Innovative techniques for quay wall renovation and stabilisation

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Abstract

Very often (old) existing harbour structures have to be renovated and stabilised because of several reasons, such as:

- deepening works for modern shipping
- capacity increase of the quay
- repairs instead of rebuilding
- harbour area restrictions

This paper will highlight the international experience (design and construct) in quay wall restoration and stabilisation works, using:

1. Marine drilling and foundation techniques (Hydro Soil Services):
   - ground anchors
   - VHP grouting
   - drain structures

2. Innovative bottom protection methods (Bitumar):
   - prefabricated and immersed fibrous open stone asphalt
mattresses and liquid asphalt under water
- other, flexible and durable bottom revetments

against bottom erosion (scour) near quay wall structures

For all those techniques specially designed materials and equipment are developed. A few case studies will illustrate the described methods of quay wall restoration and stabilisation.

1 Marine drilling and foundation techniques

1.1 Introduction

The choice for the application of renovation depends on technical, economical andexploitation issues. Up to 15 years ago, the expansion of harbours consisted in the building of new harbour areas or the hard and soft renovation was used for upgrading existing harbour infrastructure. Building of new harbour areas however is not always possible or allowed due to lack of space and environmental and socio-economical reasons.

The hard and soft renovation have for many applications disadvantages, such as:

* The mooring and unmooring of ships and vessels is impossible while building the new construction. This means that the existing berth will have to be taken out of exploitation during several months, which will be a considerable economical loss.
* The creation of a new construction in front of the existing quay over a certain length interrupts a one line quay-construction. The existence of such an extension will cause problems for the mooring and unmooring of ships.
* The existing installations of the upper structure of the quay-wall, such as crane rails, train rails, cranes, productpipes, etc., have to be moved to the new construction. The costs of this operation have to be taken into account in the calculation of the costs for deepening and renovation works.
In several cases preference has been given to the so called very soft renovation techniques. This has been made possible due to the evolution of various new techniques and products associated with anchoring, injection, drilling, grouting and drainage. In this way almost all normal activities on the quay are maintained during the renovation, strengthening or deepening activities.

The principle objective is to present here details of applied harbour renovation techniques 'the so called very soft renovation' which were developed and optimised through the years and proved that with the right degree of strategic, technical and economical awareness within Port Management and Government the demands of modern transhipment can be accomplished and satisfied both cost effectively and with an extraordinary speed.

Both traditional gravity quay walls as well as more recent sheetpiled quay walls can be deepened this way. Hydro Soil Services developed for both types of quay walls calculation methods and execution methods based on developing and combining foundation techniques so that stabilisation and deepening of the quay walls can be done while shipping traffic continues.

1.2 Installation of groundanchors

When stabilising quay walls or adapting them to greater water depths installation of groundanchors realises a.o. the global stability of the quay wall.

The level, spacing, inclination and dimensions of the groundanchors are determined from a performed stability analysis. Double corrosion protected groundanchors are installed at predetermined distance, level and gradient.

For a gravity quay-wall first the brickwork at the groundanchor locations is pre-drilled with a core drill of 50 cm diameter to a depth of ± 70 cm.

The diameter of this hole is determined by the dimension of the steel bearing plate and also by the resistance of the masonry and the concrete of the quay-wall.

Further drilling through the quay-wall is carried out using a destructive DTH drilling system with a diameter of 225 mm. Boring into the ground to the desired depth is done with a double rod system. After removal of the inner rods, the casings are rinsed and filled with grout and the groundanchor is positioned in the casing.

The grouting of the tendon is done at intervals every meter and under low pressure. After hardening of the tendon (± 28 days) the
groundanchors are tested and finally tightened up. After fully positioning of the groundanchor and protection of the anchorhead with additional grout injections, the surface aesthetics of the brickwork are restored.

In order to install the groundanchors at different levels low working platforms can be used or even a drilling bathyscaphe allowing installation under water level under normal atmospheric conditions.

![Figure 1.](image)

### 1.3 Very high pressure grouting (VHP)

The Very High Pressure grouting technique injects and mixes a cement grout with the soil in situ so to form a vertical column with high resistance. Making such columns one besides the other allows the forming of tight screens and deeper foundations at the same time. For
the deeper part of the quay-wall such screens take over the functions of the original wall.

Prior to the execution of the VHP grouting under gravity walls, pre-drillings are realised through the quay-wall at each VHP column location point using the down the hole drilling technique. The precision of the drilling path is important for the realisation of the bonding and continuity of the VHP grout screens.

