BYPASS HARBOURS AT LITTORAL TRANSPORT COASTS

by

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ABSTRACT

Maintaining sufficient navigation depth in front of the entrance at harbours on littoral transport coasts is a major operational challenge for many harbour authorities, especially for small fishery harbours located at exposed or moderately exposed sandy coasts. The paper presents an evaluation of the critical conditions related to bypass harbours at littoral transport coasts in relation to the capability of the harbour to maintain a certain navigation depth in front of the entrance. The relation between the required depth at the entrance and the corresponding maintenance dredging is discussed for different sizes of the harbours, those with extensions smaller or larger than the width of the littoral zone, respectively.

The concept of bypass harbours is discussed in Section 1. The basic characteristics of littoral transport coasts, which are used as reference for classifying the size of the harbour relative to the width of the littoral zone, are presented in Section 2. Section 3 describes basic considerations for different cases of bypass harbours and discusses the characteristics of the different cases and the possible remedial measures to maintain the required navigation depth. Section 4 provides results from studies of various bypass harbours and Section 5 presents a summary of the results.

The main conclusion is that for small harbours, ie small compared to the width of the littoral drift zone, a bypass harbour is the optimal layout for a harbour at a littoral transport coast. The maintenance requirements and the recommended remedial measures are very site specific, but for each site an optimal relation between length of the main breakwaters, depth in front of the harbour and characteristic wave conditions leading to minimum maintenance dredging can be found.

1. INTRODUCTION

Many harbours at littoral transport coasts suffer from sedimentation and cause impact on the adjacent coast. When sediments bypass the entrance it will in most cases lead to a reduction in the water depth in front of the harbour and to sedimentation in the outer harbour and in a possible entrance channel. This sedimentation may reduce the navigation depth to an unacceptable level. The amount of dredging required to maintain the navigation depth in front of and inside the harbour and the frequency of these maintenance dredging campaigns are critical operational parameters for such a harbour. The amount of sedimentation is dependent on the magnitude of the littoral transport at the site and thereby dependent on the wave climate. These sedimentation conditions are in principle of different nature for small and large harbours, where the size refers to the extension of the harbour relative to the width of the littoral zone.

The layout of the protective works is important in relation to the capability of the harbour to maintain a sufficient water depth for navigation and for minimizing the requirements to maintenance dredging. The optimal layout of a harbour on a sandy coast with a significant net and gross littoral drift will in most cases be a so-called bypass harbour, which is a harbour where the layout of the protective works is smooth and streamlined and with an exposed opening pointing directly into the sea. This is referred to as a double breakwater harbour. The reason that this is the optimum layout is that the streamlined form to the greatest possible extent accommodates bypass of sediments with a minimum trapping of these sediments in the outer harbour; however, the critical question is which natural depth can be sustained in front of the harbour under the bypass situation. This is the main issue of the present paper.

The bypass harbour is in contrast to the type of harbour consisting of one main breakwater protecting against the prevailing waves and a secondary breakwater partly sheltered for by the main breakwater.

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This is referred to as a single breakwater harbour. A single breakwater harbour will normally trap a high percentage of the bypassing sand in the entrance plus all the sand coming from the secondary transport direction. For a discussion of the single versus double breakwater harbour layout reference is given to Mangor (2004).

In the following we will only deal with the double breakwater bypass type harbours. The main parameters in this context are the following:

- The extension of the littoral transport zone in terms of the width of the littoral zone and the closure depth
- The extension of the protective works relative to the width of the littoral zone and relative to the location of the bars
- The relation between the required navigation depth and the natural depth in front of the harbour
- The accumulation pattern of sand at the upstream side of the harbour, hereunder the extension of the port from the coastline relative to the width of the littoral zone for the fully developed shoreline

The littoral transport conditions are mainly dependent on the geology of the area and on the wave climate, but also the tide/surge and current conditions play a role. The littoral transport conditions can be expressed by the net and gross littoral transport, the width of the littoral zone and the closure depth. Furthermore, the type of littoral climate at a coast can also be classified according to the wave exposure and angle of incidence of the prevailing waves. Special characteristics of the harbour site will also be of importance for the ability of the harbour to accommodate a suitable natural depth in front of the harbour, such as if the site is located at a relatively straight coast or at a headland.

The present paper extracts conclusions from various investigations of sedimentation conditions at ports of different types at littoral transport coasts and presents them in a general and generic way, which is considered of great importance for the design of new ports at littoral transport coasts. Special emphasis is put on minimizing sedimentation and accommodation of sufficient navigation depth in the bypass situation.

2. BASIC CHARACTERISTICS OF LITTORAL TRANSPORT REGIMES

Principal considerations on littoral transport coasts are discussed in the following in order to provide the basis for discussion of sedimentation and natural depth at bypass harbours. A littoral transport coast is a sandy coast with a sandy coastal profile exposed to wave action, whereby littoral transport is taking place. However, the problems related to sedimentation by sand will also be relevant for coastal profiles consisting only partially of sandy deposits, e.g. a rocky coast with patchy occurrence of sand in the coastal profile as sand will also be transported along the coast for such a coastal type.

The littoral transport at a specific coast can be characterized by the following parameters (we are considering a coast oriented towards east, which means that the coastline is running north – south):

- The annual southward and northward littoral drift rates
- The annual net littoral transport rate (southward – northward transport), defined by an annual transport rate in m^3/y. The net transport has also a direction (southward or northward)
- The annual gross transport rate (southward + northward), no direction

The closure depth: The depth beyond which no significant longshore or cross-shore transports take place due to littoral transport processes. The closure depth can thus be defined as the depth at the seaward boundary of the littoral zone. According to Hallemeyer (1981) the closure depth can be calculated using the expression:

$$d_l = 2.28\,H_{S,12h/y} - 68.5\,\frac{H^2_{S,12h/y}}{gT_s^2} \tag{1}$$

where d_l is the closure depth relative to mean low water level, $H_{S,12\ h/y}$ is the nearshore significant wave height exceeded 12 hours per year, and T_S is the corresponding significant wave period.

The concept of the equilibrium profile says that a coastal profile possesses an average, characteristic form, which is referred to as the theoretical equilibrium profile. The equilibrium profile has been defined as “a statistical average profile, which maintains its form apart from small fluctuations, including seasonal fluctuations." The depth d [metres] in the equilibrium profile increases with the distance x from the shoreline according to the equation, Dean (1987):

$$d = A\,x^m \quad \text{[x and d in metres]} \qquad (2)$$

where A is the dimensionless steepness parameter and m is a dimensionless exponent. Based on fitting to natural upper shoreface profiles, Dean has suggested an average value of m = 0.67. However, the value of m is subject to large variability. The steepness parameter A has empirically been related, Dean (1987), to the sediment characteristics and considering normal beach sand with d_{50} = 0.20 mm a characteristic value will be: A = 0.08, which gives the following equation for the equilibrium profile:

$$d = 0.08\,x^{0.67} \quad \text{[x and d in metres]} \qquad (3)$$

The equilibrium profile is only valid for the littoral zone, i.e. out to the Closure Depth.

