GENERAL GUIDELINES FOR GOOD QUALITY ARTIFICIAL BEACHES AND LAGOONS, AND CASE STORIES

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ABSTRACT

Artificial beaches behave as natural beaches, i.e. they adjust to the natural and man made conditions at the site. Good quality recreational beaches in the nature occur only when the beach is exposed to a minimum of waves and when the beach sand is of a good quality. The following main requirements shall be fulfilled to obtain a good quality artificial recreational beach:

- Moderate wave exposure in the bathing season
- The beach shall be stable in plan shape and in profile shape
- Stabilizing structures must not generate dangerous rip currents
- Good quality sand fill for construction of the artificial beach
- Good bathing water quality (clear and clean water)

Furthermore, the new beach scheme shall be well adjusted to the existing coastal environment in terms of social activities and urban development and in terms of landscape characteristics.

These principles were utilized for the hydraulic design of a new beach park in the Copenhagen area, i.e. the Amager Beach Park. The site is located in an area with a moderate wave exposure; however, the natural shoreface was so shallow that there was hardly any wave exposure of the beach. The old beach was therefore of a very poor quality.

In order to provide maximum possible wave exposure the new beach was moved seawards on an artificial island located off the shallow shoreface, whereby sufficient wave exposure was established. The new beach was divided into two sections separated by a headland. The two sections are orientated against the prevailing wave directions NE and SE, respectively, whereby both sections are made stable. The shallow area behind the new beaches was excavated to form a lagoon and the excavated material was used to form the body of the island. The beach park has been very successful and has received several distinctions.

Keywords: Beach Park, artificial lagoon, quality of beaches, wave exposure, Amager Beach Park.

INTRODUCTION

There is presently a huge development pressure on the coastal zone all over the world, which has resulted in the planning or construction of a large number of coastal developments. This situation calls for more than protection of the existing coasts against the natural hazards of nature, such as coastal erosion and coastal flooding. There is typically a need for rehabilitation of many coastal areas, which in the past have been under pressure by the development on land and by coastal erosion and coastal degradation. However, in many areas there is such a high demand for new coastal recreational facilities that rehabilitation of existing beaches is not sufficient; in these cases more comprehensive waterfront developments are required. Such waterfront developments are typically of the following types:

- *Artificial beaches* are constructed by supplying beach fill to an existing beach thereby widening the beach, but providing no new coastal land. Artificial beaches are always constructed in the equilibrium orientation to obtain lateral stability, and often supported by terminal structures to prevent loss out of the project area
- *Beach reclamation* is a very wide artificial beach also providing new coastal land by reclamation
- A *beach park or coastal development* expands and improves the quality of beaches and other marine assets in a coastal area, such as coastal lagoons and dune areas. A beach park often consists of many elements, such as breakwaters and marinas, different hard perimeter structures, artificial beaches and dunes, new reclaimed areas for parks and amenity facilities and dredged areas for lagoons. *Beach park* concepts are characterized by artificial nature with limited area for facilities whereas *coastal developments* are very developed schemes with all kinds of facilities, such as marinas, housing schemes, amusement parks, retail areas and infrastructure etc.

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- An *offshore development* is an artificial island or peninsula connected to land, built some distance from the coast. Such developments will normally have the same character as the coastal development, i.e. a scheme including all kinds of facilities
- *Artificial lagoons* can be of different nature, such as:
  - *Closed Lagoons* or *Inland Lagoons*, which are a kind of artificial lake without direct connection to the sea, however maybe with seawater being pumped and circulated in the lagoon system
  - *Open Lagoons* or *Tidal Lagoons*, which are connected to the sea by one or more tidal inlets

The present paper deals mainly with the marine elements of waterfront developments, which can be considered as “pieces of artificial nature” plus the necessary support structures. These marine elements are the following:

- Artificial beaches
- Artificial lagoons
- Protective structures necessary to support the artificial beaches and the lagoon entrances, such as breakwaters, terminal groynes and inlet jetties

The successful design of these marine elements is crucial to the proper functioning of the waterfront developments. The special issue about these marine elements is that they are dependent on the local hydrographic conditions, which are specific for a given site and which cannot be changed. This means that the design of the marine elements has to follow given hydrographic conditions and the associated natural hydraulic and morphological mechanisms, which means that the degrees of freedom for designing these elements are restricted. Consequently, the layout of these elements shall be some of the first to be designed whereas other elements, which are not so much dependent on the natural conditions at the site, shall be designed to fit into the layout of the marine elements. This again means that it is important for the proper functioning of waterfront developments that coastal and marine issues are included from the very first planning phase. It is therefore important that developers and master planners are aware of these specific requirements and that they take the initiative to involve hydraulic and coastal experts in the early planning stage.

THE CHARACTERISTICS OF NATURAL MARINE ELEMENTS

The new marine elements, although partially artificial, behave according to the natural mechanisms which are valid for natural beaches and lagoons. This means that it is important to understand the natural processes which result in good quality *natural* beaches and coastal lagoons in order to be able to create good quality *artificial* beaches and lagoons.

Good quality recreational and safe *natural* beaches are always characterized by the following conditions:

- They are exposed to waves, but not so exposed that it becomes dangerous to bathe from the beach
- They can be exposed to micro to moderate tidal conditions, but the tidal range should not be larger than approx. 1.5 m
- The bathing water quality is good, which means that the water shall be clean and transparent
- There is a minimum of structures/rocks on the beach, as bathing close to structures may be dangerous
- The sand is good quality beach sand with minimum content of gravel/shingle and silt/clay
- There is no floating debris

Attractive *natural* tidal lagoons are normally characterized by the following conditions:

- They have one or more connections to the sea, so-called tidal inlets. The inlets shall be stable and open at all times of the year
- Good flushing conditions which contribute to maintaining a good water quality
- There is a negligible discharge/seepage of pollutants (sewage, storm water, brine, cooling water, pesticides and nutrients) into the lagoon
- Attractive sandy beaches are normally only present in lagoons when they have a considerable magnitude, say dimensions greater than 2 – 5 km and average water depths greater than 2 - 3 m. For small and shallow lagoons, the waves will be too small for maintaining a reasonable quality sandy beach.

GENERAL LAYOUT GUIDELINES FOR GOOD QUALITY ARTIFICIAL BEACHES

A waterfront development scheme will as a minimum go through the following phases:

- Master planning

- Approval procedures, including adjustments of local land use plans etc.
- Conceptual design
- Environmental Impact Assessment
- Detailed design

The layout guidelines presented in the following are mainly general guidelines useful in the master planning and conceptual design stages of a waterfront development project. These are the stages where the overall layout of the scheme is decided. Guidelines for detailed design of artificial beaches are outside the scope of the present paper.

