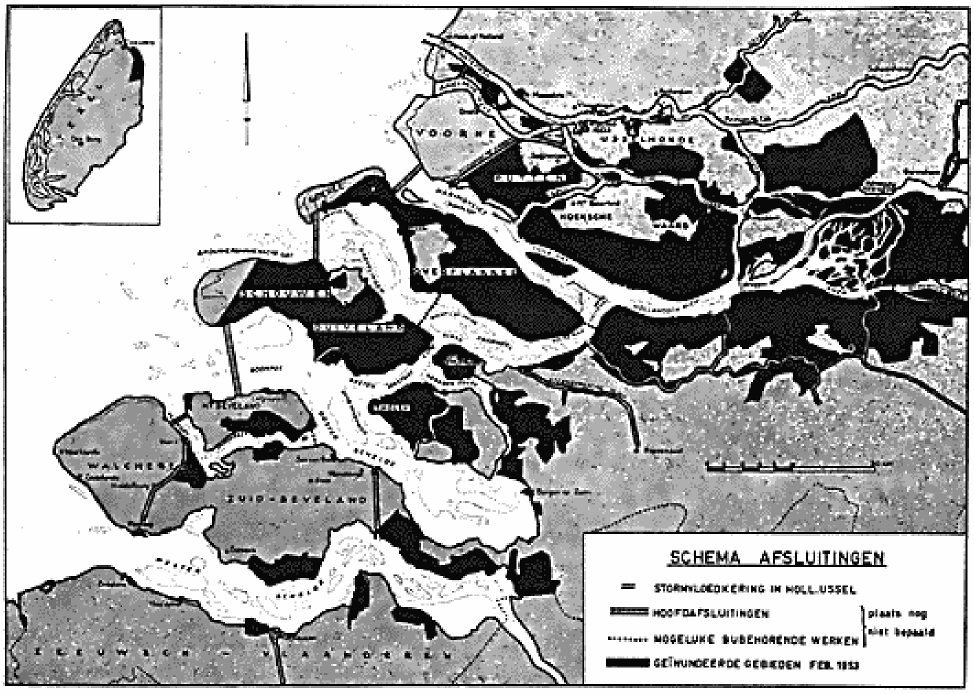

Fig. 11. Layout of the Delta Project, Netherlands (J. van Veen).

It was called to attention that a conservative rigged pipeline would not be a proper solution under the given circumstances, but it was built in that »headed-for-trouble-way« anyway and became an expensive »baby« for this reason. A little research — such as suggested — would have saved the company tens of thousands of good American dollars.

Half wet coastal work includes reclamation of land in swampy areas and in marshland. Here again it is true that the intelligent method of procedure is to let selected plants do reclamation work instead of hauling in all the dirt over perhaps long distances. Examples of such reclamation work are found in the British and Dutch Spartina Grass marshland and in the Danish reclamation work on the North Sea coast.

The dry counterpart to this vegetation reclamation are the measures against sand drift by proper plants as e. g. *ammophila* species (helme). Where formerly wind blew away dunes and piled up sand on roads and agricultural land proper plantings have been able to build up dunes and dykes where they were wanted for coastal protection reasons such as the Danish West Coast sand dykes. In the United States, Cape Hatteras National Park is now using mechanical planting machines pulled by crawler type tractors and developed by

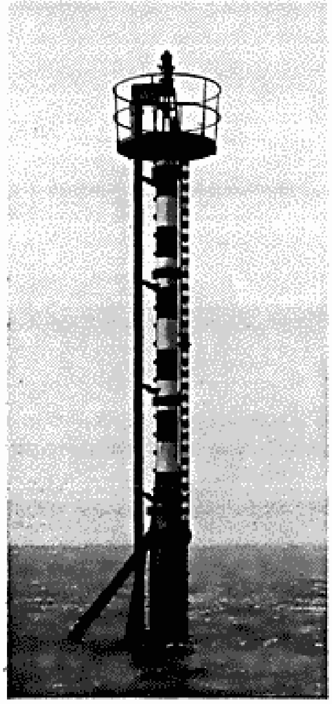

Fig. 12. Symbol of Modern Coastal Research — Dutch Survey Pole in the North Sea (Delta-Werken).

its own research. The practical dunes planting research by the National Park Service is expected to be able to decrease the unit price of planting to about 50% of the cost of conservative methods of planting by hand.

Plants have been imported to Florida from North Carolina and Denmark and are doing fine, but more research is necessary to find plants which will fit the different climatological zones.

Let me finish this »sermon« on coastal research by mentioning one of the largest — if not the largest — coastal engineering research projects the world has ever seen, which is the research programme associated with the Dutch »Delta-Project«. This huge undertaking was initiated after the 1953 flood-disaster which killed approximately 2.000 people and caused a billion dollars worth of damage (2.000.000.000 fls).

The contours of the Delta-Project are shown in Fig. 11 (14). It includes three big dams in the river entrances and two smaller ones further inland. The waters of the Delta area will be divided into two separate basins by means of dams. The southern basin will be entirely cut off from the sea and become a freshwater lake. The northern one, which comprises the mouths of the Rhine and Meuse Rivers, will continue to be connected with the sea because the waterway to Rotterdam must remain open to shipping. Tidal waves will, therefore, still be able to penetrate inland by way of this basin but they will only cause high tides in the waterway itself.

In order to secure the best and most economical result from this huge project the cost of which may be as high as one billion dollars worth (almost 2.000.000.000 fls) before it is completed in the course of approximately 25 years the Dutch have undertaken an extensive research programme including research on tides, tidal currents and density currents in the Delta area itself and in the connecting areas. Furthermore, detailed studies of wave action and sand movement are under way using the most modern techniques including the establishment of permanent automatically operated »pole-stations

(Fig. 12) out in the North Sea which are loaded with instruments such as wind recorders, tide recorders, wave recorders, current recorders, etc.

Perhaps the most intriguing part of the enormous research programme is the tidal research including the influence of structures on the penetration of tides whether they are of astronomic type or are mainly storm tides (12). In the Netherlands no less than three different methods of tidal prediction are now in use: the hydraulic model, the computation method, and the electric analogue method. Each method has its typical merits and limitations. For some purposes one may be more suitable than the other. Perhaps a coastal researcher in the applied sciences will get the most impressive look he can ever have by visiting Prof. *Thijsse's* Dutch Nordoostpolder »Open Air Laboratory« where up to 30 models from the Netherlands and elsewhere may be seen at one time.

If you ask the Dutch if all this research pays they will most likely answer that »they simply cannot afford not to do it«. Furthermore, you should remember that the »Lord made the world but the Dutch built Holland«.

Conclusion.

From the above causerie of examples of economic justification for coastal research it may appear that the author of this paper is inclined to believe that coastal research is something which we should always do considering it at least from a face-saving point of view.

This it not the idea at all. He honestly considers it as being entirely irresponsible and foolish not to *plan ahead* because nobody can defend or afford to spend $25.000.000 for a second-class product if he can secure a first-class product for $20.000.000 or perhaps $30.000.000 with the additional $5.000.000 well spent for urgently needed improvements.

A designer's »sense of responsibility« should always be related to knowledge about his safety factor which he studied carefully before proceeding and not to overdimensioning of boundary conditions and design related to lack of adequate knowledge about the problem.

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