A coastline can be classified according to the wave characteristics in different ways. Mangor (2004) proposes the following classification as function of the angle of incidence of the prevailing waves and the wave exposure:

1. *Perpendicular wave approach*, angle of incidence close to zero, net littoral transport is zero
2. *Nearly perpendicular wave approach*, angle of incidence 1° - 10°, net transport small to moderate
3. *Moderate oblique wave approach*, angle of incidence 10° - 50°, large net transport
4. *Very oblique wave approach*, angle of incidence 50° - 85°, large net transport
5. *Nearly coast-parallel wave approach*, angle of incidence >85°, net transport near zero

The angle of incidence is measured with respect to the normal to the coastline. This angle of incidence between the coast orientation and the prevailing waves can also be expressed as the angle between the present coastline and the coastline orientation of net zero transport.

This classification has been subdivided according to the wave exposure as follows:

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 equilibrium profile and the concept of closure depth provides a correlation between $H_{S,12h/y}$, the closure depth d_l and the width of the littoral zone W_l as given in Table 1.

$H_{S,12\,h/y}$ [m]	d_l [m]	W_l [m]	Exposure classification	Order of magnitude of net littoral drift
1	2.0	100	Protected, w_l < 100m	Few thousand m^3/year
2	3.7	310	Moderately exposed, 100 < w_l < 580	Up to a few 100,000 m^3/year
3	6.0	580		
4	8.0	880	Exposed, w_l > 580	Several 100,000 m^3/year
5	10.0	1250		

Table 1 Correlation between $H_{S,12\,h/y}$ and width of littoral zone W_l, exposure classification for a equilibrium profile with d_{50} = 0.2 mm and magnitude of littoral drift.

It should be noted that the concept of equilibrium profile does not take the presence of longshore bars into consideration. Furthermore, longshore bars tend to migrate seaward and the location and top level of the bars are therefore changing with time. This variability of the cross-shore location and top level of the bars implies that the ability to bypass sediment with a given natural depth will vary in time.

3. BASIC CONSIDERATIONS ON BYPASS HARBOURS

3.1 Definition of Study Cases and their General Characteristics

The characteristics of different categories of harbours are presented in Table 1. The situations considered are the following:

- A double breakwater bypass harbour, same size in all cases
- Two different littoral transport climates on a straight coast:
  - Exposed, moderately oblique in which case the extension of the harbour is small compared with the width of the littoral zone
  - Moderately exposed, moderately oblique in which case the extension of the harbour is large compared with the width of the littoral zone
- The harbour extends right out to the navigation depth, which means that that there is no navigation channel in the initial situation
- Two situations are considered for each transport climate:
  - The initial situation, where no upstream accumulation has taken place.
  - The fully developed situation, where a considerable upstream accumulation has taken place, which also means that the littoral zone has been moved offshore

It has been indicated on the sketches in Table 2 that there is a bar in the coastal profile, which is very often the case. It should be noted that this is a simplification as there are often 2 or 3 bars and they constantly vary in position and height. The typical development of the shoreline and the bar has been indicated in the four situations as these situations highlight the principle difference between the two main situations, namely the harbour with a small extension relative to the width of the littoral zone and the harbour with the large extension relative to the width of the littoral zone, respectively. The characteristics of these cases with relation to the restrictions in the navigation depth conditions imposed by the bypass of these harbours are discussed in the following. It should be noted that only moderately oblique wave climates are considered, as these are the most common. The case of an exposed site with a negligible net transport and a large gross transport, i.e. two large opposite transport components of the same size, will constitute an ideal location for a successful bypass harbour as there will hardly be any accumulation along adjacent beaches and the bypass will consequently not increase with time. A large extension bypass harbour at such a location will be virtually without any sedimentation problems.

The location of the bar relative to the harbour is also of importance as the extension of the harbour in some cases is smaller than the distance from the coast to the inner bar. This is especially the case for small fishing ports at ocean coasts, e.g. an extension of 100 m at a coast with the width of the littoral zone of 1 km or more. This issue will be discussed further under the examples.

3.2 Discussion of the 4 Cases of Bypass Harbours

Case 1: Small bypass harbour relative to width of littoral zone, exposed coast, initial situation

This type of harbour is typically a small fishing harbour located at an exposed coast, such as an ocean coast. There is a large net southward (downwards on the sketch) littoral drift and the coastal profile has at least one distinct bar with a water depth of say 3 m. The required navigation depth could be in the order of 5 m. The protective breakwaters are extended out to the water depth of 5 m, which is on the offshore side of the bar. This is the situation in the design stage and immediately after the harbour has been constructed.

With respect to sedimentation and bypass the situation is as follows in this initial situation:

- There is a substantial bypass of the harbour as the littoral zone goes beyond the extension of the breakwaters
- There is a minimal sedimentation in the outer harbour because of the optimized streamlined layout of the harbour
- The navigation depth is maintained in the initial situation, it may even increase slightly immediately following the construction due to the convergence of the streamlines off the entrance

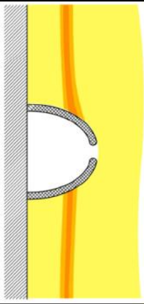
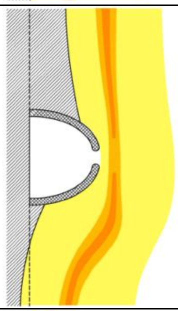
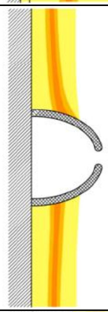
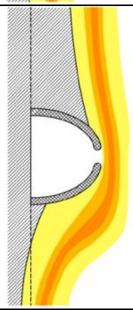
Type of harbour	Coastal classification	Development situation	Sketch of harbour and littoral cond. Yellow: Littoral zone Orange: Bar	Navigation depth	Maintenance dredging to maintain navigation depth	Sedimentation in outer harbour
Bypass harbour, small ext. relative to width of littoral zone	Exposed, Moderate oblique	Case 1 Initial		Ok	No	Minimal
		Case 2 Fully developed		Likely restricted by depth over bypass bar	Most likely required	Minimal
Bypass harbour, large ext. relative to width of littoral zone	Moderately exposed, Moderate oblique	Case 3 Initial		Ok	No	No
		Case 4 Fully developed		Restricted by depth over bypass bar	Required	Minimal

Table 2 Characteristics of navigation depth for bypass harbours in different littoral transport climates

The question is now: How will the situation develop and which natural depth in front of the harbour can we expect to end up with and how often and how much sand do we have to dredge to maintain the required navigation depth in front of the harbour at all times? This leads us to case 2.

Case 2: Small bypass harbour relative to the width of the littoral zone, exposed coast, fully developed situation

We have the same situation as in case 1 but some years have elapsed since the harbour was constructed and the sand has accumulated along the beach north of the harbour. This has resulted in an offshore movement of the beach north of the harbour and furthermore the entire littoral zone has also shifted offshore.

