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Author(s): George Alexandrakis, Nikolaos kampanis (FORTH subcontract)

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	Name	**Organisation**	**Date**	**Signature (initials)**
Coordinator	Ioannis Tsoukalidis	Paggaion Municipality		
WP Leaders				

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1 Abstract

This deliverable aims to integrate the knowledge gathered throughout the project, and presented in previous deliverables, with scope to contribute to the implementation of soft engineering techniques against costal erosion. The overall aim of the project isto promote the use of soft engineering coastal protection techniques by promoting a methodology which will allow the non-expert to assess the erosion problem byidentify the likely causes and quantify its strength, and further to provide information on the environmental impact of variouscoastal protection and management solutions.Finally, the project intends to supply reference information on coastal processes and identify useful environmental and historical data sources. An overview of the types and functions of Coastal Structures used in coastal defence schemes with the objective of preventing shoreline erosion and flooding of the hinterland are presented.

2 Introduction

Cyprus is the third largest Mediterranean island, situated east of Greece. The coastline measures about735 kmof which 50% is under the control of the Republic of Cyprus and 50% under Turkishoccupation. The coastline is characterised by sand, gravel and rock formations. Themain climate change impact Cyprus has to deal with is persistent drought resulting in freshwatershortage. In addition, 30% of the coastline under control of the Republic of Cyprus is subject to erosion. Cyprus has not experienced any severe floods from the sea in the past. Also in the coming years,Cyprus is not expected to become very vulnerable to sea flooding. Research results (e.g. IPCC)suggest only a small SLR and the country is experiencing a land lift-up counteracting this potentialeffect.Nevertheless the coastal zoneof Cyprus is a valuable and vulnerable area. This zone, in which mosturban development and economic activity takes place, covers 23% of the total country's area, 50% oftotal population and 90% of the tourism industry. The most vulnerable part in this regard is thelow-lying region of Larnaca located on the south coast of the island.Erosion constitutes a greater threat than flooding especially for the sandy and gravel beaches of theisland. At the moment, 38% of the coastline is already subject to erosion, mostly the result of humanactivities such as beach mining, dam and illegal breakwater construction and urbanisation. Climatechange could worsen this situation.

The *Coastal Section of the Ministry of Communications and Works* is the main actor involved in coastal defence. Permission for coastal defence works needs to be obtained from differentgovernmental departments as well as local authorities.The *Coastal Section of the Public Works Department, Ministry of Communications and Works*, is theagency responsible to plan, design and survey coastal protection and improvement works. Before anyprotection works can be carried out, permission needs to be obtained by the *District Officers, Ministryof the Interior*, who are the owners of the coastal zone. Such a permit is subject to an environmentalimpact assessment to be approved by a *Technical Environmental Committee*, subordinate to the *Environment Service of the Ministry of Agriculture, Natural Resources and Environment*. Severalgovernmental departments are represented in this Committee as well as delegates of the ecologicaland environmental NGOs of Cyprus.At sub-national level the municipalities are involved. Municipalities have their own technicaldepartment responsible for issuing town planning permits in their area. However, for coastalstructures they also need to obtain the permission of the District Officer, *Ministry of the Interior*.Financing of the coastal protection structures is shared between the government and themunicipalities.The *Water Development Department, Ministry of Agriculture, Natural Resources and Environment*, isthe agency responsible for water resource management in Cyprus.

3 Coastal defence

Coastal defence covers two related but distinct issues: (i) coast protection, concerned with works designed to manage or prevent erosion of the coastline; and (ii) sea defence, which relates to schemes intended to manage or prevent flooding or inundation of the coastline. Currently, coast protection works are the most common type of coastal defence, mainly consisting of structures designed to resistnatural processes, such as wave action and sediment movement; they are commonly called "hard engineering" options, they include various constructions such as vertical sea walls, Groynes, breakwaters, revetments, flood embankments, placement of gabions and rock armouring. Along the Cyprus coast, vertical seawalls (built of concrete or rock) usually accompany and protect coastal roads. In many cases, especially where the beach zone is narrow, rock armouring is used to protect the toe of the seawall against undermining. The most common 'hard' defence currently employed to protect private property and infrastructure of low importance and economic value is designed walls and revetments constructed of boulders of a rather uniform size (rock armouring), typically many tonnes in weight.

Similar structures, formed from precast concrete blocks, are commonly used for the protection against coastline retreat of reclaimed coastal lands, coastal installations of greater importance, or areas of higher aesthetic value.