Most countries have legal requirements for Environmental Impact Assessment (EIA) of major waterfront developments, which dictate that the scheme shall be constructed so that it imposes negligible environmental impact on the adjacent coastal environment. This procedure secures that possible impacts are identified and that optimization of the scheme or mitigating measures are introduced in order to minimize these impacts on the surrounding environment. This is of course important for the environmental condition in the area surrounding the scheme; however, the main objective for a developer of a coastal scheme is to develop attractive recreational marine elements inside the scheme, e.g. artificial attractive and beautiful beaches and lagoons. This is not secured via the EIA procedure and should consequently be an integrated part of the master planning and design phases.

The general requirements to artificial recreational beaches are similar to the conditions, which generate attractive natural beaches as mentioned above; however, there are also additional requirements. The requirements to artificial beaches can be summarized as follows:

- Wave exposure: moderately exposed to secure a good quality sandy beach and shoreface
- Longshore stability of the beach: an artificial beach shall be dynamically stable, which means that it shall be orientated towards the direction of the prevailing waves, or with other words, an artificial beach shall be constructed in the equilibrium orientation thus having zero net littoral transport. Terminal structures shall be introduced to prevent loss of sand out of a beach section
- Cross shore stability of the beach: to be secured by constructing the beach according to the equilibrium profile
- Safety: bathing hazards are related to the occurrence of high waves and associated wave breaking and to the occurrence of wave generated rip currents. Bathing safety is secured by a requirement to maximum waves during the bathing season and by proper layout of coastal structures to avoid dangerous currents adjacent to the structures
- Minimize trapping of seaweed and debris: convex corners and sheltered areas tend to trap floating seaweed and debris wherefore the layout of an artificial beach section shall be made as open and smooth as possible
- Beach sand: artificial beaches shall be constructed by good quality marine sand: medium, i.e. 0.25 mm < d_{50} < 0.5 mm, well sorted, attractive colour, minimum content of fines and minimum content of coarse fractions and no content of organic matter
- Visual appearance: few long sections are preferable for several short sections as this provides the impression of a natural beach. Short sections tend to be visually dominated by the structures

These conditions are discussed further in the following.

Beach Exposure to Waves

The beach shall be exposed to waves in order to obtain a good quality beach. However, a recreational beach shall not be too exposed, as this endangers bathing safety. This means that there are two opposing requirements:

- There shall be a certain exposure to secure a self-cleaning beach and
- The exposure shall not be too large in order to secure safe bathing conditions

Exposure in Relation to Securing a Good Beach Quality

A requirement for a good quality recreational beach is that the zone, where a person can walk on the seabed having his head over water, i.e. an approximate depth of 2 m, shall have an active clean sandy bed without depositions of fine material and biological particles and without growth of sea grasses. This zone is identical to the littoral zone, which reaches out to the Closure Depth d_l. The Closure Depth is according to Hallemeyer, 1981 defined as follows:

$$d_l = 2.28\, H_{S,12\,h/y} - 68.5 \frac{H_{S,12\,h/y}^2}{gT_s^2} \qquad \text{or} \quad d_l \sim 2\, H_{S,\,12h/y}$$

The quality of a beach is thus closely related to the exposure of the specific beach, which means that the exposure can be used for classification of beaches in relation to the recreational quality of the beach. The exposure of beaches is part of a coastal classification system developed in Mangor 2004, which uses the following wave exposure classification:

P Protected, the "once per year event" having $H_{S,\ 12h/y} < 1$ m
M Moderately exposed, the "once per year event" having 1 m < $H_{S,\ 12h/y}$ <3m
E Exposed, the "once per year event" having $H_{S,\ 12h/y} > 3$ m

Combining the concepts of Closure Depth and wave exposure it is thus evident that an attractive sandy beach shall be moderately exposed to exposed (M to E), which means that the significant wave height which is exceeded 12 hours per year ($H_{S,\ 12h/y}$), shall be higher than 1.0 m:

$H_{S,12h/y} \geq 1.0$ m for good quality recreational beaches

See also under the discussion of the beach profile form later in this section.

If the existing beach site is protected, the reason for the protection shall be investigated in order to clarify if this can be changed by artificial interventions. Note that this guideline operates with two definitions of exposure as follows:

- *Exposure of the site* is an expression of the wave exposure at deep water at the site
- *Exposure of the beach* is an expression of the wave exposure near the shoreline. A protected beach often occurs at an exposed site, e.g. if a reef breaks the waves before they reach the beach. A protected beach can be transferred into a moderately exposed beach if the site is exposed or moderately exposed. However, if the site is protected the beach cannot be converted to a moderately exposed beach

An example of the influence of wave exposure on the quality of natural beaches is discussed in the following.

Protected beach at an exposed/moderately exposed site
Many sites offer only a poor beach quality in relation to recreational requirements because the beach is partially sheltered by reefs or a very shallow shoreface. The reason for poor beach quality in such cases is lack of wave exposure, which in many cases leads to settling of fines on the shoreface and on the beach, and sea grass vegetation on the shoreface and land vegetation on the backshore. In dry and hot climates (desert climate) the land vegetation will normally not be a problem. Examples of the difference between an exposed and a protected beach within the same area are presented in Figure 1.

At this location it will not be advisable to construct an artificial beach in the southern part of the area, as such a beach by the time will be suffering from settling of fine sediments due to lack of wave exposure. However, the northern area is suitable for construction of an artificial beach because of the natural wave exposure.

Demonstration of the impact of wave exposure on artificial beaches
The impact of wave exposure on the quality of artificial beaches is discussed in the following on basis of some examples from Qatar and Dubai. Figure 2 shows two different artificial beaches in the area north of Doha. The left panel shows a very protected artificial beach built of graded sand with content of fines as well as coarse fractions. The graded sand has resulted in a swampy beach due to lack of permeability. The beach is furthermore suffering from deposition of fines; algae growth and beach crabs have invaded the site resulting in a beach dominated by crab pellets. These conditions have resulted in an unattractive beach. The right panel shows an artificial beach, which is a little more exposed, however still in the protected category. The sand quality is good but the lack of wave exposure leaves the beach as a "dead" sand slope, which suffers from siltation of fines resulting in a muddy seabed from a water depth of 0.3 m and seawards.