This has resulted in a new situation for the harbour and for the bypass situation, namely that the extension of the harbour relative to the littoral zone has decreased because the shoreline and the littoral zone have moved seaward. The bar has also moved seaward and its general alignment north of the harbour is now seaward of the entrance, which potentially causes a reduction in the depth in front of the entrance. However, the harbour still extends some distance into the sea and will therefore cause a convergence of the streamlines in front of the entrance thereby increasing the current speed and the transport capacity, which to some extent causes a lowering or even disappearance of the bar in front of the entrance. The question is: Will the natural depth in front of the entrance be larger than the required navigation depth?

This is a delicate balance between the wave climate at the site and the distance from the upstream coast to the entrance. The chance in this situation is that the site is so exposed that the longshore currents are so strong that they will erase the bar. But the violent wave climate will on the other hand also cause accumulation of large amounts of sand along the upstream coast. If the natural depth is smaller than the required navigation depth there are in principle the following solutions:

- Dredge in front of the entrance every time the depth is reduced due to the bypassing sand. This may be required rather often, probably after each storm due to the tough wave climate at the site. If a reservoir is dredged this may reduce the frequency of maintenance dredging operations but the total volume of dredged material will increase as a reservoir will tend to trap all sand coming into the area. A long and shallow reservoir is better than a short and deep reservoir in that respect. The dredged sand shall preferably be deposited along the downstream coast in order to reduce the leeside erosion
- Extend the breakwaters even further out into the sea. This will work for a period but eventually the beach will again move out to a position close to the entrance and we are then back to the same situation. This situation will cause an increase in the leeside erosion as the distance from the entrance to the downstream shoreline has now been increased. This solution is not recommended as there will be large construction costs and adverse leeside erosion
- Excavate the beach and the shoreface upstream of the harbour thereby transferring the situation back to case 1, where the depth in front of the entrance is sufficient. The excavated sand shall be deposited along the downstream coast. This situation requires constant maintenance in the form of moving sand from the upstream side to the downstream side. This method has the following characteristics:
    - The navigation operations are not interrupted
    - No new construction works
    - The leeside area will be restored and there will be no future leeside impact if artificial bypass is implemented
    - The initial excavation of the upstream beach will be costly

These solutions are illustrated in Table 3.

The challenge for this case is to find a balanced solution whereby the natural amount of wave energy and transport capacity is utilized optionally to obtain an optimal combination of structures and maintenance dredging which results in:

- The best operational conditions for the harbour, i.e. no interruption of navigation
- Most possible natural bypass as this will minimize the need for maintenance dredging and minimize the leeside erosion
- Minimum sedimentation in the outer harbour

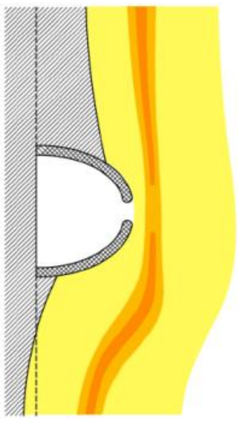
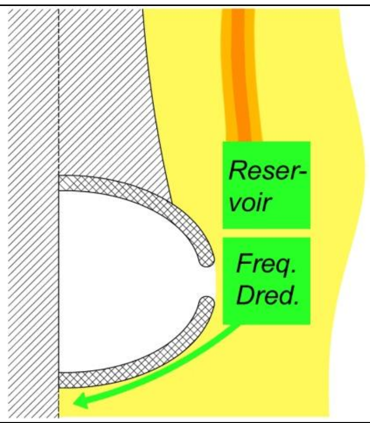
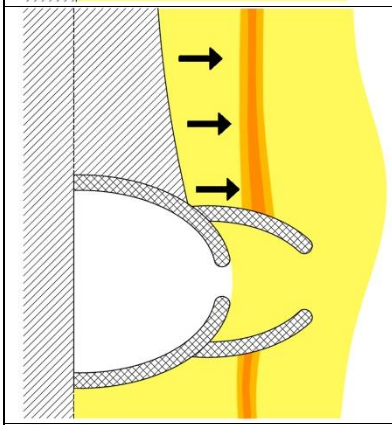
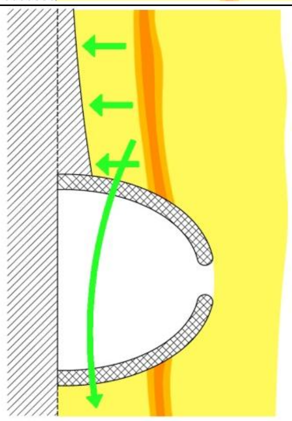
Start situation, Case 2	Alternative remedial measures	Comments
		Risk for interruption of navigation Frequent maintenance dredging Volume < net littoral drift Some natural bypass Artificial bypass Leeside erosion stabilized
		Risk for interruption of navigation Dredging may be required Major construction works Some natural bypass No artificial bypass Upstream shoreline will continue to accrete, solution not durable Leeside erosion continues
		No risk for interruption of navigation Major beach excavation →artificial bypass Volume >> net littoral drift Some natural bypass Restoration of downstream beach Upstream beach will accrete Requires regular excavation of beach No leeside erosion of restored beach

Table 3 Alternative remedial measures for maintenance of navigation depth for harbour with shorter extension than the width of the littoral zone

Case 3: Large bypass harbour relative to the width of the littoral zone, moderately exposed coast, initial situation

This type of harbour is typically a marina or a fishing harbour located at a relatively sheltered coast, which is only moderately exposed. This could typically be in semi-protected waters but not on an ocean coast. There is a relatively small net southward littoral drift (downward on the sketch) and the coastal profile has at least one distinct bar with a water depth of say 1.5 m. The required navigation depth could be in the order of 3.5 m. The protective breakwaters are extended out to the water depth of 3.5 m, which is well on the offshore side of the bar. This is the situation in the design stage and immediately after the harbour has been constructed.

With respect to bypass, sedimentation and navigation the situation is as follows in this initial situation:

- There is no bypass of the harbour as the littoral zone does not reach out to the entrance. The water depth along the breakwater outside the littoral zone is too large for any transport to take place in the initial situation; however, sand accumulation will start along the north beach and the bar will start developing along the north breakwater

- There is no sedimentation in the outer harbour because there is no transport at this water depth
- The navigation depth is maintained until the accumulation and the sand bar in the area north of the harbour has developed out to the entrance. The time horizon for this to happen is dependent on the magnitude of the net littoral drift, the extension of the harbour and the equilibrium orientation of the beach

The question is now: How will the situation develop and which natural depth can we expect to end up with in front of the harbour and how often and how much sand do we have to dredge to maintain the required navigation depth in front of the harbour at all times? This leads us to case 4.

Case 4: Large bypass harbour relative to the width of the littoral zone, moderately exposed coast, fully developed situation

Some years have elapsed since the harbour was constructed and the sand has accumulated along the beach north of the harbour. This has resulted in an offshore movement of the beach north of the harbour and furthermore the entire littoral zone has also shifted offshore.