In rare cases, gabions (wire baskets filled with stone and stacked vertically or damped horizontally) have been used temporarily for shore zone stabilization. In other cases, the dumping of piles of rocks tipped over the coastal edge has been applied to prevent further erosion in areas of low conservation value.

The second most popular protection method during the past decades has been the construction of Groynes, generally perpendicular to the coastline, designed to intercept sand and gravel movement along the beach; these have usually been constructed of boulders with a concrete or asphalt top pavement in areas of high wave activity, or of timber in beach zones that experience relatively low wave energy. Recently, concrete-filled geotextile tubes have been used for the construction of less obtrusive Groynes in recreational beaches, with limited success especially in beaches with significant on-offshore transport. During the last couple of decades the construction of groynes is being gradually abandoned, mainly due to their limited success in areas with low longshore sediment transport rates, their obtrusiveness and problems with downdrift erosion. In open beaches with a significant onshore component in the nearshore wave energy field, the construction of emerged shore-parallel offshore breakwaters has been quite successful.Offshore breakwaters are becoming increasingly popular during the last two decades and in some cases they have replaced existing groynes systems.

In areas with a high conservation value, “soft engineering” options are often preferred. These are designed to emulate, harnessor manipulatenatural processes. The most commonly used “soft” protection methods are beach nourishment or recharge, sediment recycling and stabilization of coastal dunes with vegetation.Beach nourishment (addition of sand or gravel to a beach to restore former levels or to improve current ones) has been used primarily for the maintenance or creation beaches associated with large hotel units or coastal recreational facilities, either as a standalone measure or in conjunction with a “hard protection” measure, usually a detached submerged breakwater. In many cases, such actions were undertaken during the low-season touristic periods either without the required permissions or by public authorities without proper studies.

Sediment recycling (transport of beach sediment from the down-drift end of a beach back to its up-drift end) has been used in beaches with significant longshore sediment transport.Additionally, other semi-technical, semi-managerial schemes may be considered, that incorporate coastal defences by combining elements of hard and soft engineering and a managed back retreat (removal of coastal defences inland to permit the natural evolution of a beach and, if the coastline is retreating farther, supply of beach sediment).

4 Need for measures

Beaches have significant value to the tourism industry and this makes their protection vital for the economy. Protecting resort beaches is a major challenge, not only for engineers, but also for coastal managers, since they have to balance the economic, social and environmental aspects of the beaches. Therefore, the appropriate design of mitigation measures for erosion should be properly analysed from a technical point of view, taking into consideration their economic viability(van der Weide et al., 2001). Beach nourishment has been used primarily for the benefit of the tourism industry, due to its relatively low cost in construction and periodic maintenance. Benefits from a beach nourishment projectinclude reduction of storm risks to seafront property and recreational benefits from the wider beach resulting (Phillips and Jones, 2006).For these reasons, beach nourishment has become a popular beach management option and is used to combat erosion in many parts of the US Atlantic and Pacific coasts (Gopalakrishnan et al., 2011), following the successful example of Miami Beach (Houston, 2013). In Europe, during the last 15 years, 20 million tons of sand were used to nourish Britain's beaches (Symes and Byrd, 2003) and approximately 20 million cubic metres of marine sands to nourish beaches in Italy (Cipriani et al., 2004). Artificial beach nourishment can provide satisfactory results in low energy environments. It can be also effective in more energetic ones, if the nourishment is complemented by the installation of submerged detached breakwaters, for wave energy dissipation and retention of sediments.

Risk assessment suggests that, since the whole beach has similar vulnerability values, the risk is mainly related to the exposure variable, estimated by considering the current beach values and revenue losses from the shoreline retreat. Moreover, using risk assessment, one can identify and prioritize the sectors of the beach where mitigation measures must be undertaken.

4.1 Policy options

For each coastal system, the commonly applied policy options are given. It should be noted that more than one policy option may be present at the same area. Besides this, the distinction between the policy options is not always crystal clear. Nourishment of a beach to compensate structural erosion, can fit the policy option of limited intervention as well as hold the line policy. After the policy options, strategies to execute these policy options are described. These vary from European level down to the local level. In some case studies, coastal defence policies at a national level have not yet been adopted, leaving management of erosion problems often to local and/or regional authorities. A proactive approach refers to a policy of anticipating erosion processes. Technical measures or plans (management plans, flood warning systems etc.) are adopted to prevent erosion or minimize the expected effects of erosion. A reactive approach refers to the policy of performing coastal defence measures to reduce the effects of existing erosion processes. Another part of the strategy is to decide whether to use hard or soft measures to deal with erosion. In a next step, the policy options and strategy are positioned within the framework of integrated coastal zone management, together with a description of the available legislation and responsible authorities in the coastal zone.

