HYDRAULIC STRUCTURES FOR COASTAL PROTECTION

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Summary

A brief overview is given of coastal defense structures, including breakwaters, used to protect low-lying areas (polders) against flooding, to stop erosion of existing coastlines, and to provide protection to ports which are part of the life supporting transport system. Possible coastal structures include dikes, revetments, block sea walls, bulkheads, rubble mound sea walls, groins and offshore and land-connected breakwaters. The choice of structure depends mainly on its function, the availability of suitable construction materials and economic considerations. If close to recreational areas, environmental aspects will also play an important role. In these cases, artificial beaches are often considered.

The main design parameter for coastal structures is the local wave conditions. The understanding of waves has greatly improved over the past fifty years or so but the wave-structure interaction can only be approximated by empirical formulae, such as the Hudson formula for the stability of armor units on a structure slope. These formulae can be used for a conceptual design, but to check and optimize the design, use is normally made of hydraulic models. Particularly in the case of large structures with steep slopes, the geotechnical stability of the structure as a whole (including the foundation), of the outer (and inner) slope, and of a possible crown wall must also be checked.

Materials available for the construction of coastal protection works are listed. By far the most commonly used materials are sand and natural rock (armoring). Improved filter action is achieved by using geofabrics. Special care must be taken when using steel in the sea environment (galvanizing), while asphalt products fill a particular niche (waterproofing).

Due to limited knowledge of the design conditions on account of their stochastic nature, and the lack of "exact" design formulae, significant damage to coastal structures, has occurred and still occurs. Therefore, performance monitoring of the behavior of coastal structures is essential to improve the design techniques, for better interpretation of hydraulic model test results, and for proper maintenance planning.

1. Introduction

In the low-lying countries of the world, like the Netherlands, humanity has been involved with coastal protection works since the first millennium. Dikes and elevated living quarters have been built using available materials and hand-tools in an attempt to provide adequate "life support systems" against the onslaught of the sea.

Transport has always been, and still is, one of the most important life-support systems, and transport by sea was, and still forms, the backbone of human transport activities. The ancient Mediterranean ports go back to about 2000 BC when large natural rock blocks were used to protect the required harbor areas from wave action. These early placed block breakwaters were followed at Piraeus in 500 BC by a tipped-rubble breakwater covered by heavy block armor, doweled together.

Due to lack of proper design tools, and sometimes, lack of skill, many of these early sea defense works have suffered extensive damage and had to be repaired or rebuilt several times over the years. More recently, the understanding of the natural forces, which attack these structures, due to waves, winds, currents, tides and earthquakes, has greatly improved, and appropriate design procedures have been developed over the years (see *Hydraulic Structures in Ocean Engineering*).

2. Types of Coastal Protection Structures

There are a great variety of structures developed for coastal protection, which are described in this section, together with the considerations leading to the best choice between the different options.

2.1 Different Types of Structures

The following are types of structures which can be used for coastal and harbor defense projects (see Figure 1):

- Sea dikes or levees. These are generally made of sand covered by a clay layer which is protected by some kind of armoring or revetment in the area attacked by waves; these structures are used to protect low lying areas or "polders" and areas subjected to large tidal variations.

- Revetments. These are slope protection works consisting of pattern-placed natural rocks, e.g., basalt, or relatively light interlocking concrete elements, laid on a graded gravel filter and/or geotextile fabric; revetments are used on dikes and for the protection of shorelines, particularly in areas with strong currents and/or light wave action.

- Sea walls. These are near-vertical or sloping structures, built either of natural rock blocks, interlocking concrete elements, or solid concrete. They are often built with a curved splash-wall on top; and founded on piles or gabions, sometimes provided with a sheet-pile toe-scour protection. These types of structures are normally used on the upper beach to protect back-shore developments against storm waves.