This has resulted in a new situation for the harbour and for the bypass situation, namely that the extension of the harbour relative to the littoral zone has decreased because the shoreline and the littoral zone have moved seaward. The bar has also moved seaward and its general alignment north of the harbour is now more or less in alignment with the entrance, which causes a reduction in the depth in front of the entrance. The difference between this situation and the case 2 situation is that the wave energy and littoral transport capacity in this case are so small that the bypass of the sand can only take place at fairly shallow water. The shallow water (the bar) will therefore develop into the area in front of the entrance, which limits the navigation depth. However, the harbour still extends some distance into the sea and will therefore cause a convergence of the streamlines in front of the entrance thereby increasing the current speed and the transport capacity, which to some extent causes a lowering of the bar in front of the entrance. This lowering will be much smaller than in case 2 because of the relatively small wave energy available in this case to generate the current. It is therefore clear that the natural depth in front of the entrance will be drastically decreased and that it will be much smaller than the required navigation depth. As the natural depth is smaller than the required navigation depth there are in principle the following solutions:

- Dredge in front of the entrance and possibly some distance upstream, typically once a year. The volume of required maintenance dredging will be in the same order of magnitude as the annual net littoral transport because practically all sand will be trapped in the deepened area as no sand can be transported at such large water depth with the mild wave climate in this case. This is different from the situation in case 2, where part of the net littoral drift will be bypassed due to the wide littoral zone. The dredged sand shall preferably be deposited along the downstream coast in order to reduce the leeside erosion. This solution will satisfy the navigational requirements
- Extend the breakwaters even further out into the sea. This will work for a period but eventually the beach will again move out to a position close to the entrance and we are then back to the same situation. This means that a lot of sand will be trapped on the upstream side; this sand is thus taken out of the littoral transport budget which will lead to adverse leeside erosion. No bypass to the downstream coast will take place neither in the case without an extension nor with the extension. This solution will normally not be recommended as there will be large construction costs, the problem will come back after some years and there will be increased leeside erosion
- Excavate the beach and the shoreface upstream of the harbour thereby transferring the situation back to case 3, where the depth in front of the entrance is sufficient and where the harbour extends far beyond the littoral zone. The excavated sand shall be deposited along the downstream coast. This situation requires constant maintenance in the form of moving sand from the upstream side to the downstream side. This method has the following characteristics:
    - The navigation operations are not interrupted
    - No new construction works

- The leeside area will be restored and there will be no future leeside impact if artificial bypass is implemented
- The initial excavation of the upstream beach will be costly

These solutions are illustrated in Table 4.

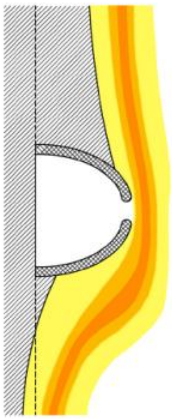
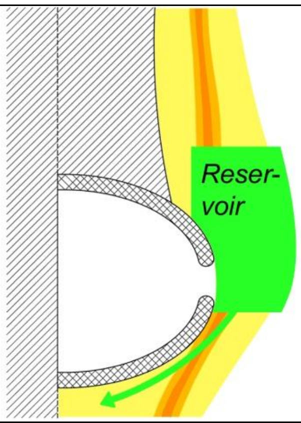
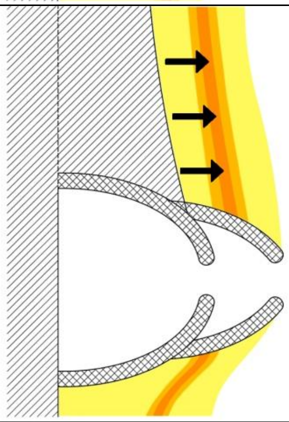
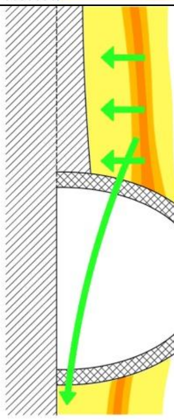
Start situation, Case 4	Alternative remedial measures	Comments
		Minor risk for interruption of navigation Yearly maintenance dredging of reservoir and entrance → artificial bypass Total amount ~ net littoral drift No natural bypass Yearly artificial bypass Leeside erosion stabilized
		Minor risk for interruption of navigation Major construction works Minor dredging may be required No artificial bypass No natural bypass Upstream shoreline will continue to accrete, solution not durable Leeside erosion continues
		Minor risk for interruption of navigation Major beach excavation → artificial bypass Restoration of downstream beach No continued leeside erosion No natural bypass Upstream beach will accrete Requires regular maintenance Volume ~ net littoral drift

Table 4 Alternative Remedial measures for maintenance of navigation depth for harbour with greater extension than the width of the littoral zone

The main differences between the case 3/4 (large harbour extension relative to the width of the littoral zone) and the case 1/2 (small harbour extension relative to the width of the littoral zone, i.e. a small harbour on an ocean coast) are the following:

Small extension harbour (Case 1/2): There may be a major problem of maintaining the navigation depth in front of the harbour as there will be sedimentation and depth reduction from the start, which means that some sort of action will have to be taken from the start, but at the same time there is a chance by optimizing the layout of the breakwaters to obtain a high percentage of natural bypass, maybe full natural bypass with sufficient navigation depth dependent on the specific conditions and requirements.

Large extension harbour (Case 3/4): There will be no sedimentation and navigation problems the first years after construction. The number of years until the problems start will depend on the capacity of the area upstream of the harbour for storage of sand relative to the magnitude of the net littoral transport. It is not possible to avoid dredging nearly the total amount of net littoral transport in order to maintain the navigation depth; however, as the littoral transport climate for this type of harbour is often mild the maintenance requirement is of a smaller magnitude than for the small extension harbour.

For both cases it is assumed that the harbour layout is optimized as a bypass harbour. It should be noted that the sedimentation problems will be considerably larger if a single breakwater layout is used, Mangor (2004).

It should be noted that the situations discussed above are simplified in order to make the message more clear. The main simplifications beyond the assumptions listed in Section 2.1 are the following:

- We have assumed a coastal profile with one main longshore bar, which interacts with the bypass harbour. However, in the real world there will often be more than one bar and the location of the bars in the coastal profile will vary over time
- We are only considering littoral transport climates with moderate oblique wave approach (see definition in Section 2)

It should also be noted that there will be no or only very minor problems related to sedimentation and reduction of the navigation depth for a harbour with an extension many times greater than the width of the littoral zone. In this case the layout of the entrance can be designed without considering sedimentation aspects.

4. EXAMPLES OF BYPASS HARBOURS, NAVIGATION PROBLEMS AND POSSIBLE SOLUTIONS

4.1 General

It is stressed that this paper only considers bypass harbours at straight littoral transport coasts with varying exposure and for moderately oblique wave approach. There can be other locations of harbours which provide different constraints or opportunities for establishing natural bypass, such as:

- A partly sheltered location, e.g. in a bay at the sheltered side of a headland, which makes natural bypass more difficult, or
- At an especially exposed location, e.g at the tip of a headland, which provides improved opportunities for establishing a natural bypass with a relatively large natural depth due to additional currents that might be present at such a location

Such locations are not covered by the general discussion of bypass harbours in the present paper, however an example of such a harbour is shown in the following in order to illustrate the difference.

