Solving a harbour sedimentation problem in Yemen

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Abstract

The Ash Shihr, Yemen harbour on the Gulf of Aden was built in 1992/93 by Nexen Inc. for the vessel fleet supporting the loading of oil into large tankers at the offshore Single Buoy Mooring (SBM).

In designing the harbour, the greatest emphasis was placed on ensuring that the harbour provided effective shelter during the SW summer monsoon season, which can generate deep water waves of up to about 6.4 m significant wave height with a period of 14 seconds. This led to the harbour entrance being placed on the east side of the harbour to minimize wave agitation within the harbour. The dominant factor proved to be the littoral drift of sediment in a westerly direction. This led to the migration of large amounts of sediment into the harbour and the build up of sand on the beach well to the east of the harbour. As this situation developed it was effectively closing the harbour.

A sedimentation study of the harbour was performed by Delft Hydraulics [1]. Various solutions were considered including by-pass maintenance dredging, a dredged sand trap, relocating the harbour entrance, and shielding the harbour with a sand trap breakwater.

Westmar Consultants Inc. provided the detailed design for a 600 metre long sand trap breakwater which resulted in economically viable construction bids. The work was successfully completed by Yemen based contractors in May 2001. The quality of the work is excellent and the breakwater is performing as designed in trapping sand and preventing the longshore drift from accreting in the entrance.
1 Introduction

Nexen Inc. (formerly Canadian Occidental Petroleum Ltd.) first discovered oil in the Masila Block in Yemen in late 1990 and developed production and storage facilities for the handling of the oil in 1992/1993. The facilities include a 2.5 million-barrel onshore oil storage Terminal, complete with export pumping equipment, near Ash Shihr on the Gulf of Aden. To support the export operation, a marine fleet is under contract to handle the tankers hooking up to the off-shore Single Buoy Mooring (SBM) loading point and to protect and maintain the SBM. This fleet operates out of the Ash Shihr harbour, a small purpose-built structure at the site. A map of the Middle East showing the site location can be found in Figure 1.

Two rubble mound breakwaters protect the harbour from swell waves generated in the Indian Ocean, and from storm waves generated in the Gulf of Aden by Summer Monsoons. The main breakwater on the west side of the harbour is L-shaped, with a small wharf on the offshore leg and road access and utility services via the shore leg. The closure breakwater on the east side of the harbour limits the wave heights within the harbour, and defines the harbour entrance. An aerial photograph of the harbour prior to construction of the sand trap breakwater can be found in Figure 2.

Prior to constructing the harbour, the wave and current climate were measured using wave rider buoys and current meters to supplement the wave hindcasts performed using a global atmospheric model. The wave climate was modelled numerically, and as a result of the analysis the harbour entrance was placed on the east side of the harbour primarily to minimise the wave climate within the harbour. A geotechnical investigation identified the foundation as
dolomite bedrock covered by a 1 m to 2 m thick layer of sand (Gulf Interstate [2], HAM Dredging [3]).

After construction, it was found that there was a net longshore drift of sand from east to west, which resulted in silting in of the entrance. The complex wave and current climate was studied in more detail and it was estimated that the littoral drift in the wave affected zone results in a net movement of about 260,000 m³/year of sand. The sand is being swept along the coast from wadis and other sources in Yemen and Oman.

Initially a variety of dredging methods were used to keep the harbour open, including water injection, diver directed air lift, a plow, and trucking the material around the harbour. All these approaches were relatively ineffective due to the shallow water depths, the high-energy wave environment during the Summer Monsoons, and the thin layer of sand overlying bedrock.

Eventually the harbour entrance was overwhelmed by the volume of sand, resulting in the costly deployment of maintenance vessels, tugs, etc. from the port city of Al Mukalla approximately 42 km from the site. This situation was deemed to be a risk to the continued safe operation of the oil loading facilities, due to the much longer response times required and the lack of control of access to shore support facilities.

As a consequence, Nexen needed to find a permanent solution and retained Delft Hydraulics in 1998 to examine the sedimentation problem and propose solutions.

2 Sedimentation study

2.1 Estimate of sand transport

Delft Hydraulics [1] carried out a study of the longshore sediment transport that would occur at the Ash Shihr harbour site before construction of the harbour. The sand in the region is characterized as fine grained with a median grain size (D₅₀) of about 0.1 mm.

