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Spaan, G.; Lindo, M.; Kant, Gijsbert

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Optimisation of Scour Protection Measures

By

G.B.H. Spaan[1], M.H. Lindo[2], G. Kant[3]

ABSTRACT

For most construction works, the final design of scour protection measures focuses on finding a balance between the extent and impact of possible damage (scour hole development and subsequent construction damage) and the costs of the required scour protection measures. In this paper the basic questions are discussed which all scour protection designers have to deal with: Which rock size and scour protection layer thickness is required to guarantee the stability of the main structure and what is the required horizontal extent of the scour protection? This extent of the scour protection determines the total protected area and is thus a significant part of the total cost calculations.

Several, principally different, solutions are discussed from a practical (installation contractors) perspective:

1. Conventional design approach: based on the provision of a hydraulic and geo-technical statically stable scour protection;
2. Falling apron principle: erosion is permitted to the extremities of the scour protection, resulting in a reduction of the area covered by the scour protection;
3. Dynamic design approach: scour hole development both in and behind the scour protection is permitted whilst the primary function of the scour protection, which is to guarantee the geo-technical stability of the structure, is still maintained.

Three examples from practice are given: two offshore gravity based structures and a storm surge barrier. Based on these examples some recommendations regarding design, execution and operational aspects are discussed.

INTRODUCTION

It is well-known that when a structure is placed in a marine environment, the very presence of the structure will change the existing wave and current induced flow patterns leading to the development of complex phenomenon such as flow contraction, horseshoe vortex formation, lee-wake vortices, generation of turbulence and adaptation of possible waves. These structure-induced changes will usually cause an increase in local sediment transport capacity. When the seabed consists of transportable sediment the flow

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[1] Marine Engineer, Engineering Department, Van Oord ACZ Marine and Dredging Contractors, Gorinchem, The Netherlands (gspaan@voacz.com).
[2] Head Engineering Department, Van Oord ACZ Marine and Dredging Contractors, Gorinchem, The Netherlands.
[3] Senior Advisor Harbour and Offshore Technology, Marine, Coastal, and Industrial Infrastructure Department, WL | Delft Hydraulics, Delft, The Netherlands.

pattern changes may lead to scour which, in turn, might be a direct threat for the geo-technical stability of the structure and should therefore be prevented or controlled. Most structure designs take account of some limited scour, however the changes in flow patterns are usually such that specific scour protection measures around the structure are required.

Due to the complex three-dimensional situation the design of such a scour protection is usually not straightforward. In general the scour protection design can be divided into the following issues:

1. Required armour grading stable under survival (design) conditions;
2. Required filter grading (if necessary);
3. Layer thickness, derived from the grading requirements;
4. Horizontal extent of the scour protection.

Based on physical scale model experiments, various semi-empirical relations have been derived which describe the progression of the scouring process with time and estimate the ultimate equilibrium scour depth around a marine structure under the local environmental conditions. During the extensive research for the Dutch Delta Works, design criteria for the horizontal extent of the scour protection were also deduced (e.g. Delft University Press, 1987).

In the Scour Manual of Hoffmans and Verheij (1997) some practical scour relations are given that designers can use to calculate the dimensions of the scour holes and subsequently determine the required scour protection measures (see Figure 1):

- Equilibrium scour depth and horizontal scour extent;
- Slope stability;
- Critical velocity and amplification factor for the local velocity.