The selection of the technical measures to deal with any erosion or flooding problem dependspartly on the value of the land or property threatened. The valuesat stake in coastal areas – people, property and associated economic values, ecological andcultural values – determine the need for intervention. Once these values are assessed, theselection of the most appropriate solution/s can be made.Coastal protection measures can generally be divided between hard and soft ones. The hard engineering measures involve the construction of solid structuresdesigned to fix the position of the coastline, while, soft measures are designed to work with thenatural processes. Theseenable the natural dynamic behaviour of the coastal area, and thus, thecoastline may change and self-adapt over time.Application of possible measures will vary according to the local situation or "Geodiversity" (typeof coast, physical circumstances), the desirable being to identify the best option/s (most efficient andcost effective). In order to achieve this, a good knowledge is needed of the scale of the problemand the causes of erosion/flooding under which the optional measures are to be applied.For example, when the erosion problem is caused by a net longshore transport, a seawall isgenerally not a sufficient solution. The seawall would eventually be undermined by the longshore transportand fail. Such a seawall would not stop the longshore transport, while Groynes for example could.When the problem is caused by cross-shore transport, a seawall could be efficient. Anothertypical example concerns cliff protection, where the geology, location and orientation of the beddingplanes will determine the type of erosion (rock fall, toppling failure, wedge failure, slide,rotational slump or flow) and, therefore, the appropriate type of protection required.Successorfailfactors of technical measures depend on Geodiversity and the combination ofthe type and causes of erosion, the measures itself and the surrounding physical conditions.Furthermore, success or failure depends on the choice of policy and, sometimes, the way the measures are implemented.

In the followingparagraphs, for each of the coastal systems, the most commonly applied technical measures will be described, the locations where they have been applied and the observed success and fail factors. This information is drawn from the case study descriptions. A more detailed description of measures and their effects can be found in the case studies themselves.

5 Overview of coastal erosion management techniques

5.1 Hard techniques

Breakwaters are protective structures, placed offshore, generallyof hard materials, such as concrete or rocks, to absorb the wave energy before the waves reach the shore. Breakwaters reflect or diffract wave energy in destructive ways, or concentrate it in local hot spots. Erosion problems and the scouring effects of the misdirected energy lead to the loss of beach / coastline and undermine the structures that were meant to be protected. Gabion is a metal cage filled with rocks, about 1 metre by 1 metre square. Gabions are stacked to form a simple wall. They are used to protect a cliff or area in the short term only, since they are easily damaged by powerful storm waves and the cages tend to rust quite quickly. Gabions have the advantage of ease of use and are relatively cheap but their life span is short. Geotextiles are permeable fabrics which are able to hold back materials while water flows through. Geotextiles are relatively recent but provided good results to prevent beach from retreating. Plus they are very flexible and can be re-arranged if their configuration does not provide good results. Geosynthetic tubes are large tubes consisting of a woven geotextile material filled with a slurry-mix. The mix usually consists of dredged material (eg. sand) from the nearby area but can also be a mortar or concrete mix. Groynes are structures that extend perpendicularly from the shore. Usually constructed in groups called groin fields, their purpose is to trap and retain sand, nourishing the beach compartments between them. Groynes may be made of wooden or rocky materials. They interrupt the longshore transport of littoral drift. When a well-designed groin field fills with sand, longshore transport continues at about the same rate as before the Groynes were built, and a stable beach is maintained. Sand accumulated between Groynes contributes to a sediment deficit down-drift. Coastal erosion problems are then shifted to other locations. Thus, to be effective, Groynes should be limited to those cases where longshore transport is predominantly in one direction, and where their action will not cause unacceptable erosion of the downdrift shore. Revetment is a sloping feature which breaks up or absorbs the energy of the waves but may let water and sediment pass through. The older wooden revetment consists of posts fixed into the beach with wooden slats between. Modern revetments have concrete or shaped blocks of stone laid on top of a layer of finer material. Rock armour, or riprap, consists of layers of very hard rock with the largest, often weighing several tonnes, on the top. Riprap has the advantage of good permeability and looks more natural. Revetments are adapted to foreshore with a gentle slope. It has the same adverse effect as seawalls though with a reduced intensity. It also results in changing the nature of the sea frontage which may lead to further changes in the foreshore ecosystems. Bulkheads and seawalls protect banks and bluffs by completely separating land from water. Bulkheads act as retaining walls, keeping the earth or sand behind them from crumbling or slumping. Seawalls are primarily used to resist wave action. Design considerations for these types of structures are similar. Such structures,however, do not protect the shore in front of them. When bulkheads and seawalls are used in areas where there is significant wave action, they may accelerate beach erosion (much of the waves' energy, breaking on the structure, is redirected downward to the toe). Bulkheads and seawalls are most appropriate where fishing and boating are the primary uses of the shore, whereas, mildly sloping areas for sunbathing or shallow-water swimming are not needed. They are also of use when risks associated to coastal erosion are imminent on infrastructure on the shoreline.