An example of a successful artificial beach is presented in Figure 3 left panel, which shows the artificial beach at Mamzar Sea Beach in the Mamzar Beach Park in Dubai. This site is exposed and the beach sand is good quality, medium well sorted sand without any content of fines or coarse fractions. This beach can be compared with the beach in the Mamzar Lagoon, which is presented in the right panel of Figure 3. This beach is built of the same good quality fill sand. However, this site is protected and the water is not as clear as the sea water on the open Mamzar Sea Beach (left panel). The lagoon beach is of moderate quality, as it has more the character of a sand slope than of a beach due to the lack of wave exposure. It lacks the freshness of the exposed beach. The bed of the shoreface will by the time become soft due to settling of the fines, which are clearly present in the lagoon water.

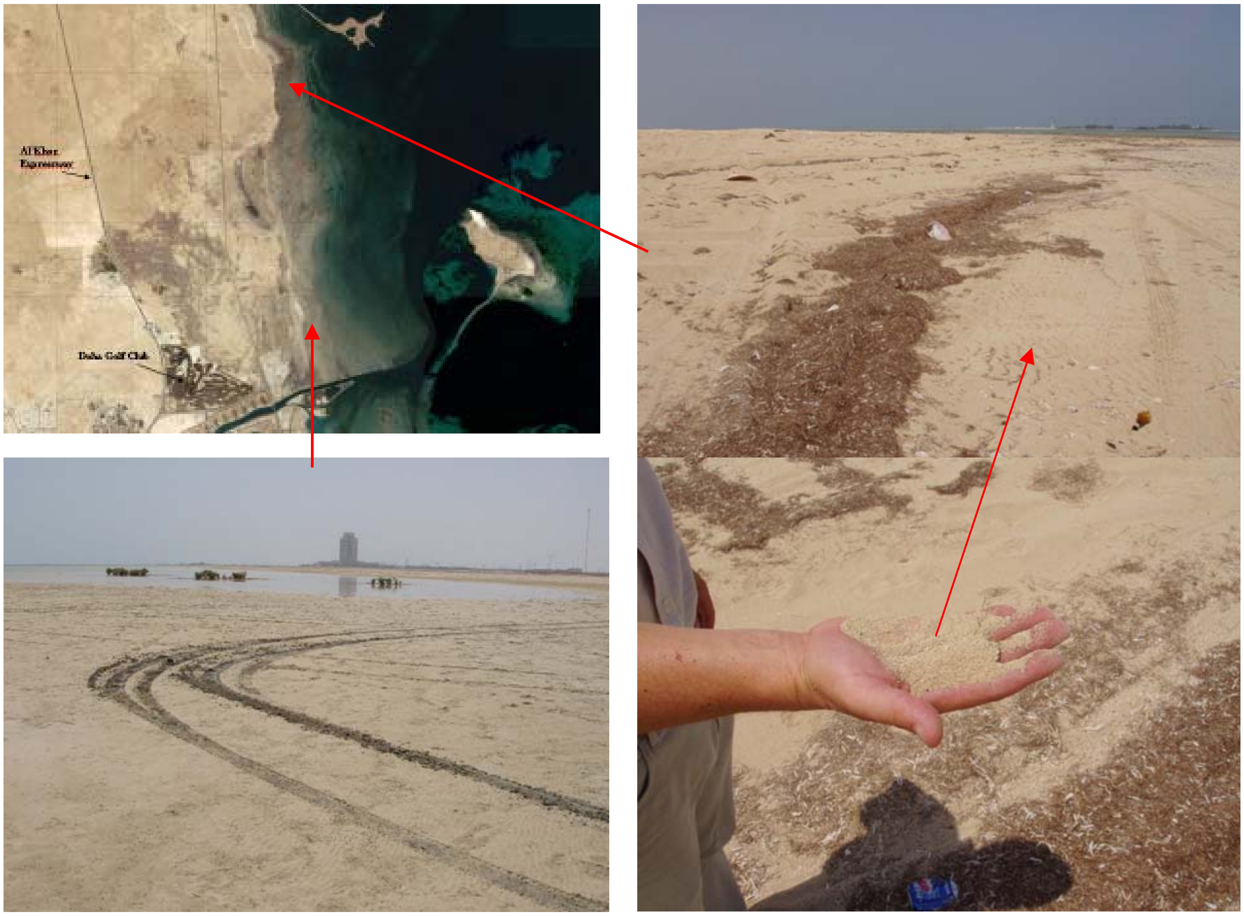

Figure 1. Example of correlation between type of beach and wave exposure. Upper left: location map, North Beach in Doha, Qatar. Note that the southern part is protected by an island and associated reefs and has a muddy tidal flat (photo lower left) whereas the northern part is exposed and has a sandy beach (photos to the right).

Figure 2. Artificial beaches north of Doha, Qatar. Left: a very protected location. Beach material is fine graded sand with content of both fines and coarse material, the shallow shoreface is suffering from siltation of fines. The beach is swampy and wet with greenish algae areas and the beach is occupied by crab pellets and scattered shingle, all in all an unattractive beach. Right: same location, but a little more exposed and the beach has been built of medium well sorted sand. This beach has a much nicer appearance; however, it has more the character of a sand slope than of a beach. It suffers from siltation of fines and the shoreface is muddy at water depths greater than approx 0.3 m.

Figure 3. Mamzar Beach in Dubai. Left: good quality exposed artificial beach at the Mamzar Sea Beach. Right: moderately good quality protected artificial beach at the Mamzar Lagoon Beach. The fill sand is in both cases medium well sorted with no content of fines or coarse material.

Exposure in Relation to Securing Safe Bathing Conditions

There exist no internationally agreed criteria related to wave height relative to safe bathing conditions. A beach Safety Study performed in Dubai, Kay 2004/05, has surprisingly shown that there is no correlation between rough wave conditions and Bather Safety Incidents. The study shows that the highest number of BSI relates mainly to the pattern of beach usage, i.e. the number of visitors and lack of swimming skills. However, it is also recommended to use field measurements as well as physical and numerical modelling in the coastal engineering design of beach schemes in order to eliminate safety hazards. The hazards are mainly related to the occurrence of breaking waves and of rip currents. These conditions are discussed in the following.

Breaking waves

Breaking waves are generally divided into three main types: spilling, plunging and surging.