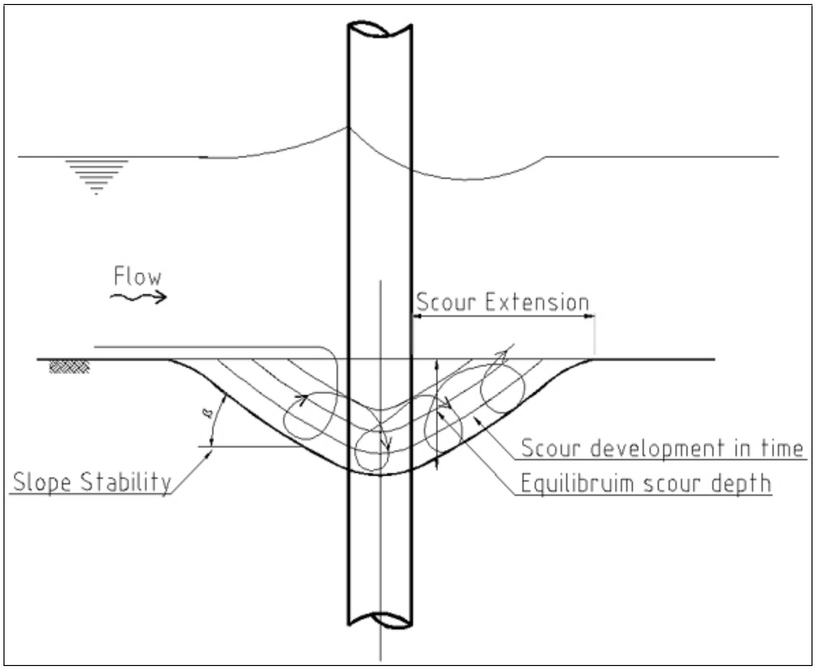

Fig. 1 – Scouring around marine structure

This paper, however, is not intended to describe these different relations. Here considerations are discussed on the incorporation of the design and ultimate construction of marine structures based on, in principle, different solutions: conventional design, falling apron and dynamically stable design.

SCOUR PROTECTION PRINCIPLES

Several in principle differing solutions have been applied in the past to prevent structure failure due to scour:

1. Conventional design;
2. Falling apron principle;
3. Dynamically stable principle.

The above scour protection solutions are described briefly in the following.

Conventional design

A conventional scour protection consists of a hydraulically and geo-technically stable scour protection of sufficient length, see Figure 2. The rock grading of the top layer must be stable under the extreme design conditions. This usually results in a heavy rock grading; depending on the environmental conditions e.g. 40-200 kg up to 6-10 tonne rock grading behind a storm surge barrier as in the Eastern Scheldt in the Netherlands. Beneath the armour layer either one or more filter layers or alternatively, and in order to reduce the number of layers, a sand tight geotextile must be applied to comply with the filter rules.