5.2 Soft techniques

An artificial reef, which absorbs the wave energy (thus providing coastal defence), while providing a natural habitat for marine biodiversity and opportunities for recreational activities, is a common practise. Just few examples of artificial reef deployment exist in Europe (in Sea Palling, UK, mainly) though it seems they often provide good results. Beach drainage decreases the volume of surface water during backwash by allowing water to percolate into the beach, thus reducing the seaward movement of sediment. Beach drainage also leads to drier and "gold" coloured sand, more appreciated for recreational activities. The technique is relatively new and experience lacks to assess its performance. It has to be noted, however, that beach drainage is adapted when erosion mainly occurs cross-shore (non-significant long-shore drift) Sand supply, or nourishment,artificially increases sand volumes in the foreshore, via the supply of exogenous sand. Sand supply may be achieved through the direct placement of sediment on the beach, through trickle charging (placing sediments at a single point), or through pumping. Beach and underwater nourishment is very popular in the North, because of the vast availability of sediments offshorewith similar properties as the beach sediment. When sediment is not available, and has to be imported from another region, beach nourishment may not be the best decision. Nourishment schemes have also to be placed in the emerged part of the foreshore ("beach nourishment") or under the water line ("underwater nourishment") which is generally cheaper. Nourishment schemes have also to be carefully designed as they may alter the biota (both on the beach and in the dredging area). Nourishment may not be, eventually, the best decision in many cases.

Beach scraping is the artificial re-profiling of the beach when sediment losses are not severe enough to warrant the importation of large volumes of sediments and is usually achieved using existing beach sediment. Beach scraping is among the cheapest techniques, as it does not require importing sand. However, the process may have to be carried out several times before the right profile is found. It is also restricted to those beaches where cross-shore erosion is dominant and storms not heavy. Cliff drainage is the reduction of pore pressure by piping water out of the cliff and, therefore, preventing accumulation of water at rock boundaries.This may not be applicable to all types of cliffs.

Change of cliff face angle to increase cliff stability. The angle at which cliff become stable depends on rock type, geologic structure and water content. It may not be applicable for all types of cliffs, and the techniques requires a fairly good knowledge of the cliff geologic structure and watering process. Cliff toe protection is the protection of the cliff base by placing blocks at the foot of potential failure surface. This technique is easy to achieved but do not stop erosion completely. It may therefore be adapted in those case where further loss of lands is still acceptable. Creation of stable bays consists of increasing the length of the coastline to dilute wave energy per unit length of coast. While some coastline segments are protected, erosion continues between these hard points leading to the formation of embayment. This technique is practically not used in Europe and is still experimental. However, it has been envisaged for a number of sites (especially the Holland coast). Dune regeneration is performed by windblown accumulation of drifted sand located in the supra-tidal zone. Wind velocity is reduced by way of porous fences made of wood, geo-textile, plants, which encourages sand deposition. It is adopted for those cases where wind plays an important role. Marsh creation consists of planting mudflats with pioneer marsh species, such as Spartina sp. Marsh vegetation increases the stability of sediment due to the binding effects of the roots, increasing shear strength and decreasing erodibility. Marshes also provides cost-effective protection against flooding by absorbing wave energy. Marsh creation is particularly popular in United Kingdom. However, the technique may be jeopardized by accelerated sea level rise. In this case, the accumulation of fine sediments necessary to the marsh creation may not occur in the proper way and the marsh finally collapse. Mudflat recharge consists in supplying existing mudflats with cohesive sediments. This is achieved via trickle charging (see beach feeding), rainbow charging, and polders. Same as marsh creation, mudflat recharge may be jeopardized by accelerated sea level rise. Rock pinning by preventing slippage in seawards dipping rocks by bolting layers together to increase cohesion and stability. This does not prevent wave attack at the cliff base, but does reduce the threat of mass movement and thus reduces net erosion rates. It may not be applicable for all types of cliffs.