4.2 Thorsminde Harbour, (very) Small Extension Harbour at a Straight Coast

Thorsminde Harbour is located in the northern part of the very exposed North Sea coast of Jutland, Denmark, where the net littoral drift is southward with an order of magnitude of 0.4 million m^3/year, see Figure 1.

The natural (equilibrium) water depth at the entrance to the harbour is 2-3 m, if no maintenance dredging is carried out. The harbour entrance is at present dredged to 3.5-4 m. The harbour is very "small" compared to the width of the littoral zone; the entrance is actually located landwards of the average position of the most landward longshore bar. There is a need for maintenance dredging after almost every storm due to deposition in front of the entrance. On average, 100,000 m^3 were dredged every year. The downdrift coastline suffers from erosion due to the partial blockage of the littoral drift by the harbour. The downstream beach is protected by beach breakwaters and some of the dredged material is artificially bypassed to the eroding beach via a pipe system from a berth in the outer harbour, where the dredger can moor and connect to the downdrift pipe discharge system. This is a very flexible system which allows bypass also in rough weather.

A new layout was developed for Thorsminde Harbour using the principles of natural bypass as discussed above. The new layout includes a downdrift breakwater, streamlining of the entrance by a small curved extension of the existing main breakwater to the southwest and a shortening of the updrift groyne. The philosophy for this layout was that the contraction of the wave-driven currents around the harbour entrance would be enough to maintain an equilibrium depth in front of the harbour,

Figure 1: Left: Location map of bypass harbours. Middle: Aerial photos. Right: Satellite images (approx. same scale, line = 500 m). Thorsminde (old layout at aerial photo and new layout at satellite image) and Hvide Sande Harbours at a straight coast and Hanstholm at a headland

which was sufficient for unhindered navigation. Strong, but well-defined, currents will be present in front of the entrance during storms. The large outer harbour basin makes this current pattern acceptable for navigation in rough weather. The present sedimentation problem related to waves from a south-westerly direction will be alleviated. The naturally bypassed sediment from north to south, will, with time, develop a bypass shoal and start to feed the downdrift beach. The tested layout is presented in Figure 2 lower row.

The critical parameter for the new harbour layout is the equilibrium depth at its entrance. This equilibrium depth is reached when the sediment transport capacity in front of the harbour is similar to the updrift transport capacity. The equilibrium depth has been evaluated using short term morphological modelling, i.e. simulation of waves, currents, sediment transport and bed level changes, with continuous updating of the bed levels and the subsequent re-calculation of waves, currents and sediment transport, see Brøker et al (2007) and Brøker (2006). The use of a morphological model makes it possibility to follow the bed development with time during selected storm conditions; however, the long term development over years, e.g. of the upstream coast in response to the small extension of the harbour, can still not be modelled with this model complex.

Detailed surveys of the harbour entrance are carried out regularly, especially after severe storms. These surveys were used to verify the performance of the morphological model.

The upper row in Figure 2 shows the pre- and post-storm bathymetry. It can be seen that the sand shoal off the main breakwater was pushed to the south during the storm thereby partly blocking the entrance. This development is in perfect agreement with the results of the soundings.

Figure 2 lower row shows the result of a repetition of the simulation of the October 1997 storm with the new bypass layout. The left panel is the initial bathymetry and the right panel is the bathymetry after the storm. It appears that a water depth of about 3.5 m can be maintained in front of the entrance after the storm with the modified layout. Furthermore, no sedimentation seems to have taken place in the entrance area.

Several more simulations were performed. The results seem to indicate that the 3 m depth contour never reaches the tip of the northern breakwater. A shoal develops immediately downdrift of the harbour, in the area where the contracted current expands after flowing across the entrance. This shoal keeps growing until the depth decreases to a level where the sediment transport capacity, due to wave breaking and wave-driven currents, corresponds to the amount which bypasses the harbour.

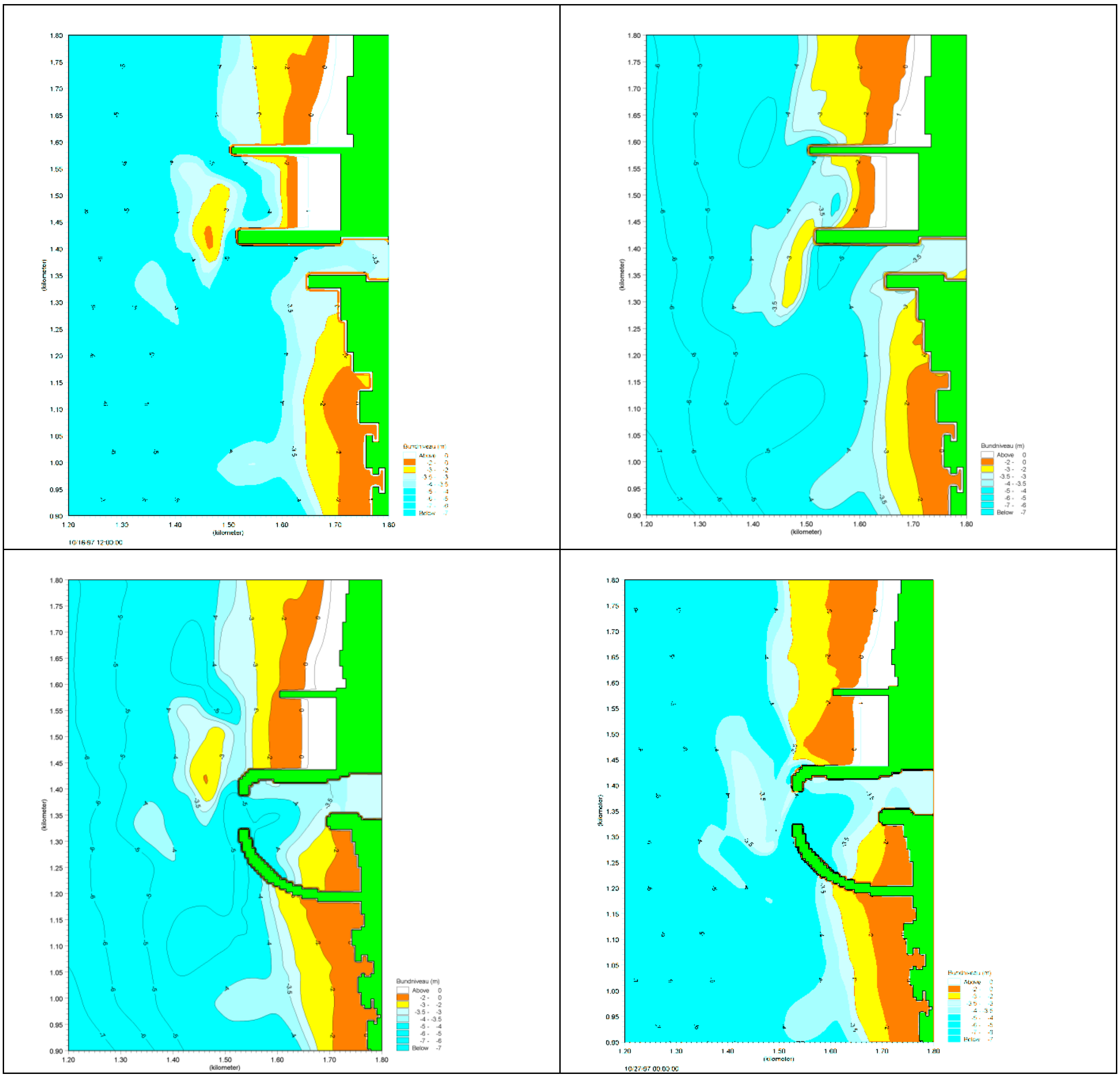


Figure 2: Thorsminde Harbour. Upper row: Simulated pre-storm and post-storm bathymetries for Oct. 1997 storm. Lower row: New layout. Morphological modelling of the October 1997 storm, from Brøker et al (2007)