The major findings of Delft are summarized as follows:

- The gross westward rate of longshore transport of sand is in the range of 450,000 to 600,000 m³/year.
- The gross eastward rate of longshore transport of sand is in the range of 250,000 to 400,000 m³/year.
- There is a net westward transport of approximately 260,000 m³/year at the harbour location. This is the mean of the range implied by the difference in the above transport rates.
- A sensitivity analysis indicated that this net transport might vary in a range of 0.5 to 1.5 which would indicate that the net transport could range from 130,000 to 390,000 m³/year.
The net eastward transport of sand occurs during the summer SW monsoon season when there are storm waves from the SW. Practically all wave induced longshore transport is generated in the breaking wave zone shoreward of the -3 m to -4 m CD water depth contours (CD is Chart Datum, which is defined as the level of the Lowest Astronomical Tide or LAT).

The greatest longshore transport is at the 0 m CD water depth, which is about 100 m from the shoreline. Continuation of the by-pass dredging strategies will become less effective with time.

2.2 The predicted effect of the sand trap breakwater

Delft examined a number of options to reduce sedimentation in the harbour entrance including:

- A dredged sediment sink east of the harbour.
- Moving the harbour entrance to the west.
- Constructing a sand trap breakwater east of the harbour to block the flow of sand.

The dredged sediment sink was eliminated as an option because of the shallow depth to bedrock at the site and the consequent inability to create a sufficiently large dredge pocket to trap sand. Relocation of the harbour entrance was not found to be as effective as the sand trap breakwater at reducing sedimentation in the harbour mouth.

The Delft study therefore recommended building a 600 m long sand trap breakwater about 500 m to the east of the harbour entrance. The length is the total length of the breakwater, from the upper beach to the toe of the breakwater in about the 6 m water depth. Based on a numerical model, Delft concluded that such a breakwater would trap most of the sediment for 15 years, which is the projected life of the harbour.

The detailed estimates of sand transport and deposition made by Delft for the 600 m long sand trap breakwater are summarized as follows:

- The majority of the sand would be trapped east of the breakwater.
- There would still be some deposition in or near the harbour entrance.
- Over a 15-year period, the deposition on the west side of the sand trap breakwater would average about 10,000 m$^3$/year in the first five years.
- The deposition will increase to about 12,000 m$^3$/year by year 10 and to 40,000 m$^3$/year by year 15.
- The total amount of sand accumulating in the area between the sand trap breakwater and the harbour entrance over 15 years is expected to be about 235,000 m$^3$. 
3 Breakwater design

3.1 General description

In the summer of 1999 Westmar Consultants Inc. was retained by Nexen Inc. to perform preliminary designs of sand trap breakwater options as follows:

- A conventional rubble mound breakwater constructed using land-based or marine equipment.
- A berm breakwater constructed using land-based or marine equipment.
- A submerged or low crested breakwater constructed using marine equipment.

The option of a 600 m long conventional rubble mound breakwater was selected by Nexen Inc. for final design. This option was preferred because it enabled Yemen based companies without marine construction equipment to bid on the work, and had a lower volume of rock than the berm breakwater option.

The conventional breakwater incorporates 144,000 m$^3$ of rock. The structure slope is typically 2H:1V, except at the head where the slope is 2.5H:1V (H = horizontal projection, V = vertical projection).

The crest of the breakwater at the head is 8.6 m CD and the water depth at the breakwater head is approximately -5.0 m CD. The elevation of the top of the filter layer in the trunk of the breakwater was set at a minimum elevation of 4.2 m CD for constructability reasons, i.e., so equipment could operate on top of the breakwater with minimum down-time due to wave action. This elevation is the run-up height of the 2% exceedance level of the waves in the one month winter storm.

3.2 Wave climate

Wave data was collected at the site at 50 m and 10 m water depths over a six month period in 1992-1993. This data set was deemed to be of too short a duration to provide wave heights for large return periods. In addition, a five year time series was hindcast from the Global Wave Model (GWM) as part of the sedimentation study, but this data set was also considered to be of too short a duration to be statistically accurate.

Therefore, the design wave heights were obtained from the SSMO (Summary of Synoptic Meteorological Observations) data set. This data set is comprised of wave observations from passing ships. Based on this data set, the 25 year significant offshore wave height is calculated as 6.4 m with a peak period of 14 s.

Nearshore wave modelling was performed by Westmar using the computer model MIKE 21 NSW licensed by the Danish Hydraulic Institute. MIKE 21 NSW is a frequency domain model that describes the growth and decay of waves in nearshore areas. The model includes the effects of refraction and
shoaling due to varying depth, wave generation due to wind and energy dissipation due to bottom friction and wave breaking. The results of the numerical model indicate that the 25 year significant wave height at the breakwater head is 4.3 m.