Reactivation of sediment transport processes by pumping sediments accumulated up-drift by coastal infrastructure normal to the coastline and injecting them down-drift. A variant of sand by-passing is to use materials dredged for navigational purposes to reactivate the sediment transport. This technique has been implemented by a number of harbour authorities (or dams' authorities) in Europe as volumes of sand trapped by harbour breakwaters (resp. dams) are generally considerable. When sediments are trapped by a series of Groynes (or consecutive dams) the technique might not be cost effective anymore. It has to be noted that in the case of dams, accumulated sediment may be contaminated may not be reinjected in the sediment transport system. Vegetation planting and/or stabilisation Colonisation of coastal soils by vegetation whose roots bind sediment, making it more resistant to wind erosion. Vegetation also interrupt wind flow thus enhancing dune growth. As for cliffs, vegetation increases cohesion of surface soils on cliff slopes to prevent downhill slumping and sliding Vegetation adapted to dune (eg. Marram grass) is generally very fragile and require integral protection and daily care to the dune system.

6 Types and Functions of Coastal Structures

6.1 Sea dikes.

Sea dikes are onshore structures with the principal function of protecting low-lying areas against flooding. Sea dikes are usually built as a mound of fine materials like sand and clay with a gentle seaward slope in order to reduce the wave run up and the erodible effect of the waves. The surface of the dike is armoured with grass, asphalt, stones, or concrete slabs.

6.2 Seawalls.

Seawalls are onshore structures with the principal function of preventing or alleviating overtopping and flooding of the land and the structures behind due to storm surges and waves. Seawalls are built parallel to the shoreline as a reinforcement of a part of the coastal profile. Quite often seawalls are used to protect promenades, roads, and houses placed seaward of the crest edge of the natural beach profile. In these cases a seawall structure protruding from the natural beach profile must be built. Seawalls range from vertical face structures such as massive gravity concrete walls, tied walls using steel or concrete piling, and stone-filled cribwork to sloping structures with typical surfaces being reinforced concrete slabs, concrete armour units, or stone rubble. Erosion of the beach profile landward of a seawall might be stopped or at least reduced. However, erosion of the seabed immediately in front of the structure will in most cases be enhanced due to increased wave reflection caused by the seawall. This results in a steeper seabed profile, which subsequently allows larger waves to reach the structure. As a consequence, seawalls are in danger of instability caused by erosion of the seabed at the toe of the structure, and by an increase in wave slamming, run-up, and overtopping. Because of their potential vulnerability to toe scour, seawalls are often used together with some system of beach control such as Groynes and beach nourishment. Exceptions include cases of stable rock foreshores and cases where the potential for future erosion is limited and can be accommodated in the design of the seawall.

6.3 Revetments.

Revetments are onshore structures with the principal function of protecting the shoreline from erosion. Revetment structures typically consist of a cladding of stone, concrete, or asphalt to armour sloping natural shoreline profiles. In the Corps of Engineers, the functional distinction is made between seawalls and revetments for the purpose of assigning project benefits; however, in the technical literature there is often no distinction between seawalls and revetments.

6.4 Bulkheads.

Bulkhead is the term for structures primarily intended to retain or prevent sliding of the land, whereas protecting the hinterland against flooding and wave action is of secondary importance. Bulkheads are built as soil retaining structures, and in most cases as a vertical wall anchored with tie rods. The most common application of bulkheads is in the construction of mooring facilities in harbours and marinas where exposure to wave action is minimized. Some reference literature may not make a distinction between bulkheads and seawalls.