Development since implementation. The new breakwater was finished in the autumn of 2004. The maintenance dredging volumes during the period 1999 through 2009 are presented in Figure 3. The first two winters indicate a reduction in dredging to about 40% of the amounts before the re-design. This improvement was so large that it was not necessary to have a permanent dredger stationed at the harbour to secure safe navigation. However, the last 3 years the maintenance dredging requirements have increased again up to the level before the construction of the new layout was implemented.

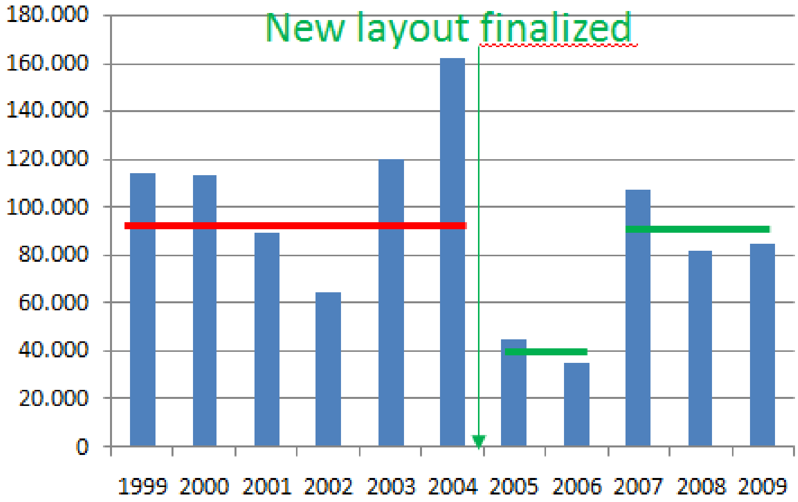


Figure 3: Annual maintenance dredging [m^3/year] in front of Thorsminde Harbour in the period 1999 through 2009. The new layout of the breakwaters was implemented in late autumn 2004

This indicates that the implementation of the new breakwater layout was able to reduce the maintenance dredging requirements and to improve the navigation conditions for about 2 years. This improvement was due to two changes:

- The slight increase in extension of the breakwaters
- The more streamlined layout of the breakwater

However, these changes are not capable of maintaining the improved conditions, probably because the bathymetry around the harbour gradually adjusts to the new conditions by an offshore movement of the depth contours updrift of the harbour. It can thus be concluded that the optimization of the layout is not sufficient to reduce the maintenance dredging requirements permanently. It was possible to obtain a short term improvement in maintenance dredging requirements and not least in the navigation conditions by optimizing the layout but it was not possible to maintain this ideal situation with the low maintenance dredging efforts. This new situation has not been studied yet, but a preliminary conclusion could be that the improved navigation conditions provided by the optimized layout have to be supported by a maintenance dredging effort of the same magnitude as before in the form of dredging the near-shore area upstream of the harbour thereby maintaining the extension of the new harbour relative to the near-shore depth contours. Such a maintenance dredging procedure might be able to maintain the improved navigation conditions, however, at the expense of a constant maintenance dredging effort. It can be said that such a dredging philosophy would be proactive as opposed to the traditional procedure, which is reactive in nature. The advantage of this proactive method is that it secures a high navigation safety but the price is that the maintenance dredging effort is not reduced.

The morphological modelling complex proved to be a useful tool in supporting the short term understanding of the processes around the harbour and thereby in the optimization of the layout of the re-designed harbour.

4.3 Hvide Sande Harbour, Small Extension Harbour at a Straight Coast

Hvide Sande Harbour is located at the central part of the very exposed North Sea coast of Jutland, Denmark, where the net littoral drift is southward with an order of magnitude of 1.1 million m^3/year, see Grunnet et al (2009). The present sedimentation and shoaling problems affecting the harbour entrance are illustrated in Figure 4.

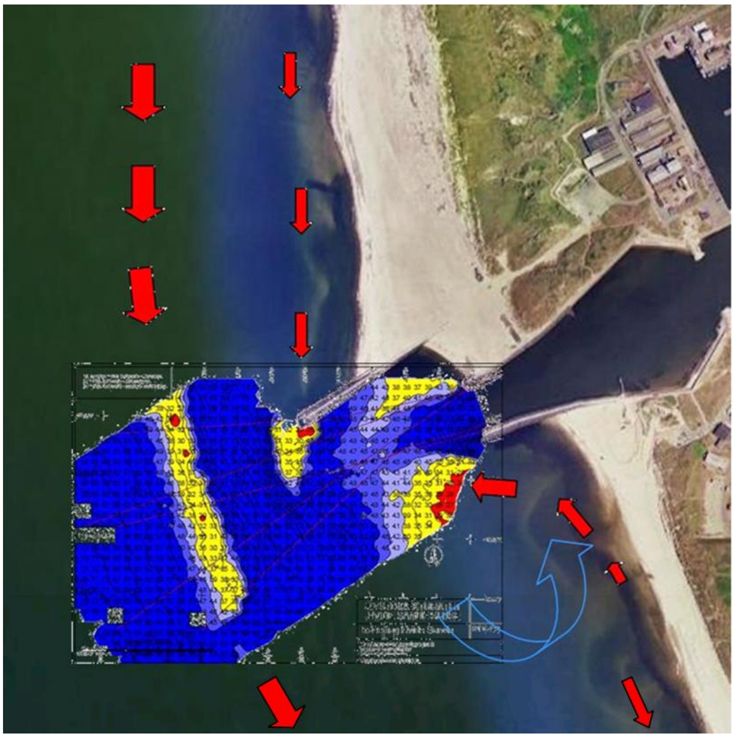


Figure 4: Typical bathymetric survey of the access channel superimposed on an aerial view of Hvide Sande harbour; the yellow colour shows depths between 3 and 4 m, red shows depths less than 3 m. The red arrows illustrate the sediment transport pattern and the blue arrow the circulation pattern in the lee of the harbour

The conditions are very similar to the conditions in Thorsminde; however, the net littoral drift is larger and the extension of the harbour is also larger. The existing layout of the harbour entrance has been developed over the years by extending the north inlet jetty, which worked until the beach accreted. However, this development has led to the situation, where sand coming from south is trapped in the entrance area and the bar develops from north across the entrance. The sedimentation constitutes a major operational problem for the harbour.