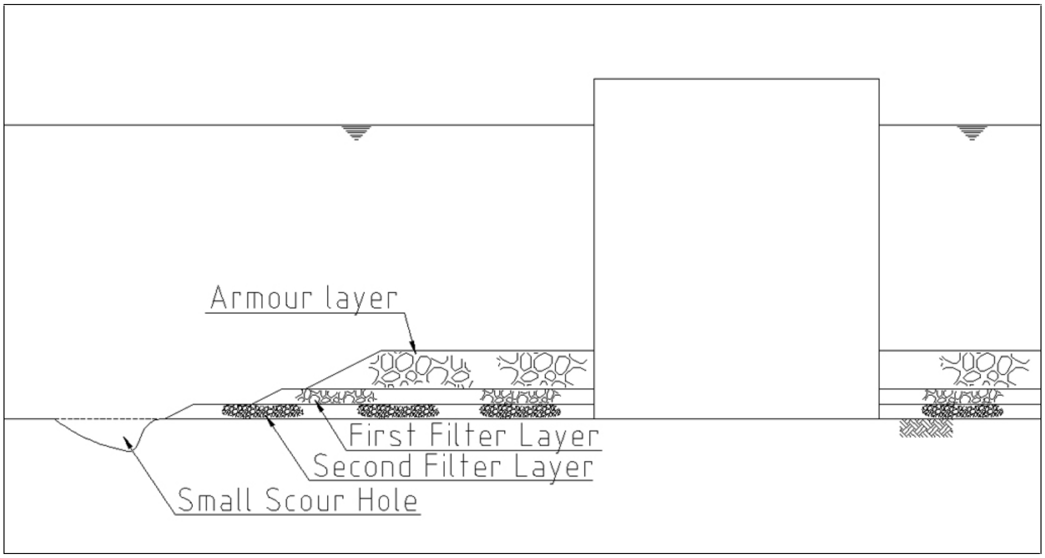

Fig. 2 – Scour protection based on conventional design

An increased turbulence occurs at the downstream side of the scour protection under the influence of the flow contraction due to the presence of the structure and because of the differences in roughness between the scour protection and the seabed. This increased turbulence subsequently introduces scouring of the seabed material at the edge of the scour protection. The resulting scour hole partly undermines the edge of the statically stable scour protection, especially when liquefaction is possible. Some of the rock will relocate thereby eventually stabilising the scour slope. The depth of the scour hole that will form at the edge of the scour protection system as well as the resulting slope influences the partial or global geotechnical stability of the structure and must therefore stay within certain limits.

Falling apron principle

A falling apron is an amount of granular material at the toe of a revetment or around a structure. When scour starts to develop the material is redistributed onto the developing slope, see Figure 3. The loose rock material is assumed to cover the scour hole slope to a thickness large enough to retain the original bed material (Hoeven, 2002). The rock in the falling apron should be large enough to withstand the possible flow forces (Schiereck, 2001).

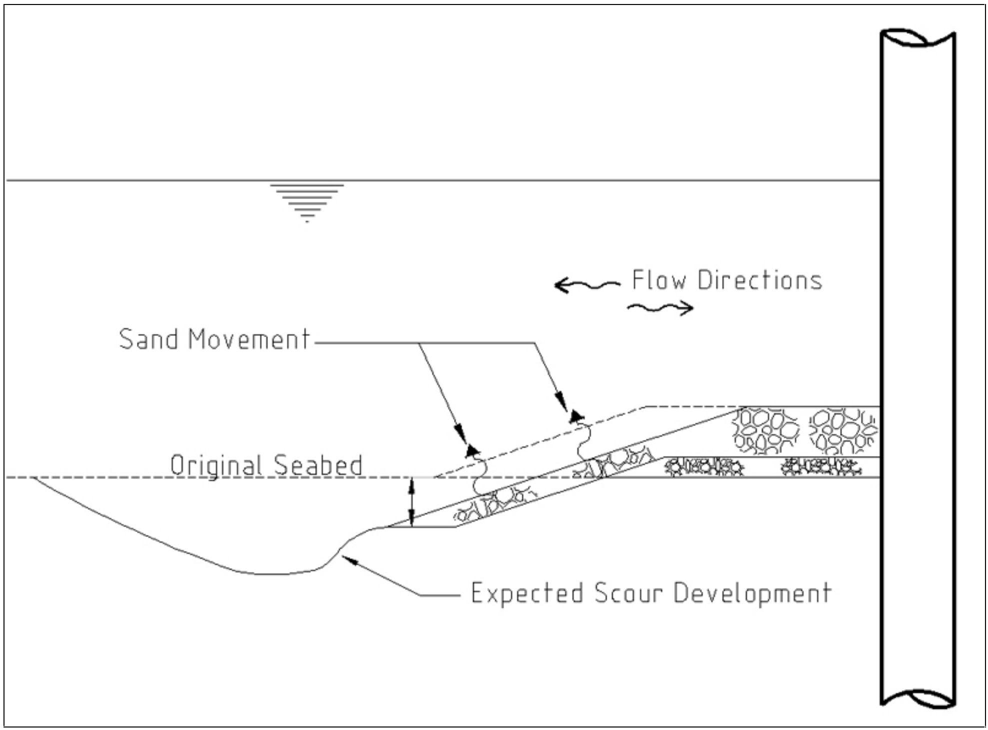

Fig. 3 – Scour protection based on falling apron principle (after several storms)