- Rubble mound sea walls. These are major protective structures, usually consisting of a core of mixed quarry run, e.g., 1–1000 kg, covered by one or more under layers of different sized rocks and a cover layer of large armor rocks, e.g., 5–10 tons. These structures are used in areas of heavy wave attack to protect an eroding shoreline, and as "stand alone" protection for reclamation works.

- Bulkheads. The main function of these near-vertical face structures is to retain fill, but they must be able to withstand moderate wave action and associated bottom scour when built in the sea environment. They are usually built from steel or concrete sheet-piles, or interlocking blocks, for protecting reclamation areas, or for supporting unstable back-slopes.

- Groins and jetties. Although in the past there were many examples of solid timber or concrete groins, these structures are now usually made of a core of mixed quarry run, covered with some type of underlayer and natural rock or concrete units placed randomly or in a pattern as main armoring. Groins are used extensively to stabilize eroding beaches, particularly where there are strong long-shore currents. When used to stabilize river mouths on a sandy coast for improved navigation, these structures are normally referred to as jetties in the US.

- Offshore breakwaters. These can either be built as vertical structures, such as may be created by means of hollow floating concrete caissons that are lowered into position to the sea bottom and then loaded with sand and provided with a concrete crest structure, or they can be constructed as normal rubble mound structures, similar to the rubble mound sea walls. They can either be non-overtopping (with a high crest level), medium-overtopping (with a low crest level, say about two meters above sea level), or submerged structures. They are used extensively for beach formation and protection, and also to provide protection to littoral-drift sand-bypassing systems at coastal inlets.

- Artificial beaches. If adequate quantities of suitable sand are available, the shore can be protected by building a beach in front, possibly together with a system of groins or offshore breakwaters. If necessary, these can be artificially maintained by means of additional sand supplied at regular intervals. This "soft" solution is both technically and environmentally attractive, particularly for sensitive areas and other areas where there is a need for recreational beaches.

- Breakwaters. There are three main types—rubble-mound, vertical and composite.

  - The rubble-mound breakwater, consists of a mixed-rubble core (quarry run) covered by underlayers of different rock sizes and a final armor layer of large rocks of up to about 20 tons, or specially designed concrete armor units, e.g., cubes, parallelepipeds, tetrapods, dolosse, which could weigh up to 150 tons each, normally topped by a solid concrete crest-wall structure.
  - The vertical breakwater is made from stacked large rectangular natural blocks or interlocking concrete units, or lately, from large concrete caissons, that are floated into position and then sunk and loaded with sand-fill.
  - The composite breakwater is a combination of the first two; it consists of a rubble-mound base, reaching to about half the water depth, with stacked vertical sections on top. These structures protect existing harbor areas, and are also used for harbor-extension works and for the development of new ports.

- Floating structures. Temporary protection to a specific coastal area could be provided by wooden rafts or steel/concrete caisson-type floating structures, which provide partial protection, particularly to waves of shorter periods. Because of the inefficiency of these structures against longer period swell and storm waves, their main application is for protecting temporary works only.