The VHP grouting technique used for the realisation of a new foundation under a gravity quay-wall, exists of for example a ground- and watertight front screen consisting of 2 rows of interlocking VHP columns and transversal screens each 6 m consisting of 7 VHP columns. A U-form foundation layout for gravity quay-walls is chosen as a durable ground- and watertight caisson foundation with respect to a uniform dispersion of bearing loads and to meet all stability requirements to cope with the calculated moments and tensions including sufficient safety factors. A sheetpiled wall is deepened by making a double row of interlocking piles behind the sheetpiles and this from a depth even below the sheetpiles up to the deck level.

A steel bar, of a predetermined diameter, can be inserted into each VHP column as a reinforcement between the masonry, the concrete and foundation columns. For the deepening of sheetpiled quay-walls the VHP columns can be reinforced by installing HEB profiles in the columns over the full height to cope with tension.

![Figure 2.](image-url)
A special feature of using VHP piles under gravity quay-walls is that it allows to improve considerably the quality of the footing of those quay-walls which often exists of open brickwork or stonework only. By pulling up the jetting device through the footing, also the footing is consolidated. VHP columns at the waterside front screen do protect the toe with respect to its erosion to water jets caused by the ships' propellers. So VHP columns are a solution for instability problems arising out of such erosion initiated by the ever increasing draft of ships.

1.4 Drainage techniques

In order to decrease loads on old quay-walls along waterfronts with tidal influence or to allow increased loads on them for deepening purposes or changed use, a drainage system can be installed allowing to lower the water table behind the wall. Such drainage system should have following features:

* allow groundwater to be evacuated to the quay-wall front preferably by gravity
* being the groundwater down as low as possible as far back as possible from the quay-wall front
* allow installation without major disruption to the quay-wall and traffic.

The drainage system developed by Hydro Soil Services incorporates these features.

Behind the quay-wall, at calculated distances sandpiles are made. The diameter of the sandpiles is determined by the flow each pile should take. Now the drain is installed. The drain is composed of PVC pipe with a filter glued to it and is installed by drilling. This drilling is done from within a bathyscaph allowing work to be carried out under all tidal conditions.

1.5 Conclusion

Combining the above techniques i.e. VHP grouting, installation of groundanchors and drains has already proven to be an economical and technical solution for deepening quay-walls. It allows to upgrade valuable marine assets with minimum disturbance to ports activities.
2 Innovative bottom protection methods

2.1 Introduction

In the past few years, container, ro-ro and other special purpose ships have grown considerably in size requiring a commensurate increase in propulsion power. These ships spend less time in ports and tend to make their way to their berths under their own power. Vessels can use their propellers when arriving at and leaving berths, and they tend to use both their bow and stern thrusters to keep clear of the berth when tying up and leaving. The evolution in ship dimensions results more often in a limited port keel clearance or in the necessity to dredge away the natural soil buffer, especially at older ports.

The impact of high powered propellers just above an existing natural bottom near to berths can provoke serious scour, particularly when bottom soil is non-cohesive and fine. One solution to the problem of instability of berth structures caused by propeller jet erosion of the natural bottom is to install bottom protection near the berth. Design for protection systems must satisfy a number of primary criteria, including:

* The revetment must allow sufficient water permeability, but must prevent the passage of subsoil
* The protection has to be adequately resistant to turbulent currents, induced by the propeller jet
* The protection must be sufficiently flexible to adjust to differential settlement or profiles of the underlying soil, and to soil loss near its ends.
* The extremities of the revetment must not lift up as the result of pressure differences and/or turbulence, and
* In no case should there be any danger of the protection floating upwards.
* The system should be highly durable and have a minimal repair status which can be executed easily and efficiently.
* The protection should have sufficient strength to withstand damage caused by mechanical impacts (e.g. anchors, falling objects, ...)
* In many cases, due to stability reasons combined with the necessary depth, only thin protection layers can be adapted
* The hindrance to the on-going operations of the quay must be minimised.

Specialised engineering and hydraulic contractor, Bitumar N.V., of Belgium, has developed computer calculation methods for the
determination of bottom velocities and scour pits in the natural bottom, as induced by propellers, and for assessing the necessary dimension of protection systems near open piled or wall-type structures.

Several thin, but durable and resistant bottom revetments, such as asphalt or stone gabion ‘mattresses’ and rock layers penetrated with liquid asphalt, have already proven, in a number of different circumstances and locations, to be an efficient solution against propeller scour and berth instability.