- *Spilling* takes place when steep waves propagate over flat shore faces. Spilling breaking is a gradual breaking which takes place as a foam bore on the front topside of the wave over a distance of 6 – 7 wave lengths.
- *Plunging* is the form of breaking where the upper part of the wave breaks over its own lower part in one big splash whereby most of the energy is lost. This form of breaking takes place in cases of moderately steep waves on moderately sloping shorefaces
- *Surging* is when the lower part of the wave surges up on the foreshore in which case there is hardly any surf-zone. This form of breaking takes place when relatively long waves (swell) meet steep shorefaces

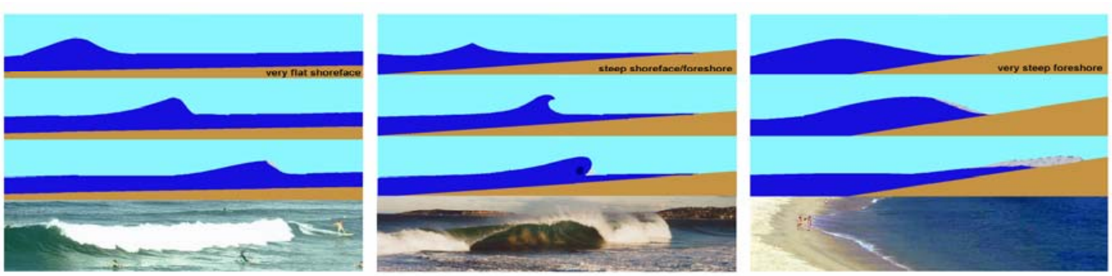

Figure 4. Wave breaking on the shoreface: spilling, plunging and surging. (From Mangor 2004).

Plunging waves are dangerous for swimmers because one can be hit by violent breaking and thereby get hurt by hitting the seabed. The violence of the breaking is proportional with the wave energy and thereby with the square of the wave height. Plunging breakers typically occur on ocean coasts with moderate wave conditions, such as under monsoon and trade wind conditions on coasts with relatively coarse sand.

It is thus seen that it is more the wave steepness, or the wave period, than the wave height which is important for the breaking type and therefore for bathing safety. It is evident from the above that ocean coasts are the most dangerous for swimmers. However, if an upper limit for wave heights shall be recommended in relation to safe bathing conditions, an estimated criterion will be: $H_s < 0.8 - 1.2$ m during the bathing season. The low limit is valid for long period waves (swell) and the high limit for steep waves (wind waves). This means that protective measures are required if a site is more exposed during the bathing season than given in the above rough criteria, e.g. in the form of specially designed coastal structures.

Dangerous currents associated with wave exposure
Dangerous currents generated by waves are mainly of two types: rip currents at a barred coast and circulation currents adjacent to structures, as discussed in the following.

Spilling waves are often associated with the formation of bars and *rip currents*, which are dangerous for swimmers because they may carry a swimmer out into deep water. This situation is typical for strong wind and storm conditions at sandy (ocean) coasts, see Figure 5.

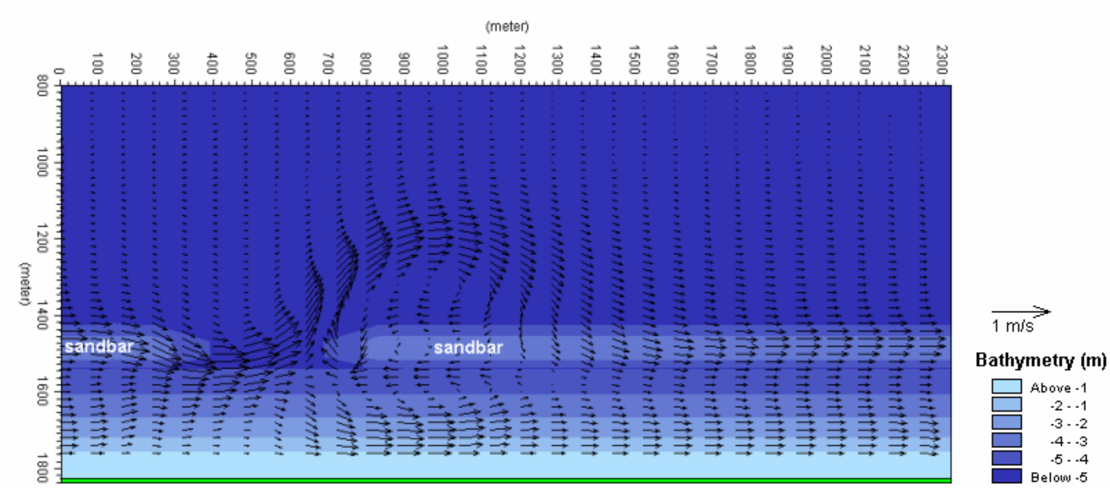

Figure 5. Distribution in longshore current and rip currents in a coastal profile with bars and a rip channel (numerical simulation) in a situation with incoming waves from the NNW (north upward). Note the seaward rip current in the rip channel. (From Mangor 2004).

Dangerous *circulation currents* generated as a result of the presence of coastal structures can also be dangerous for swimmers. The condition which makes this situation dangerous is that during a storm situation there will be partial shelter for the waves behind the coastal structure, but in the same area there will be strong currents due to eddy formation which can carry poor swimmers out into deep water, see upper panel in Figure 6.

A smooth filled coastal structure, such as the headland-type structure presented in the lower panel of Figure 6, does not generate any sheltered areas with circulation currents. There are strong currents along the structure; however, these areas are also exposed to waves and the danger is therefore more evident.

It can be concluded that coastal structures generate relatively strong currents and that coastal structures consequently impose a danger for bathers. The most dangerous coastal structures are those which offer a combination of a sheltered area, which is also exposed to circulation currents. This type of structures offers a false feeling of safety.

However, partial shelter at an exposed site can be provided without introducing dangerous circulation currents. The principle of providing partial shelter and shoreline stability at an exposed coast is presented in Figure 7, which shows a project for an artificial beach and a marina in Alexandria, Egypt, see also later.