3.3 Armour design

Rock for the project was obtained from a quarry approximately 3 km from the site. The rock is identified as dolomite with a specific gravity of approximately 2.3. Despite the low density, tests show that the rock is durable with strong interlocking crystals.

Armor design was performed using both Hudson's formula [4] and the Van Der Meer Formula [5]. In Hudson's formula, the median armour size, $D_{50}$ is a function of the structure slope, specific gravity of the rock, wave height, and whether the wave is breaking or not. Van der Meer's formula accounts for additional parameters including the surf similarity parameter, porosity of the structure, the storm duration and the wave period. Readers are referred to CIRIA [6], which provides a detailed comparison of the two formulae. The Coastal Engineering Manual [7], which will replace the Shore Protection Manual [4], will incorporate both formulae.

Due to the application of the breakwater as a sediment transport barrier, some damage is acceptable over the life of the structure. In Hudson's formula the damage level is quantified through a reduction in the design wave height from $H_{10\%}$ to $H_s$. This corresponds to a damage level of 15% to 20%. In the Van der Meer formula, the damage parameter $S$ was set to 5, which corresponds to intermediate damage.

For Hudson's formula, breaking wave damage coefficients from the 1973 US Army Corps of Engineers Shore Protection Manual [4] were used. The median armour mass at the seaward end of the breakwater trunk calculated using Hudson's formula is 13 tonnes. The median armour mass calculated using the Van der Meer formula is 11 tonnes. The average rock size from these two formulae, 12 tonnes, was adopted for construction, which was further increased to 13 tonnes to provide a wear allowance of 25 mm on all surfaces of the rock due to the soft nature of the Dolomite. The specified gradation limits of the largest armour, Armour Stone Type 1, is shown in Figure 3, from which it can be noted:

- The maximum rock size is to be no smaller than 16 tonnes and not greater than 20 tonnes.
- The median size of rock is to be no smaller than 13 tonnes and not greater than 15 tonnes.
- The minimum size of rock is 10 tonnes, except for breakage in handling of no more than 5% of the total rock weight.
4 Construction

Mobilization commenced the first week of January 2000. Construction of the breakwater was started by mid January by sorting core and filter rock from waste rock produced during the construction of the harbour breakwaters in 1992 and 1993. The quarry proved to be an excellent source of large armour, producing up to 40% armour stone in the 10 tonnes to 20 tonnes range.

Construction proceeded at a high rate with core and filter rock placement reaching 600 m offshore by the end of February. This placement technique enabled the contractor to armour the head of the breakwater and the mid-breakwater simultaneously.

Turnouts were constructed at three locations to enable different rock materials to be delivered simultaneously at different areas along the breakwater. A 200 tonne crane was used to place the largest armour size at the head of the breakwater, while a 110 tonne crane was used at mid-breakwater to place the smaller armour rock types. A photograph of armour rock placement can be found in Figure 4.

The weather cooperated and the breakwater was completed on time and under budget by June 1, 2000 before the Summer Monsoons set in, and while the temperatures and the humidity were still bearable.
5 Performance / conclusions

The sand trap breakwater is expected to trap the majority of the westward moving sediment over a 15 year period. Depending on the occurrence of more severe storms, some maintenance dredging may be required during the 15 year period.

The practical land-based construction method developed for the breakwater was tailored to enable Yemen based companies with expatriate managers to bid on the work. This resulted in competitive pricing and a contract price that was under budget, but more importantly it provided work opportunities to local contractors and generated local employment.

Another consideration in selecting the breakwater option was that it allowed continued use of the existing harbour by the workboats involved with tanker loading. With large oil tankers loading, on average, every two and a half days from the SBM, Nexen could ill afford any disruption to its operations.

Evidence of the successful design and construction of the breakwater came quickly. In October 2000, a major rainfall occurred, causing an extensive outfall of sediment from wadi outlets in the region. The photographic evidence (Figures 5 and 6) clearly show the sediment being transported around the end of the breakwater and past the mouth of the harbour.
In the summer of 2001, during the monsoon season, Nexen will be operating out of the harbour for the first time in four years. Continued minimal use of a plow dredge on the back of a line boat, averaging three days per month, has been sufficient to maintain optimal water depth at the mouth of the harbour.

In summary, initial results suggest that the design and construction of the breakwater was successful in countering the build-up of sediment in the Ash Shihr harbour, allowing Nexen to maintain its base of offshore operations there and continue contributing to the economic and social well-being of Yemen.

6 References

2) Gulf Interstate Engineering, Drawing of the existing service harbour showing pre-construction bathymetric contours, 1993.
3) HAM Dredging, Surveys of the site showing bathymetry and depth of sand over bedrock, 1998.