2.2 Fibrous open stone asphalt mattresses and asphalt mastic

FIBROUS OPEN STONE ASPHALT is a hot mix (140° to 150° C) of fibrous mastic with a coarser, fairly uniformly graded limestone fraction, usually of stone size 16/22 mm or 20/32 mm. The proportion of mastic to stone is such that an open, i.e. water-permeable mix is obtained. Generally the ratio is toughly 80 % (m/m) stones and 20 % (m/m) mastic. The composition of the fibrous mastic is in the region of 22 % (m/m) filler, 18 % bitumen, 60 % (m/m) sand and 0,4 % inert fibres.

The addition of fibre makes it possible to add more bitumen without increasing the effect of slip (better adhesion, more flexibility and reinforced mastic). Mixing takes place in three phases. First of all the mastic is prepared by dry mixing the fine aggregates and fibres, adding
the bitumen and then the fibrous mastic is mixed with the coarser preheated aggregate. In this way a uniform and relatively thick coating (1 to 2 mm) of the stone obtained. The mastic clumps the stones together.

Fibrous open stone asphalt has a high percentage of voids (about 20 - 30 %). Moreover the relatively large pores are interconnected. As a result fine granular material (such as sand) can pass through the asphalt. If the surface on which the revetment is laid consists of a material of this nature, its integrity must be safeguarded by providing a filter. This may be a granular filter, a filter in synthetic material or a layer of sand asphalt. After cooling, fibrous open stone asphalt forms a thin continuous and very flexible slab.

When fibrous open stone asphalt is used in the form of prefabricated mattresses applied under water on the bottom or an embankment, the joints and the connections of the mats to various structures (quay wall, sheet piling, piles, bridge piers, etc.) must be sealed with ASPHALT MASTIC or liquid asphalt to prevent the passage of sand. The asphalt mastic is a hot mix (140° - 160°C) of sand, filler and bitumen in the following proportions ± 58 % : ± 23 % : ± 19 % (by weight)

Fibrous open stone asphalt layers are very durable, flexible and can withstand water velocities up to 6 m per second. The thickness of the layer can be determined by calculating the necessary weight against sliding down a slope and against lifting forces, introduced by turbulent water flow caused by ships’ propellers, which give rise to different fluctuations in water pressure above and underneath the revetment. Due to its very open structure fibrous open stone asphalt only reduces for example and under pressure with appr. 10 % through a layer thickness of 30 cm.

Another important item is the stability of the edges. Bottom protections constructed in the wet frequently consist of mattress-like elements of limited dimensions. When these elements are joined together to form a continuous bottom protection, edges are created which constitute local discontinuities when subjected to perpendicularly acting currents. In consequence locally curved flow lines arise, which give rise to deviations from the hydrostatic pressure distribution.

If the pressure difference is greater than the underwater weight, the mattress will be lifted up. This will lead to the disturbance becoming even greater, the pressure difference increased, and the mattresses may flip over, which may constitute a failure of the bottom protection.
The pressure difference (very local and extreme) can be counteracted by a ballast layer of liquid asphalt if necessary at the edges of the fibrous open stone asphalt slab, which forms in reality a cohesive whole.

The extremely open nature of this bitumen-based water engineering product means that it may not be applied hot under water. The material is applied under water in the form of prefabricated mattresses. These mattresses are constructed in a prepared framework in which a geotextile has been laid. A crane or spreading machine is used to handle the material.

The mattresses can be stacked on top of one another. The mattresses are raised, transported, and installed by means of recoverable carrying cables or belts attached to a frame suspended from a crane or floating lift. With lager mats the cables are fitted to the mats in advance and removed at a later stage, while with smaller mats they can be incorporated in the mat. Sometimes a reinforcing mesh is included in the mattresses in order to cope with tensile stresses arising during handling.
The geotextile used under the mat extends beyond the edges of the mat itself. This ensures that it will go under the next mat so that the soil cannot pass through the joint.

Fibrous open stone mattresses can be tailor made, having dimensions according to the particular case requirements. In Belgium and the Netherlands mattresses, measuring 35 m long, 10 m wide and 30 cm thick (weighing appr. 240 tons) were already applied for similar purposes, using a special lifting frame (55 tons) and a self propelled hoisting derrick (the Norma).

![Figure 5. Placing of asphalt mattresses 35 m x 10 m x 0.3 m (250 tons each).]