Facing the need to accommodate larger fishing vessels, Hvide Sande Harbour Authority wishes to increase the navigation depth in the access channel from the present 4.5 m to 6.0 m. At the same time, the Harbour Authority wishes to improve the operational conditions and if possible also to reduce the sedimentation in the entrance area. Another requirement is that the new layout of the harbour must not cause increased downdrift erosion. Therefore a possible extension of the existing northern breakwater should be kept at a minimum while at the same time the natural bypass should be improved.

The main elements of the proposed improvements of Hvide Sande Harbour (see Figure 5) are:

1. The extension of the existing northern breakwater, kept to a minimum adding only about 70 m to its present length
2. The construction of a new southern breakwater with a total length of approximately 750 m
3. Landward displacement of the shoreline in the area north of the harbour of about 160 m with the purpose of introducing a relatively larger extension of the harbour and avoiding major decrease in the natural bypass. This excavation of the upstream beach area amounts to a volume of 1,200,000 m^3 along the coast over a stretch of 1,600 m. The dredged material is planned to serve as nourishment on the downdrift coast.

The main characteristics/advantages of the proposed scheme are the following:

- The sedimentation with sand from south due to the circulation current and due to the northward directed component of the littoral drift will be eliminated
- The streamlined breakwaters will increase the bypass of sediment past the harbour mouth by increasing the flow velocity due to contraction
- The current speed past the harbour mouth will increase but constricted to a well-delimited area

- The initial removal of sand along the coast upstream of the harbour will help maintain the required additional water depth needed. It is a precondition for the sustainability of this solution that this landward displacement of the depth contours north of the harbour is maintained by regular dredging/excavation

The innovative element of the proposed scheme is the combination of the streamlined breakwaters and the retreat of the shoreline north of the harbour. Since its construction in 1963, the northern breakwater has accumulated about 3,600,000 m^3 of sand resulting in an advance of the shoreline over a longshore stretch of approximately 3.5 km corresponding to an average yearly deposition of 80,000 m^3/year. While removing a third of this accumulation could be seen as a nature rehabilitation project; the sought-after effect is an increased water depth at the harbour mouth. Thereby, relative to the landward displaced profile, the breakwaters will extend farther out in the profile and will be able to interact more with the second longshore bar than in the actual harbour setting.

Based on gained experience from Danish bypass harbours since the 1960s and physical model testing with moveable bed (Grunnet et al, 2008), an angle between breakwaters of 40° was selected.

Figure 5: Proposed future layout of Hvide Sande Harbour breakwaters (curved yellow lines). The shoreline location after the beach excavatioin north of the harbour is illustrated by a straight yellow line, which also indicates the extent of the proposed dredging

The morphological model was calibrated and validated against the documented development during selected historical storms. The modelling of a historical event is presented in Figure 6 upper part. It is seen that the bar is developing into the navigatioin area during a single storm, which is the main problem at this harbour. The calibrated model was applied to forecast the equilibrium bathymetry for the future harbour with no further tuning of model parameters. A synthetic initial upstream bathymetry was constructed based on historical coastal profile data and the depth in the access channel was set to 6 m. The constructed initial bathymetry and the modelled equilibrium bathymetry are shown in Figure 6 lower part, which shows the results for a model run with a single-barred profile (also double bar profiles were tested).

The updrift near-shore bar evolves into a bypass bar in front of the harbour with the bar crest in an approximately constant water depth of 4.5 m. The effectiveness in promoting bypass *and* increasing the water depth over the bypass bar is found to be highly coupled to the cross-shore location of the near-shore bar: The closer to the harbour mouth, the stronger is the local depression in the bar in front of the harbour. This result was expected since the increased flow velocities due to the contraction of the streamlines increase the bypass capacity past the harbour entrance. The additional landward displacement of the updrift shoreline strengthens the bypass effectiveness because the bar thereby comes closer to the mouth.

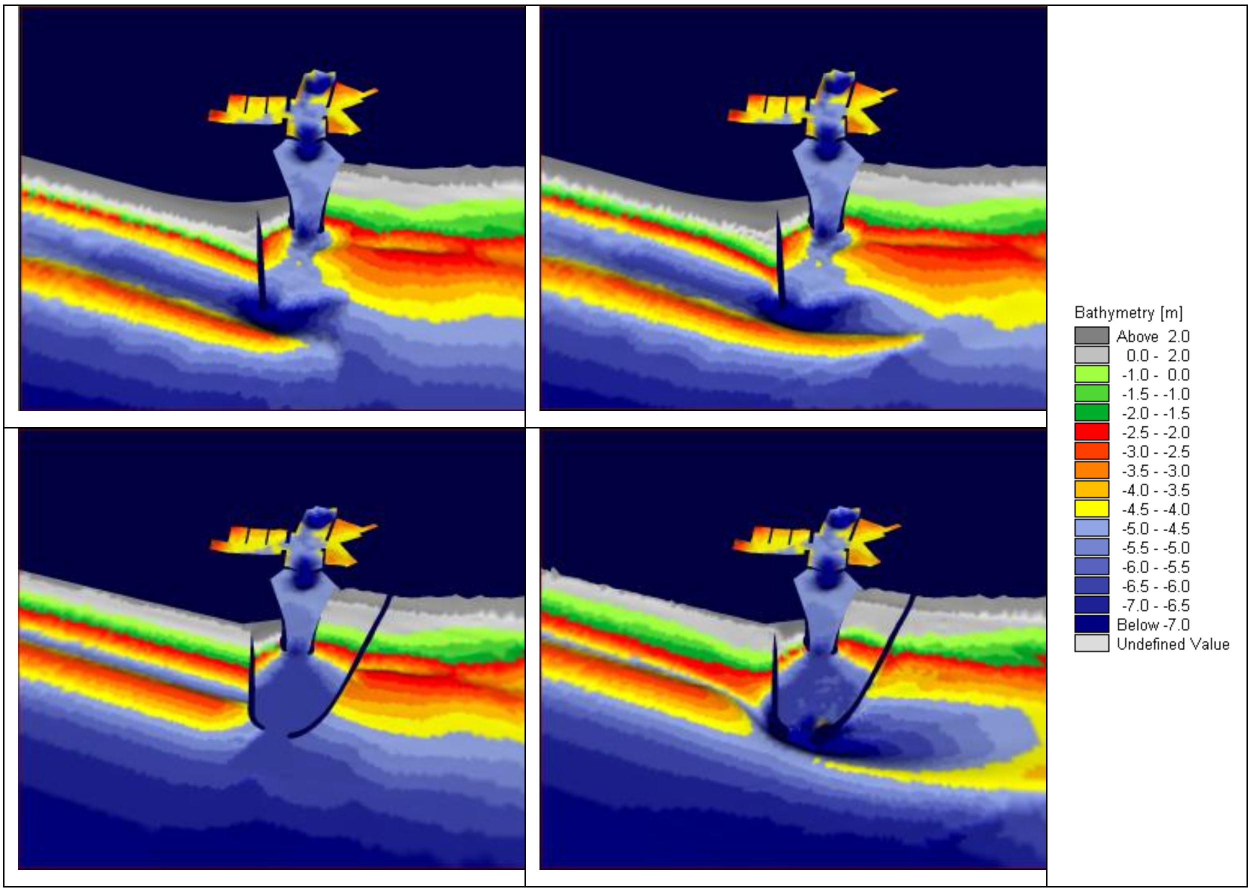


Figure 6: 3D view of initial bathymetry (left column) and following a storm (right column) for the present situation (upper row) and for the proposed layout (lower row)