6.5 Groynes.

Groynes are built to stabilize a stretch of natural or artificially nourished beach against erosion that is due primarily to a net longshore loss of beach material. Groynes function only when longshore transport occurs. Groynes are narrow structures, usually straight and perpendicular to the preproject shoreline. The effect of a single groin is accretion of beach material on the updrift side and erosion on the downdrift side; both effects extend some distance from the structure. Consequently, a groin system (series of Groynes) results in a saw-tooth-shaped shoreline within the groin field and a differential in beach level on either side of the Groynes or slow down the rate of longshore transport and, by building up of material in the groin bays, provide some protection of the coastline against erosion. Groynes are also used to hold artificially nourished beach material, and to prevent sedimentation or accretion in a downdrift area (e.g., at an inlet) by acting as a barrier to longshore transport. Deflecting strong tidal currents away from the shoreline might be another purpose of Groynes. The orientation, length, height, permeability, and spacing of the Groynes determine, under given natural conditions, the actual change in the shoreline and the beach level. Because of the potential for erosion of the beach downdrift of the last groin in the field, a transition section of progressively shorter Groynes may be provided to prevent the formation of a severe erosion area. Even so, it might be necessary to protect some part of the downdrift beach with a seawall or to nourish a portion of the eroded area with beach material from an alternative source.

Groynes are occasionally constructed non-perpendicular to the shoreline, can be curved, have fishtails, or have a shore-parallel T-head at their seaward end. Also, shore-parallel spurs are provided to shelter a stretch of beach or to reduce the possibility of offshore sand transport by rip currents. However, such refinements, compared to the simple shape of straight perpendicular Groynes, are generally not deemed effective in improving the performance of the Groynes. In most cases, Groynes are sheet-pile or rubble-mound constructions. The latter is preferably used at exposed sites because of a rubble-mound structure's ability to withstand severe wave loads and to decrease wave reflection. Moreover, the risk of scouring and formation of strong rip currents along rubble Groynes is reduced. The landward end of the Groynes must extend to a point above the high-water line in order to stay beyond the normal zone of beach movement and thereby avoid outflanking by back scour. The Groynes must, for the same reason, reach seawalls when present or connect into stable back beach features. The position of the seaward end is determined such that the groin retains some proportion of the longshore transport during more severe wave conditions. This means that the groin must protrude some distance into the zone of littoral transport, the extent of which is largely determined by surf zone width. Groynes can be classified as either *long* or *short*, depending on how far across the surf zone they extend. Groynes that transverse the entire surf zone are considered *long*, whereas those that extend only part way across the surf zone are considered *short*. These terms are relative, since the width of the surf zone varies with water level, wave height, and beach profile. Most Groynes are designed to act as *short* structures during severe sea states and as *long* structures under normal conditions. Groynes might also be classified as *high* or *low*, depending on the possibility of sediment transport across the crest. Significant cost savings can be achieved by constructing Groynes with a variable crest elevation that follows the beach profile rather than maintaining a constant crest elevation. These Groynes would maintain a constant cross section and allow increasing amounts of sand to bypass as water depth increases. At some point the crest of the groin becomes submerged. *Terminal Groynes*extend far enough seaward to block all littoral transport, and these types of Groynes should never be used except in rare situations, such as where longshore transported sand would be otherwise lost into a submarine canyon. Some cross-groin transport is beneficial for obtaining a well-distributed retaining effect along the coast. For the same reason *permeable Groynes,* which allow sediment to be transported through the structure, may be advantageous. Examples of permeable Groynes include rubble-mound structures built of rock and concrete armour units without fine material cores, and structures made of piles with some spacing. Most sheet-pile structures are impermeable. Low and permeable Groynes have the benefit of reduced wave reflection and less rip current formation compared with high and impermeable Groynes.

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6.6 Detached breakwaters.

Detached breakwaters are small, relatively short, nonshore-connected, nearshore breakwaters with the principal function of reducing beach erosion. They are built parallel to the shore just seaward of the shoreline in shallow water depths. Multiple detached breakwaters spaced along the shoreline can provide protection to substantial shoreline frontages. The gaps between the breakwaters are in most cases on the same order of magnitude as the length of one individual structure. Each breakwater reflects and dissipates some of the incoming wave energy, thus reducing wave heights in the lee of the structure and reducing shore erosion. Beach material transported along the beach moves into the sheltered area behind the breakwater where it is deposited in the lower wave energy region. The nearshore wave pattern, which is strongly influenced by diffraction at the heads of the structures, will cause *salients* and sometimes *tombolos* to be formed, thus making the coastline similar to a series of pocket beaches. Once formed, the pockets will cause wave refraction, which helps to stabilize the pocket-shaped coastline.