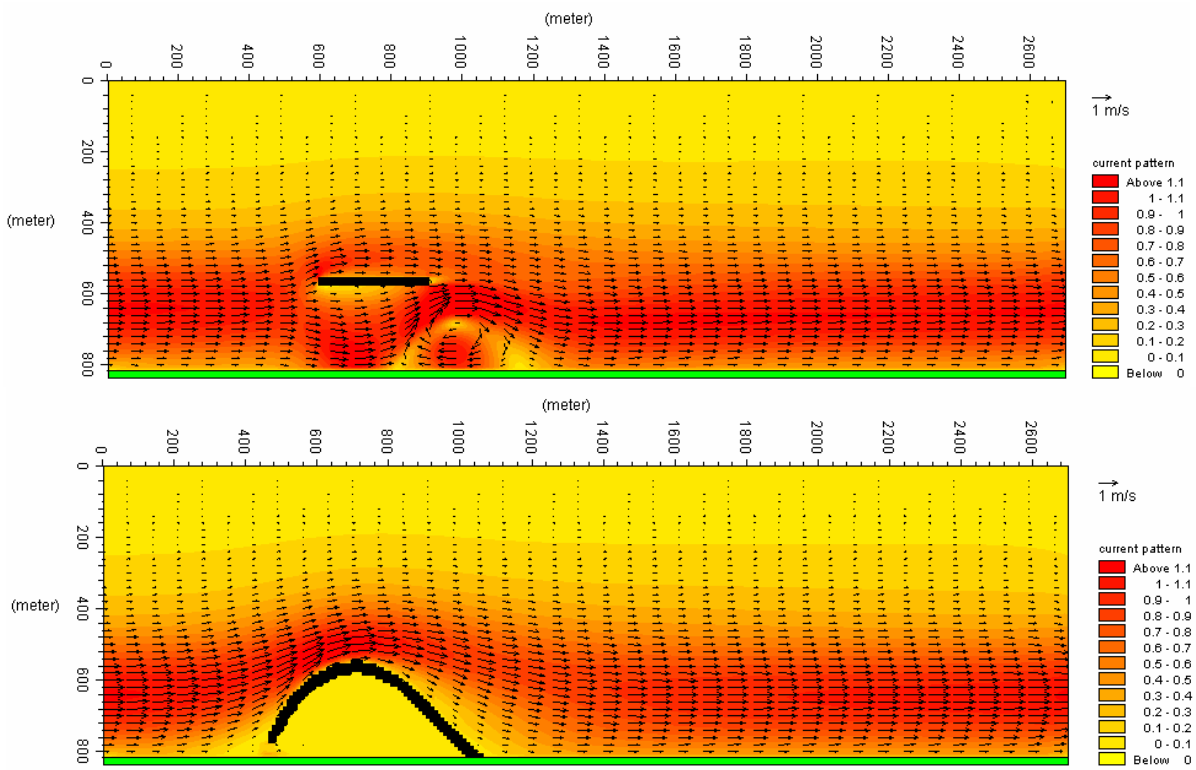

Figure 6. Upper: initial current pattern (before formation of tombolo or salient) for detached coastal breakwater for moderately oblique wave approach. Lower: same for smooth headland-type structure, where there is no sheltered area. (From Mangor 2004).

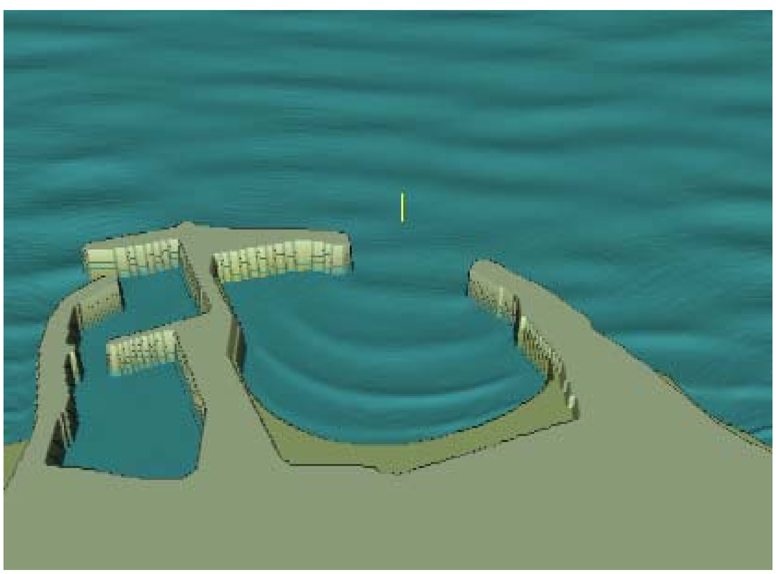

Figure 7. Modelled wave conditions at an artificial beach in Alexandria.

This concept is based on the following principles:

- Partial shelter is provided by the large breakwaters. The width of the opening has been adjusted to provide suitable wave exposure to fulfil the requirements of moderate exposure for securing a good beach quality and semi-sheltered conditions for providing safe swimming conditions
- The beach is designed to be stable under the resulting wave conditions, and a nice curved shape is obtained by the diffracting waves

- There will be no dangerous rip currents due to the long distance between the breakwaters and the beach and due to the equilibrium shape of the beach.

Beach Exposure in Relation to Tidal Range

The beach width is proportional to the tidal range, and to the wave exposure. A wide beach is attractive from a recreational point of view, which means that some tide is acceptable for an artificial recreational beach; however, a tidal flat may develop if the mean spring tidal range is much larger than the yearly average breaker wave height H_b. A high tidal range may also cause a danger to bathers. Thus, for a good quality artificial beach the tide shall be micro to moderate, which means a tidal range smaller than approx 1.5 m. It is worth noticing that the tide at a site has to be accepted, it cannot be modified by any type of reasonable intervention.

Beach Exposure in Relation to Storm Surge

In most cases there is a positive correlation between high wind speeds, wave exposure and storm surge level. In these cases the beach width is proportional to the combined action of storm surge and wave exposure. As for the tide, a reasonable storm surge is an advantage for an artificial beach as it supports a wide beach; however, a large storm surge is not suitable for artificial beaches as it makes it difficult to perform a reasonable layout of the beach. There are sites with a negative correlation between onshore winds (and waves) and storm surge, which means that high waves are correlated with negative storm surge (low water). Such locations are not suitable for artificial beaches as this negative correlation may cause too little wave exposure of the beach to maintain a good quality beach.

Beach Plan Form

The beach shall be dynamically stable in plan form (horizontally) in order to secure minimum maintenance. This means that the orientation of the beach shall be perpendicular to the direction of the resulting waves, or in other words, the orientation of the beach shall be in the equilibrium orientation, which is the orientation accommodating zero net littoral transport. This often leads to the requirement of supporting coastal structures for stabilizing the beach in an orientation, which is different from the natural orientation of the coastline in the area of interest.

At an exposed beach with oblique wave attack, the supportive coastal structures for an artificial beach shall be designed to fulfil the following conditions:

- Providing support for a stable lateral shape of the beach with an orientation providing zero net littoral transport and preventing loss of sand out of the artificial beach area
- Providing partial protection against wave action to prevent loss of sand during extreme events and to secure safe bathing conditions. This is only relevant at exposed sites
- If the supportive structures are also providing partial shelter for the artificial beach, the end of the structures should have a fairly large distance to the beach in order to avoid dangerous currents near the beach
- The structures shall have a streamlined form to minimize trapping of floating debris, angles between structures and shoreline shall preferably be concave (greater than ~ 120°)

Beach Profile Form

The beach shall be dynamically stable in profile form (vertically). Natural beaches adjust to an equilibrium profile shape in the active littoral zone, which is mainly dependent on the grain size characteristics of the sand. The equilibrium shape, Dean's Equilibrium Profile (Dean 1987), follows the shape $d = A\,x^{2/3}$ where d is the depth in the distance x from the shoreline, both d and x in metres. “A” is Dean's constant, which is dependent on the grain size of the sand according to the correlations given in Table 1.