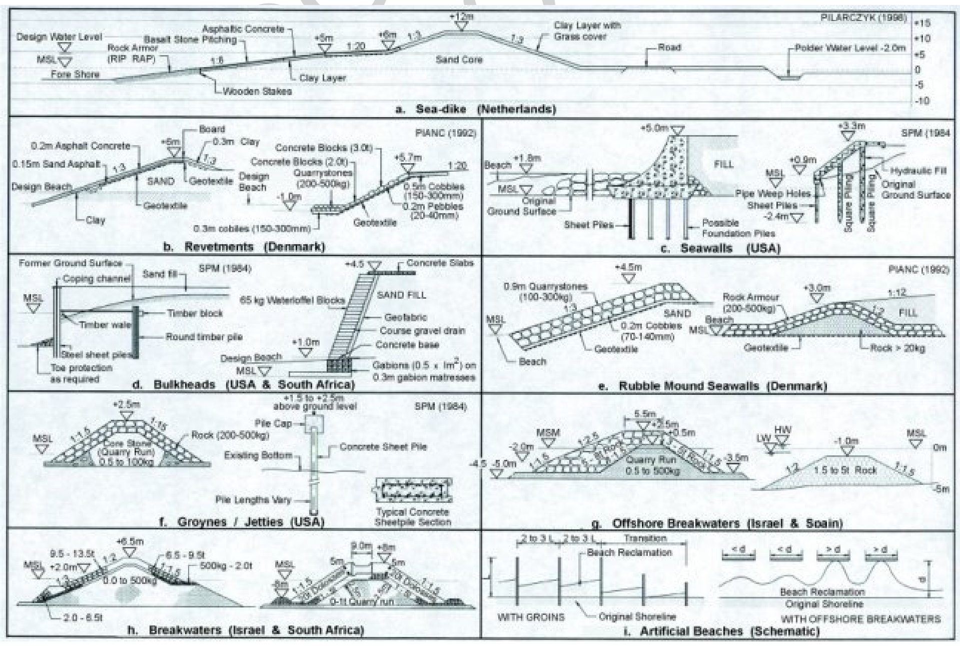

Figure 1. Types of coastal defense structures

2.2 Choice of Structure

The choice of a suitable type of coastal protection structure depends on the specific location, the purpose of the structure, the environmental conditions, the availability of building materials, design and construction skills, and the funding available.

The advantages of "hard structure" solutions such as sea walls, bulkheads, groins and offshore breakwaters, are that they afford direct protection to the area concerned, and if properly designed and built, require little maintenance. The disadvantages of such structures are that they often cause problems in the adjoining, down-drift, coastal areas. Such problems should not occur to the same extent when using "soft structure" solutions such as dikes, levees or artificial beaches. However, large volumes of suitable sand are required, particularly in the case of the latter, and regular maintenance sand-feeding may be necessary.

3. Coastal Structures Design Approach

In this section practical considerations and design data are discussed first, and then the design procedures for different types of structures are outlined.

3.1 General Considerations

The design of coastal protection structures is more of an art than a science. The understanding of the environmental forces, particularly due to wave action, has greatly improved over the past fifty years. However, the interaction of these forces with a structure, and the resulting reaction of the structure, can only be determined approximately, using semiempirical design formulae which are mainly based on the results of small-scale hydraulic model tests.

Therefore, the design process normally includes a conceptual design, based on available formulae and/or data included in design manuals for coastal structures, followed by a more detailed design, using physical and/or numerical hydraulic models.

3.2 Design Input Data

For the design of a coastal protection structure, information is required regarding the following input data:

- foundation conditions—type, bearing capacity and shear resistance of the subsoil and groundwater conditions;
- topography and bathymetry—contour plans and sections of the shore and adjoining sea bottom;
- water levels—tidal data, including data on storm surges and wave set-up;
- wave conditions—local design wave conditions, including wave direction, characteristic wave height (design significant wave height, H_s or H_{mo}) and wave period (peak wave period, T_p);
- currents—near-shore currents, including dominant and extreme current directions and current velocities; and
- sedimentology—expected sea-bottom changes and littoral sand movements, including dominant and extreme values.

Long-term data sets are needed to determine reliable design conditions, which can vary from a recurrence interval of about fifty years for an offshore breakwater, to one of a few thousand years in the case of dikes protecting low-lying highly developed areas.

3.3 Basic Design Procedures

In the following subsections some guidelines are given on the procedures to be followed in designing typical coastal protection structures, together with the engineering background and useful empirical design formulae.

3.3.1 Dikes and Levees

Since dikes are usually built to protect low-lying areas, or to avoid flooding from storm tides, extreme water levels are the most important input data.