Like Groynes, a series of detached breakwaters can be used to control the distribution of beach material along a coastline. Just downdrift of the last breakwater in the series there is an increased risk of shoreline erosion. Consequently, it might be necessary to introduce a transition section where the breakwaters gradually are made smaller and placed closer to the shoreline. In addition, seawall protection of the downdrift stretch of beach might be necessary. Detached breakwaters are normally built as rubble-mound structures with fairly low crest levels that allow significant overtopping during storms at high water. The low-crested structures are less visible and help promote a more even distribution of littoral material along the coastline. Submerged detached breakwaters are used in some cases because they do not spoil the view, but they do represent a serious nonvisible hazard to boats and swimmers.

Properly designed detached breakwaters are very effective in reducing erosion and in building up beaches using natural littoral drift. Moreover, they are effective in holding artificially nourished beach material. Optimizing detached breakwater designs is difficult when large water level variations are present, as is the case on coastlines with a large tidal range or in portions of the Great Lakes, which may experience long-term water level fluctuations.

6.7 Reef breakwaters.

Reef breakwaters are coast-parallel, long or short submerged structures built with the objective of reducing the wave action on the beach by forcing wave breaking over the *reef*. Reef breakwaters are normally rubble-mound structures constructed as a homogeneous pile of stone or concrete armour units. The breakwater can be designed to be stable or it may be allowed to reshape under wave action. Reef breakwaters might be *narrow crested* like detached breakwaters in shallow water or, in deeper water, they might be *wide crested* with lower crest elevation like most natural reefs that cover a fairly wide rim parallel to the coastline. Besides triggering wave breaking and subsequent energy dissipation, reef breakwaters can be used to regulate wave action by refraction and diffraction. Reef breakwaters represent a nonvisible hazard to swimmers and boats.

6.8 Submerged sills.

A submerged sill is a special version of a reef breakwater built nearshore and used to retard offshore sand movements by introducing a structural barrier at one point on the beach profile. However, the sill may also interrupt the onshore sand movement. The sill introduces a discontinuity into the beach profile so that the beach behind it becomes a *perched* beach as it is at higher elevation and thus wider than adjacent beaches. Submerged sills are also used to retain beach material artificially placed on the beach profile behind the sill. Submerged sills are usually built as rock-armoured, rubble-mound structures or commercially available prefabricated units. Submerged sills represent a nonvisible hazard to swimmers and boats.

6.9 Beach drains.

Beach drains are installed for the purpose of enhancing accumulation of beach material in the drained part of the beach. In principal, the drains are arranged at an elevation just beneath the lowest lowering of the groundwater table, which helps reduce the backwash speed and the groundwater outflow in the beach zone. This allows more beach material to settle out on the foreshore slope. Beach drains are built like normal surface drain systems consisting of a stable granular filter, with grain sizes ranging from that of the beach material to coarse materials like pebbles, arranged around closely spaced perforated pipes. The drain pipes are connected to few shore-normal pipelines leading to a pump sump in the upper part of the beach profile. Replacing the granular filter with geotextiles is not recommended because of the increased tendency to clog the drainage system.

6.10 Beach nourishment and dune construction.

Beach nourishment is a *soft structure* solution used for prevention of shoreline erosion. Material of preferably the same, or larger, grain size and density as the natural beach material is artificially placed on the

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eroded part of the beach to compensate for the lack of natural supply of beach material. The beachfill might protect not only the beach where it is placed, but also downdrift stretches by providing an updrift point source of sand. Dune construction is the piling up of beach quality sand to form protective dune fields to replace those washed away during severe storms. An essential component of dune reconstruction is planting of dune vegetation and placement of netting or snow fencing to help retain wind-blown sand normally trapped by mature dune vegetation. Storm over wash fans may be a viable source of material for dune construction.