When applying the falling apron (or imperfect filter) principle the previous described scour hole development at the edge of the scour protection occurs and causes some of the scour protection to re-locate. The protective influence of the re-located rock leads to the formation of gentler scour hole slopes (WL | Delft Hydraulics, 1988). These slopes are taken into account in the geotechnical stability calculations. This will give a reduction in the required extent of the scour protection. Especially when liquefaction is a concern the falling apron will reduce the risk of undermining the structure due to the gentler slopes that will occur. Under the armour layer section one or more filter layers must still be applied satisfying the filter rules. However, under the falling apron section no filter is present. The thickness here should be around 2 to 3 times D_{50} in order to allow “controllable” migration of sand from underneath this part of the scour protection. Schiereck (2001) even recommends a layer thickness of about 5 times D_{50}. The required length of the falling apron is approximately 1.5 times the design scour depth (Hoeven, 2002). It is also possible to apply a mattress underneath the rock that provides an extra support for the rock. A frequently applied rock grading for a falling apron is a 10-60kg grading. The rock of this grading is large enough to allow sand to pass, but is also sufficiently small to limit this process.

Dynamically stable principle

For a dynamically stable scour protection the development of limited scour (damage) in and/or behind the scour protection is permitted. The main principle is that a large amount of relatively small rock (e.g. 2-10″ rock grading) is placed around the marine structure. The scour protection is designed in such a way that the maximum expected scour hole in the rock protection is smaller than the total rock layer thickness, see Figure 4. “Dynamically” refers to the fact that scour holes will develop in the scour protection layer. “Stable” refers to the fact that eventually a practically stable situation will be reached. The advantages of this scour protection design are that (i) the construction is relatively simple, (ii) relatively small diameter rock is required and (iii) maintenance can easily be carried out by additional dumps of rock.

A dynamically stable scour protection requires regular monitoring and possible maintenance. It should be noted that for all types of scour protection regular monitoring is always recommended and in the offshore industry it is a compulsory activity.

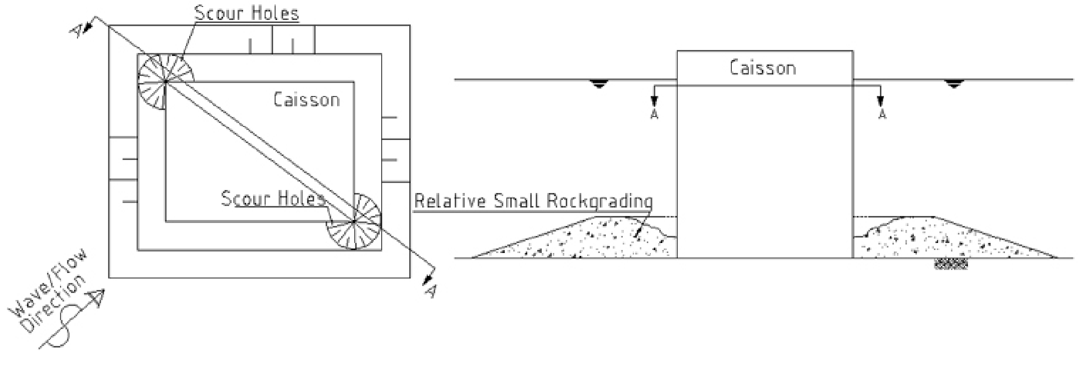

Fig. 4 – Dynamically stable scour protection

DESIGN AND CONSTRUCT PROJECT

There is a global move for large marine infrastructure works to the EPIC (Engineering, Procurement, Installation and Construction) or “Design and Build” tender approach. For this approach the Tenderer is required to perform the design activities and then to price for the construction and installation of this design. Contractors are therefore stimulated to optimise their design and generate innovative solutions taking into account their own construction tools and techniques in order to achieve a competitive price. This approach generally leads to a lower total construction cost, due to an optimal interaction between design and practical construction possibilities, than the traditional approach whereby the Client performs the design.

OPTIMISATION EXAMPLES

In the following sections some scour protection measures are illustrated and discussed based on Van Oord ACZ and WL | Delft Hydraulics practical experience. For each example case only the items that are considered relevant for the present paper are described. The link between the examples is that, based on advanced engineering, the final design of the scour protection was more cost-effective and/or technically optimised when compared to a conventional designed scour protection due to the strong interaction between design and construction.