In the present non-optimized harbour configuration, the equilibrium depth of the bypass bar is about 2.5 m and the dredging requirement is in average 170,000 m^3/yr in order to maintain a navigation depth of 4.5 m. It was found that this navigation depth of 4.5 m can be maintained with the proposed scheme for the future harbour (streamlined layout, little extension and shoreward displacement of the upstream shoreline), with an estimated minor maintenance dredging in the entrance area of say 40,000 m^3/yr plus a maintenance dredging along the upstream shoreline of 80,000 m^3/year to maintain the upstream shoreline in its displaced location, which means totally 120,000 m^3/yr. If a navigation depth of 6/7 m is required a maintenance dredging of additionally 225,000/500,000 m^3/yr is required, which means totally averagely 305,000/580,000 m^3/yr, respectively.

It should be noted that the above dredging volumes are averages between situations with one bar and two bars, respectively. Maintenance dredging is typically higher for a double barred profile than for a single barred profile; however, it should also be remembered that these results are to some extent site specific.

The navigation depths that can be achieved for an optimized bypass harbour are thus a function of the following parameters:

- The wave climate in terms of exposure and wave obliqueness
- The extension of the harbour relative to the upstream shoreline
- The number and location of longshore bars
- The amount of dredging invested in maintaining the extension of the harbour relative to the upstream shoreline and in maintaining the navigation depth in front of the entrance

4.4 Hanstholm Harbour, Medium Extension Harbour at Headland

Hanstholm Harbour is an example of a very successful bypass harbour located at a headland on the northern part of the Jutland coast, see Figure 1 for location map and layout. This coast is very exposed and has a very oblique wave approach. The harbour is a fishery and ferry harbour built in the 1960s. The headland location and bypass layout of the harbour were chosen to obtain minimum sedimentation. There is a NW-ward littoral drift component of 0.7 to 1.0 million m^3/year, corresponding to a net NW-ward littoral drift of 0.4 million m^3/year and a gross transport of around 1.5 million m^3/year), see Sørensen et al (1996) and Jensen (2005).

The symmetrical and streamlined layout creates a smooth convergence of the flow past the harbour entrance and has in combination with vertical breakwater fronts resulted in optimal bypass conditions and acceptable sedimentation rates. The natural depth in the entrance area is about 9 m. The flow around Hanstholm Harbour is mainly driven by meteorological forcing, variations in wind and pressure, and, to a smaller extent, by wave breaking. Tide is very limited in this area.

The wave statistics at 20 m water depth off Hanstholm Harbour are illustrated by the wave rose in Figure 7. The westerly and south-south-westerly directions are dominant and the significant wave height exceeds 4 m approx. 0.5% of the time and 5 m approx. 0.1% of the time. The coastal classification is exposed with very oblique wave approach. The closure depth, only counting in the wave conditions, is in the order of magnitude: $d_l \sim 10$ m.

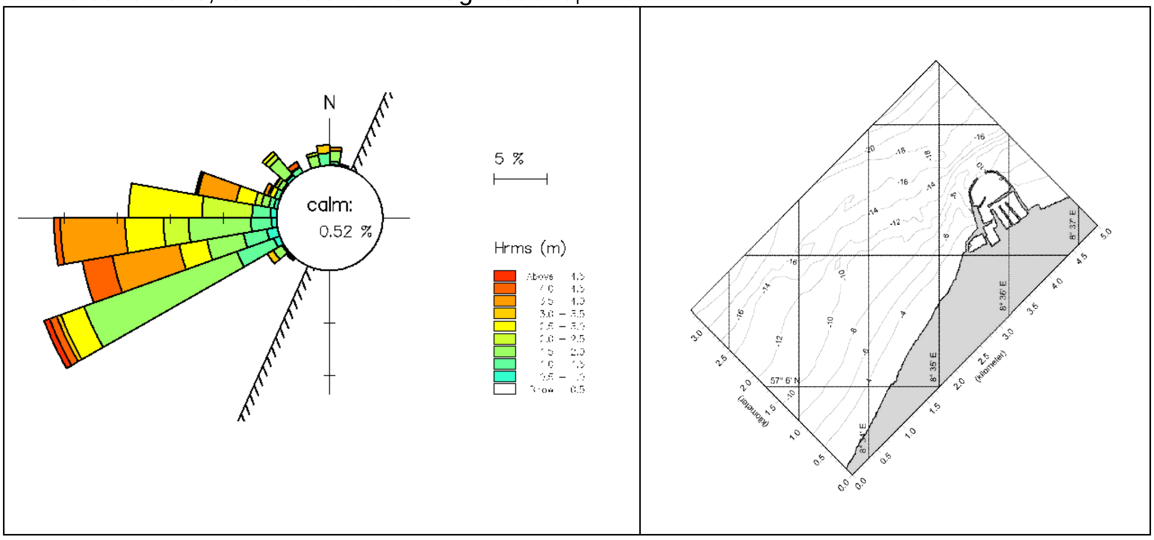


Figure 7: Wave rose at 20 m water depth off Hanstholm

The harbour layout was originally optimized by the use of physical modelling techniques to obtain minimum sedimentation in the harbour and maximum natural bypass depth. The design has been successful with a yearly maintenance dredging in the outer harbour of 80,000 m^3/yr. Dredging outside the harbour is not required. Both the headland location, the oblique wave approach and the large extension (750 m) are different from the two previous examples.

The factors making this harbour successful with respect to sedimentation and bypass are a combination of the following:

- The location at a headland, which causes additional meteorologically driven currents which accommodate bypass and a large natural depth
- The streamlined layout of the breakwaters
- The vertical face of the breakwaters
- The oblique wave climate

5. CONCLUSIONS

It can be concluded that the relations between maintenance dredging, natural depth at the entrance and navigation depth at the entrance are site specific and have to be optimized carefully for every single case. Both short term (months) and long term (years) morphological changes have to be considered.

The three cases demonstrate:

- That very good performance in terms of operational conditions and maintenance dredging can be obtained at special locations where high currents past the entrance can be obtained

- It is very difficult to obtain low maintenance dredging for small bypass harbours if the navigation depth is considerably larger than the natural depth at the entrance.

An operational advantage can be obtained by performing a preventive dredging along the upstream coast; however, the total dredging volume will be in the same order of magnitude as for traditional case by case maintenance dredging after storms. This approach will provide a solution with minimum impact on the downstream coast provided that the dredged material is bypassed to the downstream coast.

Acknowledgements

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