In order to prevent the edges of the mat from being forced upwards and to ensure that the joints are entirely soil-proof, the negative overlaps between the mats and connections to other structures are filled with hot asphalt mastic.

Special techniques must be adapted when working under water. The joints are filled with the aid of dump buckets or insulated and/or heated dumping chutes with a special nozzle. The processing temperature lies
between 100° and 150°C depending on the required viscosity and the application.

2.3 A stone revetment, penetrated with liquid asphalt

In order to reduce the unit size of the stones and thus reducing the layer thickness of a rip rap revetment and to heighten the resistance against current attack, a penetration or grouting of the stones can be considered.

The following applications can be distinguished:

* Surface-grouted stone (30 % of the voids in the stones are covered):
  if the size or weight of crushed stone is barely inadequate to satisfy the velocity conditions then the safety of the revetment can be increased by fixing the stone with a grouting.

* Pattern-grouting:
  if about 60 % of the total surface is filled. From model investigations it appears that a relatively smaller increase in stability is obtained by grouting more than 50 % of the surface of the crushed stone. Grouting 50 to 70 % of the total voids in the stone layer appears to give the best results.

* Fully grouted stone:
  Here, the effect of currents is negligible.

LIQUID ASPHALT is prepared hot and is a mixture of fine stones 2/7 mm with asphalt mastic in a proportion of 25/75 % (by weight). The correct proportions are determined on the basis of preliminary tests on the available materials and the final product partly to ensure that the hot material has a suitable in order to secure the optimal penetration (flow characteristics) of the quarry stone without excess flow.

After completion the viscosity must be sufficiently high to keep cold flow to a minimum. Flow in the hot and cold phases depend on the composition of the liquid asphalt in relation to the sizes of the quarry stone and the gradient of the revetment. The design of the poured asphalt mix must take account of the weight and dimensions of the quarry stone to be grouted under water.

Special techniques must be adopted for underwater grouting. Penetration is then carried out with dump buckets or insulated and/or heated chutes with a special pipe nozzle.
The dump buckets are lifted by a shore or floating crane to a position immediately above the layer of quarry to be grouted and are then rapidly tipped by means of a remote controlled pneumatic release system. The penetration temperature lies between $100^\circ$ and $150^\circ$C depending on the required viscosity and the application.

2.4 Gabions and stone mattresses

Gabions and stone mattresses are a structure made from a zinc galvanised wire netting, additionally coated with PVC. The tensile strength of the wire ranges from 375 to 500 N/mm$^2$.

The netting usually has a hexagonal mesh and is double twisted. The base or bottom, the sides and the two ends are a single piece of continuous netting. Dividers of the same type are provided on the bottom which separate the gabion into cells along its length. Typically the gabions are 1 m high, 1 m wide, and have a length between 2 and 4 m. The netting wire has a nominal diameter of 3 mm, while the
“selvedge” wire and reinforcing wire has a diameter of 3.8 mm. The mesh size of the gabion is 78 x 118 mm. It is filled with stone with a grain size of 90/150 mm. The stone mattresses are 0.17 m, 0.30 m or 0.50 m high, 2 m width and their length varies from 3 to 6 m. The netting wire has a nominal diameter of 2.20 mm, and the ”selvedge” wire and reinforcing wire has a diameter of 2.7 mm. The mesh size is 64 x 93 mm. The mattresses are filled with stones with a size of 90/120 mm.

Once the cells of the gabions have been unfolded, tied and filled with stones they are laid in a staggered bond underwater on top of a geotextile filter, thus forming an extremely well interconnected water permeable building block in which there are no continuous joints perpendicular to the front of the quay wall.

In order to meet the following requirements
* realisation of a continuous defence with underwater gabions placed in bond
* provision of a soil-proof structure using underlying geotextile
* reduction of the execution time to as short a period as possible so that dockside operations are not unduly disturbed.

Bitumar developed and applied a new construction procedure.

A floating installation makes it possible to install the entire revetment, namely the geotextile fabric with the filled gabions laid in bond on the bottom, using special pontoons.

The submersion system is a combination of pontoons which is used to transfer a bottom or embankment protection assembled on the deck of the pontoons to the bottom or the embankment either in a continuous operation or discontinuously, with the aid of an adjustable slide slope created by means of connected pontoons.

Apart from being used to lay gabions or stone mattresses on geotextile this installation was also used to place willow mattresses under water.
Figure 7. Submersible pontoon for the continuous installation of gabion revetments under water.