Table 1. Correlation between mean grain size d_{50} in mm and the constant A in Dean’s equilibrium profile equation. For typical beach sand (Mangor 2004).

d_{50}	0.20	0.25	0.30	0.50
A	0.080	0.092	0.103	0.132

The equilibrium profile concept is valid only for the active littoral zone, i.e. out to the Closure Depth d_l. (Hallemeyer 1981 and Mangor 2004), see description under the subchapter: Exposure in relation to securing a good quality beach.

The equilibrium shape of the coastal profile will establish itself by the action of the waves on a newly constructed beach profile. However, it may take several years before the equilibrium profile is established, especially if the wave exposure is on the limit or lower than recommended. The concept of equilibrium profile is not applicable in the case that an artificial beach is constructed at a location with very little wave exposure, as there are "no" waves to form such a profile. This implies that at such a location the wanted coastal profile has to be shaped during the construction process.

A recreational beach shall, as mentioned earlier, have an active profile out to a water depth of at least 2.0 m relative to low tide securing that bathers walking on the seabed shall experience an attractive clean sandy seabed without any deposits of fines and without any obstructions. The clean and active seabed is secured by two requirements:

- There must be no obstructions, such as rocky or coral outcrops, above the depth of 2 m relative to Chart Datum (low tide)
- The active coastal profile shall extend out to a water depth of 2 m, i.e. $d_l \geq 2.0$ m, which means that the seabed out to this water depth will be exposed to waves regularly. As mentioned earlier, the requirement in terms of Closure Depth leads to the following approximate requirement for the wave exposure expressed in terms of $H_{S,12h/y}$:

$$H_{S,12h/y} \geq 1.0 \text{ m for good quality recreational beaches}$$

If the natural shoreface at the site does not allow these requirements to be fulfilled, e.g. if the shoreface is shallower than the equilibrium profile, then there are two possibilities to fulfil the requirements:

- The beach is shifted seaward
- The existing coastal profile is excavated to accommodate the equilibrium profile

In order to allow sufficient wave action on the artificial beach it shall also be noted that there must be no shallow reefs further away from the shoreline to attenuate the waves, which means that the depth at low tide shall be ≥ 1.7 m to allow waves of minimum 1.1 m to pass during low tide without severe attenuation. This requirement relates to a relatively narrow shallow area but if the shallow reef is of significant width the depth shall be greater than 2.0 m to avoid attenuation due to bottom friction.

Beach Fill Material

The beach fill material for artificial beaches shall fulfil the following criteria in order to provide a high quality recreational beach:

- If the new artificial beach is connected to the existing beach, the characteristics of the fill sand shall be similar to that of the natural sand in the area, however, as a rule of thumb slightly coarser
- The sand shall be of marine origin and the grain size shall be medium, i.e. $0.25 \text{ mm} < d_{50} < 0.5$ mm, preferably coarser than 0.3 mm, which minimizes wind loss
- Minimum content of fines, i.e. silt content less than 1 - 2%
- Gravel and shell content less than 3%
- Well sorted sand, $u = d_{60}/d_{10}$ less than 2.0
- Colour shall be white, light grey or yellow/golden
- No content of organic matter
- Thickness of sand layer shall be minimum 1 m, preferably thicker

The requirement of well sorted sand with minimum content of fines and organic matter is especially important for artificial beaches built at protected locations. The problem is that graded sand with some content of fines will have a very low permeability, which means that the beach will drain very slowly at falling tide. This implies that the beach will be wet at all times and it will have a tendency to be swampy, and thereby unpleasant to walk on, refer example in Figure 2 left panel.

The requirement to no content of organic matter is also very important for protected artificial beaches because the combination of lack of wave exposure and content of organic matter may lead to anoxic conditions resulting in formation of hydrogen sulphide, which causes a bad smell and dark colouring of the sand, see examples in Figure 8.

Figure 8. Examples of anoxic conditions and the formation of hydrogen sulphide at protected artificial beaches. Left: dark substance suspended in the water when the seabed is disturbed at an artificial beach in the Salt Lake Lagoon in Marsa Matruh at the Egyptian Mediterranean west coast. Right: dark substance at a beach in an artificial lagoon in the Marsa Allam area in the Red Sea.

It may take several years before the organic content has been leached out.

The requirement to a small content of gravel and coarse fractions is important for the quality of the beach surface as the action of the waves will wash away the fine fractions leaving the beach armoured with the coarse fractions. Such a beach surface is unpleasant to walk on. These conditions are illustrated in Figure 9 which shows examples of artificial beaches in Denmark and in Dubai, which are dominated by coarse fractions on the surface.

Figure 9. Artificial beaches with too much coarse material. Left: Amager Beach Park, Copenhagen. Section with too high content of gravel and pebble. Right: Umm Sequim Beach, Dubai. Too high content of shells and coral debris.

It is evident from the two examples that it is inconvenient for the comfort of walking on the beach with too high content of coarse materials in the fill sand, as the coarse fractions are separated on the surface of the beach.

DESIGN GUIDELINES FOR ARTIFICIAL LAGOONS

Characteristics of Artificial Tidal Lagoons

Another important landscape elements in many coastal development schemes are attractive tidal lagoons. The characteristics of artificial lagoons are presented in Table 2.

Table 2. Lagoon elements, functions/activities/layouts and requirements.

<table>
<tr><th>Element</th><th colspan="2">Function/Activities/Layouts</th><th>Requirements</th></tr>
<tr><td>Lagoon mouth and channel sections</td><td colspan="2">The mouth/channel sections of a tidal lagoon serve as connection between the lagoon and the sea and shall accommodate water exchange and navigation</td><td>The mouth shall be stable and free of sedimentation.
The cross section of the mouth shall accommodate sufficient water exchange.
Sufficient depth and width shall be secured for navigation, if required</td></tr>
<tr><td>Marina</td><td colspan="2">Provide safe mooring conditions</td><td>The mooring area shall provide shelter for waves and currents. Sedimentation shall be negligible</td></tr>
<tr><td>Bridges</td><td colspan="2">Access across water area</td><td>According to specific requirements</td></tr>
<tr><td>Open water body</td><td colspan="2">Adding attractive water environment facing land facilities</td><td>Proper landscape design.
Can be designed for water sports, navigation and bathing</td></tr>
<tr><td>The water quality in the entire lagoon</td><td colspan="2">Attractive water environment with a nice appearance and suitable for all types of water activities, including bathing</td><td>Good water quality requires good flushing conditions</td></tr>
<tr><td rowspan="2">Water edge perimeter elements</td><td rowspan="2">Serve the purpose of providing stable transition between water and land. Can have any layout</td><td>Lagoon beach</td><td>Good quality beach sand
Exposed beaches</td></tr>
<tr><td>Perimeter structures used for viewing, promenading, parks etc.</td><td>Sloping structures
Vertical walls
Stepped walls for close access to water
Piled piers and decks etc.</td></tr>
</table>