6.11 Breakwaters.

Breakwaters are built to reduce wave action in an area in the lee of the structure. Wave action is reduced through a combination of reflection and dissipation of incoming wave energy. When used for harbours, breakwaters are constructed to create sufficiently calm waters for safe mooring and loading operations, handling of ships, and protection of harbour facilities. Breakwaters are also built to improve manoeuvring conditions at harbour entrances and to help regulate sedimentation by directing currents and by creating areas with differing levels of wave disturbance. Protection of water intakes for power stations and protection of coastlines against tsunami waves are other applications of breakwaters. When used for shore protection, breakwaters are built in nearshore waters and usually oriented parallel to the shore like *detached breakwaters*. The layout of breakwaters used to protect harbours is determined by the size and shape of the area to be protected as well as by the prevailing directions of storm waves, net direction of currents and littoral drift, and the manoeuvrability of the vessels using the harbour. Breakwaters protecting harbours and channel entrances can be either detached or shore-connected. The cost of breakwaters increases dramatically with water depth and wave climate severity. Also poor foundation conditions significantly increase costs. These three environmental factors heavily influence the design and positioning of the breakwaters and the harbour layout. Breakwaters can be classified into two main types: *sloping-front* and *vertical-front* structures. Sloping-front structures are in most cases rubble-mound structures armoured with rock or concrete armour units, with or without wave wall superstructures. Vertical-front structures are in most cases constructed of either sand filled concrete caissons or stacked massive concrete blocks placed on a rubble stone bedding layer. In deep water, concrete caissons are often placed on a high mound of quarry rock for economic reasons. These breakwaters are called *composite structures*. The upper part of the concrete structure might be constructed with a sloping front to reduce the wave forces. For the same reason the front wall might be perforated with a wave chamber behind to dissipate wave energy. Smaller vertical structures might be constructed of steel sheetpiling backfilled with soil, or built as a rock-filled timber cribwork or wire cages. In milder wave climates sloping reinforced concrete slabs supported by batter piles is another possibility.

6.12 Floating breakwaters.

Floating breakwaters are used in protected regions that experience mild wave climates with very short-period waves. For example, box-shaped reinforced concrete pontoons are used to protect marinas in sheltered areas. Floating docks affixed to piles are also used in marinas.

6.13 Jetties.

Jetties are used for stabilization of navigation channels at river mouths and tidal inlets. Jetties are shore-connected structures generally built on either one or both sides of the navigation channel perpendicular to the shore and extending into the ocean. By confining the stream or tidal flow, it is possible to reduce channel shoaling and decrease dredging requirements. Moreover, on coastlines with longshore currents and littoral drift, another function of the jetties is also to arrest the crosscurrent and direct it across the entrance in deeper water where it represents less hazard to navigation. When extended offshore of the breaker zone, jetties improve the manoeuvring of ships by providing shelter against storm waves. Jetties are constructed similar to breakwaters.

6.14 Storm surge barriers.

Storm surge barriers protect estuaries against storm surge flooding and related wave attack. These barriers also prevent excessive intrusion of salt-water wedges during high-water episodes. In most cases the barrier consists of a series of movable gates that normally stay open to let the flow pass but will be closed when storm surges exceed a certain level. The gates are sliding or rotating steel constructions supported in most cases by concrete structures on pile foundations. Scour protection on either side of the barrier sill is an important part of the structure because of high flow velocities over the sill. They are constructed as concrete caissons, concrete blockwork, or backfilled steel sheet piling.

6.15 Scour protection

The function of scour protection of the seabed is to prevent instability of coastal structures with foundations that rely on stable seabed or beach levels. Both granular material and clay can be eroded by the action of waves and currents. Scour potential is especially enhanced by a combination of waves and currents. In most cases scour protection consists of a rock bed on stone or geotextile filter; however, several specially designed concrete block and mattress systems exist. Scour protection is commonly used at the toe of seawalls and dikes; and in some instances scour protection is needed around piles and pillars, at the toe of vertical-front breakwaters, and at groin heads. Scour protection might also be needed along structures that cause concentration of currents, such as training walls and breakwaters extending from the shoreline. Highly reflective structures like impermeable vertical walls are much more susceptible to near structure scour than sloping rubble-mound structures.

7 Conclusions

Beach vulnerability estimations and the risk analysis have showed that it is highly vulnerable to erosion and exhibits high risk exposure in terms of coastal erosion and development. If no mitigation actions are undertaken, several coastal businesses are expected to lose their immediate accessibility to the beach in areas where the risk is high. This will be followed by the aesthetic degradation of the beach, which, in turn, will result to the reduction of competitiveness and revenues. Also, erosion phenomena can also be responsible for damages in tourism infrastructures and businesses, which will eventually increase the insurance cost against natural factors.

The recent trends in coastal erosion mitigation is shifting towards soft, innovative, and pro-active methods, since the hard methods have their own repercussions on coastal land and beaches such as down-drift erosion, high cost, poor aesthetics etc. Hard structures such as seawalls and revetments, stop erosion of coastal lands, but refocus the erosion into the beach. A number of soft methods are available now for erosion mitigation and are being used popularly all over the world. They are very eco-friendly, cheap and construction-friendly too. They may be unavoidably adopted on a larger scale in future erosion mitigation projects, and be the choice as aparticular solution, depending upon the local hydrodynamics and site conditions.

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