Offshore platform

Both Van Oord ACZ and WL | Delft Hydraulics have been involved in various projects concerning the design and installation of offshore platforms and the required scour protection around it. Two recent Van Oord ACZ projects are the installation of the Molikpaq Gravity Based Structure close to Sakhalin Island, Russia for the Sakhalin Energy Investment Company Ltd. (Marathon Oil, Mitsui, Shell and Mitsubishi) and the installation of the Malampaya Concrete Gravity Substructure in the Philippines for Shell.

The Sakhalin project comprised the towing and installation of the steel gravity structure Molikpaq (approximately 100m x 100m, height of 90m including topsides), preparation of the seabed and placement of the required scour protection. The initial scour protection design was developed by Sandwell Engineering Inc. for the Client based on standard model tests. Initiated by Van Oord ACZ the design was further optimised using model tests conducted by the Canadian Hydraulics Centre (Davies, 1999). These model tests involved positioning of a model of the platform on an erodable bed and applying the design current and storm conditions on the scaled situation.

Planning of the work was critical due to ice conditions occurring near Sakhalin Island. The towing and installation of the Molikpaq platform and scour protection was successfully carried out between August and October 1998.

The Malampaya project involved, amongst other things, the installation of a 112m x 70m and 16m high Concrete Gravity Substructure (CGS) and the required scour protection. Van Oord ACZ, together with Ove Arup and John Holland formed the Malampaya CGS Alliance. Within this alliance John Holland was responsible for the construction of the CGS, Ove Arup and Partners (1999) carried out the design of the CGS and subsequently of this scour protection while Van Oord ACZ was responsible for all offshore installation aspects, including the installation of the scour protection. The seabed preparation and installation works were carried out between March and July 2000.

Prior to the discussion of the Sakhalin and Malampaya project, a short description is given of the Flexible Fall Pipe System that was used for the scour protection construction of both projects.

Flexible Fall Pipe System

The Flexible Fall Pipe System guides the rock to a level several metres above the seabed and is therefore especially suitable for accurate dumping in deeper water (Lindo, 1991). Standard installation depths range from about 20 to 300 metres. However, this method has also been used to successfully install rock in depths of over 800 metres.

The system consists of a vessel from which a flexible pipe (strings of buckets) can be lowered until the bottom of the fall-pipe is a few meters above the sea bottom, see Figure 5. Major positioning is performed by the global positioning system of the vessel with the finer adjustment performed using the Remote Operating Vehicle (ROV) which is equipped with several thrusters. The ROV is also used as the platform for the survey equipment with which, in addition to the pre- and post-dump surveys, monitoring of the rock dump process is carried out.

The dump material is transported by means of a system of hoppers and conveyor belts into the fall pipe. While tracking along the structure of pipeline at a constant speed, the rock is placed at the required location. During dumping operations the vessel is kept in position by a dynamic positioning system. The vertical movement is controlled and restricted by a heave-compensating system.