If there are no waves, the crest level of the dike can be determined from the predicted maximum water level for a low-occurrence event, e.g., once in 10 000 years for the Dutch Delta Works, because of the high degree of development in the protected areas. To this extreme water level must be added a freeboard of 0.5 to 1.0 meters, which also includes allowance for possible settlement. The outer slope of a dike usually varies between 1 in 3 and 1 in 5, with an inner slope of about 1 in 3. The slopes adopted will depend on the geotechnical characteristics of the subsoil, the material to be used for the main body of the dike, and the type of surface material selected, e.g., grass or stone pitching.

In the case of sea dikes, waves form an additional major design factor for the dike-crest height and its slope protection, due to wave run-up and possible overtopping. The crest height can either be based on either a “no significant overtopping” criterion, for instance, the two percent wave run-up level; or on an “overtopping” criterion, depending on the use and accessibility of the dike. In the latter case an overtopping of not more than ten liters per second per meter is allowable, based on data from the Delft Hydraulics deltaflume.

Wave run-up can be estimated, for instance, using the formula due to Meer:

$$\frac{R_{2\%}}{H_{mo}} = 1{,}6\ \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \xi \qquad (1)$$

where:

$R_{2\%}$ [m] = the vertically measured wave run-up relative to still water level (SWL) based on the two percent exceedance wave height

H_{mo} [m] = $4\sqrt{m_o}$ where m_o is the zero’th moment of the energy density spectrum (at the toe of the structure)

$\xi[-]$ = $\tan\infty\sqrt{\left[\frac{\{gT_p^2\}}{\{2\pi H_{mo}\}}\right]}$, and is the surf-similarity parameter, with T_p being the peak period of the wave spectrum, $\propto$ the slope angle and g the acceleration due to gravity

$\gamma_b[-]$ = reduction factor for the presence of a berm
$\gamma_f\,[-]$ = reduction factor for slope roughness
$\gamma_\beta\,[-]$ = reduction factor for oblique wave attack.

Equation (1) applies for the following range of values of ($_b$ >: 0.5 < ($_b$ > < 5.

The effect of a berm in the slope (γ_b) depends on the berm dimensions and the berm height. A maximum reduction up to 40% (γ_b = 0.6) can be achieved with a berm crest level near the SWL. The roughness value γ_f depends on the type of revetment or armoring. Smooth surfaces (e.g., asphalt or close-packed blocks) have γ_f values close to 1.0, while values as low as 0.6 may be applicable for rough rubble revetments. The wave angle has a fairly small influence on run-up, particularly for short-crested waves, for instance, for β = 25°, $\gamma_\beta \cong$ 0.95 (a wave angle of β = 0° is at right angles to the shore) (see chapter *Loads on Earth- and Rock-fill Dams Arising from Water and Wind*).

3.3.2 Block and Bituminous Revetments

The design of the slope protection of sea dikes and eroding natural shores is determined mainly by the degree of wave attack, although strong current action can also sometimes play a role. The wave attack depends on the water depth at the toe of the structure, and the local wave direction, height (H_{mo}) and period (T_p). The type of wave-structure interaction is defined by the surf-similarity parameter,

$$\xi = \tan\,\infty\sqrt{\left[\frac{\{gT_p^2\}}{\{2\pi H_{mo}\}}\right]} \qquad (2)$$

as given and defined previously.

For ξ < 2 to 2.5, the waves will break on the slope, which usually applies to slopes flatter than about 1 in 3. For 1 < ξ < 2.5, "plunging" breakers may occur while for ξ > 2.5 (long waves and flat slopes) "spilling" breakers will occur. The interaction between long waves and steep slopes will result in "surging" waves.

For the design of the revetment, the surging and plunging breaker conditions are the most critical factors. Wave attack, combined with storm tide, can cause failure of the revetment structure due to:

- uplifting of blocks or asphalt protection layers;
- loss of subsoil through the filter and cover layers;

- overall geotechnical instability of the slope; and
- sliding down of the revetment.