Design Guidelines for Elements of Artificial Lagoons

Stability of lagoon mouths, so-called tidal inlet. The stability of tidal inlets is a science in itself, for which reason it shall not be discussed in detail here. It shall just be pointed out that at littoral transport coasts the stability of tidal inlets is a major issue. This means that careful studies are needed if a mouth for an artificial lagoon is constructed at a littoral transport coast.

The cross section of the mouth/channels. The required cross sections will be dependent on the tidal volume in the lagoon, which may vary considerably. Consequently, no specific criteria can be given. However, the cross section area of mouth and channel sections of artificial lagoons shall be so wide that peak tidal current velocities are not so high, that the bed becomes unstable and that they introduce too much hydraulic resistance. This means that cross sections shall be designed so that peak tidal current velocities are less than 0.8 – 1.0 m/s.

Width and depth of lagoon elements. The various lagoon elements shall be designed according to international guidelines for navigation if the lagoon is to accommodate navigation by motor and sailing yachts.

Marinas. International guidelines for the design of marinas shall be followed.

Bridges. There may be a need for bridges for crossing the lagoon according to site specific requirements. It is important to note that requirements for navigation by sailing yachts and major motor yachts impose requirements for high bridges, which may conflict with landscaping principles.

Open water areas. The main purpose of an artificial lagoon is to add attractive landscape elements to an area in the form of open water areas and channels. The lagoon may be designed to accommodate water sports, navigation and bathing, but bathing will never be as attractive in a lagoon as in the sea. The most important function is to provide the inherent attraction of water to an area which does not have this in its native condition. The lagoon shall therefore be properly designed as an important landscape element.

Flushing requirements. A requirement for maintaining a good water quality is a proper flushing of the lagoon, which means that there must not be any "dead" ends. The flushing can be expressed in terms of a characteristic "flushing time" T50, which is the time it takes before 50% of the water in the lagoon system has been exchanged with "clean" water from the sea outside the lagoon during a design scenario. In this connection "clean" means water which has never been inside the lagoon. The design scenario shall be a calm period, as this is most critical for the flushing.

There are no specific criteria for requirements for the flushing time. However, an acceptable flushing time will normally be 5 – 7 days. The flushing time is an average measure for the entire lagoon. Even if this goal is fulfilled there may be local areas in the lagoon, "blind ends", where the local flushing is poor. An additional requirement to secure sufficient flushing in such areas can be that the concentration of "lagoon water" at every location inside the lagoon shall be below 40% after 14 days. It will under many conditions be recommendable with more than one opening to accommodate sufficient flushing; sometimes forced flushing by gates or additional pumping may be required. Other rules of thumb are:

- Water depths shall not be larger than 3 – 4 m
- There must be no local depressions in the sea bed
- There must be no discharge of pollutants to the lagoon, such as sewage, storm water, brine, cooling water, pesticides and nutrients

Water quality. The above-mentioned flushing guidelines are imperative for obtaining good bathing conditions, which require clear and clean bathing water. Fulfilment of international bathing water quality standards shall be secured, e.g. the EU Standard as given in Council Directive, 2006. For artificial beaches and beach parks the bathing water quality shall be "excellent". This water quality standard shall apply for lagoon waters as well as for coastal waters in the waterfront development area.

Lagoon perimeter structures. Normally it will be difficult to obtain a good quality beach inside a lagoon for the reasons discussed in the previous section. The following guidelines should be followed to obtain the best possible lagoon beaches if lagoon beaches are embarked on despite the above "warnings":

- Use only high standard beach sand as explained under the design guidelines for beaches
- Construct the wanted beach profile from the beginning
- Build only beaches in "large" lagoons with dimensions preferable > 2 - 5 km and water depth not less than 2 m
- Build only beaches if the amount of suspended substances in the lagoon water is very small, say in the order of less than 5 – 10 mg/l

An example of an unsuccessful lagoon beach is presented in Figure 10, which shows the beach in an artificial lagoon at the Sinai Coast of the Gulf of Suez.

Figure 10. Lagoon beach in Lagoon Ras Sudr in the Gulf of Suez.

The lagoon beach suffers from the following "diseases":

- Separation of coarse material on the beach in the front of the picture

- Formation of erosion scarp
- Settlement of fine material on the beach in the local bay and on the shoreface in general
- Silty water
- Steep shoreface

All these “diseases” are caused by mainly three conditions:

- Lack of wave exposure
- Poor quality beach material
- Lack of flushing

Other perimeter structures than beaches are consequently recommended, such as fixed sloping structures, stepped structures, quay type structures and pier deck type structures.

EXAMPLES OF ARTIFICIAL BEACHES AND LAGOONS

Amager Beach Park, Copenhagen

History

The Amager Beach is located just 5 km from the centre of Copenhagen, at the east coast of the island of Amager which faces The Sound, the strait between Denmark and Sweden. The site is located just north of Copenhagen Airport and the fixed link to Sweden. The site is presented in Figure 11 and has the following characteristics:

- The Sound is one of the connections between The Baltic Sea and The North Sea, which means that there are good flushing conditions in the area due to the tidal exchange and the meteorologically generated water exchange between the two major seas
- The island Saltholm is located east to southeast of the site which means that the main wave directions are NE and SSE
- The site is moderately exposed but the original beach is protected due to a very shallow shoreface. The main littoral activity is taking place at the outer shoulder of the shallow shoreface leaving hardly any wave energy for the littoral processes on the beach
- The original beach is of a poor quality characterized by a shallow slightly muddy shoreface in front of a low wooden sheet piling supporting a filled sand area
- There are often accumulations of seaweed on the shallow shoreface
- The ambient water quality in the Sound is good due to the results of 20 years of water environment improvements performed by the Danish society, but occurrences of storm water discharges occur from numerous storm water outlets in the area
- The active depth is clearly indicated by the distinct limit between the exposed seaward part of the sandy shoreface and the area covered by sea weed.