No generally applicable formulae are available for determining the maximum velocities, U_{max}, during wave up-rush and down-rush. These velocities are critically important for the stability design of the armoring for the large variety of revetment types and slopes. A first estimate of these velocities for smooth slopes can be made with the following formula:

$$U_{\max} \cong 1.5\sqrt{(g\ H_{mo}\xi)} \qquad (3)$$

The cover layer of the revetment can consist of pattern-placed natural rock (basalt), interlocking concrete blocks, hollow blocks of various shapes and blocks connected with wires. Asphalt cover layers normally consist of stone-asphalt or sand-asphalt. All these cover layers must be underlain by a properly designed inverted filter, including geotextile fabric, to avoid leaching out and the loss of sand or subsoil.

For major structures it would be worthwhile to check the conceptual design by means of large-scale model tests in one of the available large wave channels (see chapter *Hydraulic Methods and Modeling*).

3.3.3 Rubble Mound Structures

Rubble mound structures form the major part of existing coastal protection and breakwater structures. These include sea walls, groins, jetties, breakwaters and offshore breakwaters.

The main body of these structures consists of various sizes of rock material, the design of which is largely dependent on available quarry output. Optimum design requires the utilization of the full range of rock material sizes available from the nearest possible quarry. For design wave heights $H_{mo} < 7$ m, the main armoring could also be rock, but concrete armor units may be more economical. For $H_{mo} > 7$ m, rock sizes become impracticably large and main armoring made of concrete blocks has to be used.

The main components of this type of structure are the following (see Figure 2):

- Filter layer (1)—0.5 to 1.0 m thick, and consisting of fascine mattresses, reinforced fabric, gravel, crusher run or quarry spalls; this layer must extend several meters beyond the toe of the structure to prevent under-scour.
- Core material (2)—quarry-run with a specified minimum and maximum stone size, e.g., 1 to 1000 kg.
- Underlayer rock (3)—well graded rock to cover the core material and to act as a filter between the core and the main armoring; the rock mass (W_u) must satisfy $W_u = W/10$ to $W/5$, where W is the mass of the main armoring units
- Toe berm (3)—toe support, made of suitable rock size, to the main armoring, also acting as transition between the main armoring and the filter or seabed;

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Biographical Sketch

Joop Zwamborn obtained the Civil Engineering Degree (*Ingenieur*) in 1955 from Delft University, The Netherlands, and the ICHE Delft (Diploma in Coastal Engineering) in 1962. He is a member of the South African Institution of Civil Engineers (SAICE), the International Association of Hydraulic Engineering and Research (IAHR) and the Permanent International Association of Navigation Congresses (PIANC).

His field of expertise is in Coastal Engineering, including harbor design, optimization of the dimensions of harbor entrance channels and shipping operations, coastal protection works, beach development projects, break-waters, field tests and model studies. He has also been involved in Hydraulic Engineering, including model studies on spillways and outlet works for a major concrete arch dam in Lesotho, storm water drainage, river training, hydraulic structures (bridges and spillways), water clarification (settlement) and pipe-flow problems.

His engineering experience record is as follows:

Two years with the South African Railways and Harbours

Two years with the Municipality of Benoni, South Africa, and

Thirty-three years with the Council of Scientific and Industrial Research (CSIR), South Africa

He has been involved in some twenty-six major projects since graduation. After retirement in 1992, he became a specialist consultant in Coastal and Harbor Engineering Hydraulics. The most recent projects he is presently actively involved with as specialist advisor for Israel, are the Ashdod and Haifa Port extensions, the break-waters for cooling water basins in Hadera, Tel Aviv, Ashdod and Ashkelon, and for the Israel Electric Corporation.

He is also advisor on:

Design of Coega Port, South Africa.

Ashkelon Marina Break-water and Haifa Marina lay-out, Israel.

Beira Project , an off-shore bulk-carrier jetty, Mozambique.

He attended a number of International Conferences on Coastal Engineering and Hydraulic Research, and is fluent in English, Afrikaans and Dutch, with technical language capability in French and German.