The problems in relation to recreational activities on the old beach are thus: a) The shallow shoreface which means that there is more than 100 m to a water depth of 1.0 m, b) The seabed is slightly muddy, c) The water quality is poor due to frequent accumulation of seaweed and rare occurrences of storm water discharges, d) Lack of space between the road and the shoreline, e) Frequent flooding of the filled sand area causing loss of sand and trapping of water behind the sheet piling. It shall, however, be noted that the ambient water quality is in general good. This means that there are good general conditions in the area for upgrading the area to an excellent bathing location. It “only” requires local improvements and mitigation of the above-mentioned problems.

The New Amager Beach Park

A local association of marine clubs in the area started working on a plan for a new beach park 2 decades ago and the Ministry of Traffic initiated a baseline investigation for a new beach park back in 1995. The investigations concluded that it would be possible to build a new beach park in the area. Following many political discussions a financing plan for the beach park was agreed between the County of Copenhagen and the Municipalities of Copenhagen and Frederiksberg in 2003.

The new beach park was designed according to the following principles:

Figure 11. Amager Beach, Copenhagen, Denmark, before construction of the New Amager Beach Park.

- Good quality beaches were secured by moving the beaches out to deep water thereby securing most possible wave exposure; however, the wave exposure was slightly less than optimal
- The beaches were constructed of sand with the following characteristics: SAND, fine to medium (d_{50} = 0.24 to 0.41), sorted to well sorted (u = d_{60}/d_{10} = 1.4 to 1.6, however with a few samples as high as 2.9), light grey of marine origin, no silt content, small content of gravel, averagely 0.6 % but with some samples containing up to 13 %

- The new beaches have been constructed at an island and a new lagoon (deepened to 2 m) has been excavated between the island and the old shoreline. The lagoon is connected to The Sound via openings in the northern and southern ends. The island is so low that it allows view to The Sound over the island from the beach road
- The stability of the two beach sections are secured by orientating them towards the two main wave directions NE and SSE, and by building terminal structures in both ends of the sections and a headland separating the sections. The structures have also recreational and landscaping functions, such as viewing points and a marina
- The angle between the terminal structures and the beach sections is concave thereby optimizing the flow along the beaches which minimizes trapping of seaweed and debris. Note also the Y-shape of the headland structure providing a smooth transition between the structure and the beaches
- Due to the location of the beach park in a narrow section of The Sound there is always a good current just off the new island which also results in a good flushing of the lagoon. The flushing time T_{50} has been simulated to 24 hours
- The discharge of storm water has been minimized by introducing retention basins and all the old outlets have been cut off and collected in one main outlet at deep water. This has secured excellent bathing water quality at all times in the entire beach park

The hydraulic design of the beach park was performed by extensive numerical modelling of waves, hydrodynamics, littoral transport, flushing, and water quality by application of DHI's numerical modelling suite.

An aerial photo of the new beach park just after finalization in August 2005 is presented in Figure 12.

Figure 12. Aerial photo of Amager Beach Park, which consists of the following main elements: island with terminal structures north and south and a separating headland between northern and southern beaches and a lagoon.

The beach park has been very well received by the local population and the beach park has been nominated with several prizes for popularity, functionality and good landscaping architecture.

Problems during the Construction Phase

Due to necessary savings introduced during the construction the specifications to the beach sand were relaxed allowing the contractor to deliver sand with "some" content of gravel and coarser fractions. This caused the exposure of these coarse fractions at some sections of the beach as presented in Figure 9.

The Amager Beach Park was, as mentioned above, constructed at a location where the wave exposure is just on the limit of what is recommended for obtaining a good quality beach. This means that it was forecasted to take some years before the equilibrium coastal profile would establish itself due to the natural processes, if the profile was not constructed to the equilibrium shape from the beginning. However, in an attempt to save money during the construction, the profile of the shoreface was initially not built in the equilibrium shape, but the calculated volume for the equilibrium profile was just bulldozed out in a deposit with top level just below MSL and a monitoring programme was set up to follow the profile development over the winter months. The development towards the equilibrium profile was, contrary to what was hoped but according to forecasts, very slow.

The built profile was characterized by a shallow nearly horizontal shoreface flat with a width of approximately 40 m followed by a very steep slope.

During the four months following construction, the profile developed only slowly as follows:

- Slight smoothing of the steep slope
- Development of shallow beach bars and beach lagoons, a kind of barrier formation
- Poor water quality developed in the beach lagoons and algae started growing in the shallow lagoon

This development is seen in Figure 13.

Figure 13. Development of beach bar and beach lagoon with algae growth on the shallow shoreface at Amager Beach Park during the construction process.

This development was absolutely unacceptable, and it was decided to shape the profile as close as possible to the equilibrium profile by bulldozing the sand seawards, whereby the steep slope, the beach bars and beach lagoons were removed and a gently sloping bathing beach was established before the opening of the Beach Park.

These examples of last minute marginal savings in the form of relaxation of sand specifications and sand placement principles may compromise the quality of the artificial beaches as demonstrated above. Such savings should consequently be carefully considered, involving advices by the marine engineer, as the main attraction of waterfront projects are high quality artificial beaches.

San Stefano Marina and Private Beach, Alexandria

The beach frontage along the Corniche in Alexandria on the north coast of Egypt is very narrow. The 29-storeyed San Stefano Grand Plaza apartment complex is under construction right out to the Corniche. The complex houses nearly 900 apartments. Part of the development is an associated marina and private beach located opposite the apartment complex. There is no beach at the site due to a recent expansion of the Corniche and the site is very exposed to the rough wave climate of the Mediterranean. The objectives for the new beach were therefore:

- To provide space for construction of a new artificial stable beach
- To provide partial protection for the beach in order to make it safe for bathing
- To design the beach so that dangerous circulation currents are avoided

Figure 14. Artist's impression of the Marina and Private Beach for the San Stefano Grand Plaza Development, Alexandria (From www.san-stefano.com).

These objectives were obtained by applying the following principles:

- Provision of space for the beach and partial shelter for the waves by the construction of an artificial bay defined by two major breakwaters. The exposure of the beach was regulated by optimizing the width of the opening
- The shape of the new beach was designed to fit to the diffracting pattern of the waves entering the bay
- The concept of keeping good distance between the structures defining the bay and the beach secured that no dangerous currents are generated along the beach and that no loss of sand is taking place out of the bay

The hydraulic design of the beach park was performed by extensive numerical modelling of waves and wave penetration, hydrodynamics, littoral transport, flushing and water quality by application of DHI's numerical modelling suite. Some results of the wave penetration modelling are presented in Figure 7. Furthermore, physical modelling was performed to optimize the breakwater design. The Marina and the Private Beach are presently (2007) under construction.

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