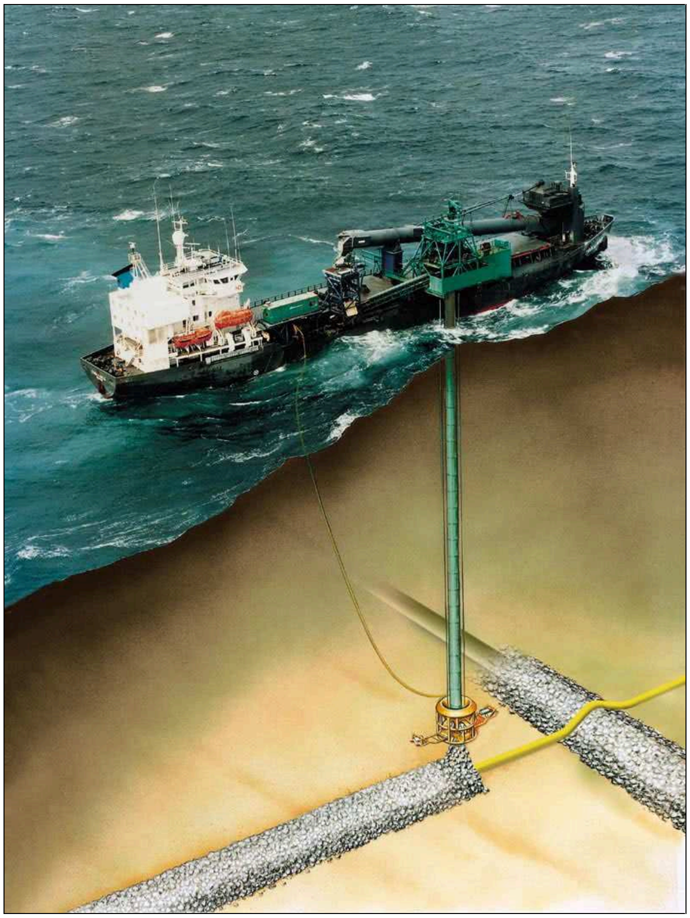

Fig. 5 – Flexible Fall Pipe Vessel “*Trollnes*”

Sakhalin

Boundary conditions

The water depth at the Sakhalin platform was approximately 30m. The scour protection for this platform had to be resistant with minimal damage to an extended duration annual storm with H_s=6m and a crosscurrent of 1.0m/s. The design conditions (return period of 100 years) were H_s=9.8m and a crosscurrent of 1.5m/s (Hollowell, 1999).

Armour layer

The scour protection for the Sakhalin Molikpaq platform was tested at the Canadian Hydraulics Centre at 1:70 scale. As installation was foreseen using Van Oord ACZ's flexible fall pipe system, the rock grading was pre-specified, resulting in a maximum grading of 60-400kg (with D_{100}<600mm). The model tests indicated that a 1.5m thick armour layer thick on top of a (closed) filter of 10-100mm would be adequate.

Horizontal extent

In front of the armour layer for the Sakhalin Molikpaq platform an 8m (4m along the sides) wide falling apron was designed to control erosion of the scour protection toe (open filter layer 60-200mm). The horizontal extent of the armour layer in the more exposed eastern corners was 9m, in the western corners this was only 6m. Along the sides of the platform the extent of the armour layer was limited to only 3m.

From the model tests it was found that the extent of the scour protection could be significantly reduced due to the shape of the Molikpaq platform, see Figure 6. The fact that the Molikpaq, being tapered over the upper 15m of the water column, created a 'wave-shadow' meant that the protection was required mostly to protect against current acceleration around the corners and sides. Protection was only required close to the structure.

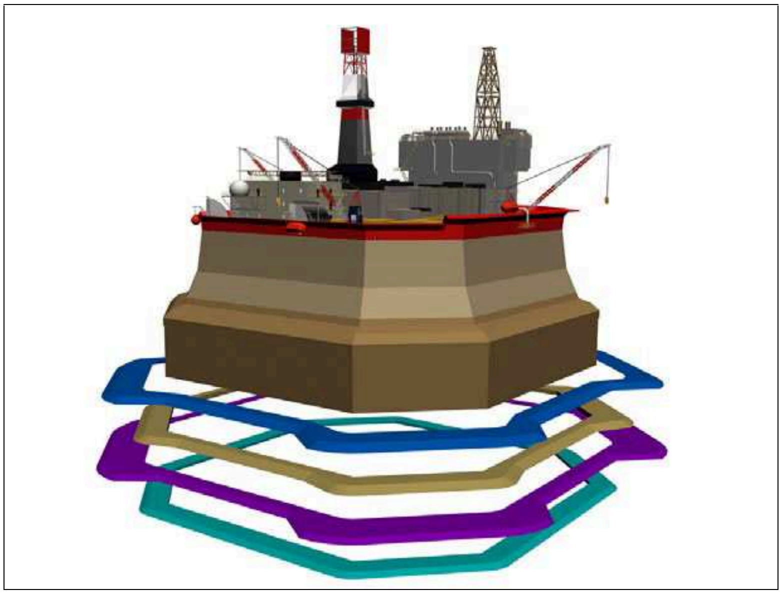

Fig. 6 – Sakhalin Molikpaq platform

The application of the 3-dimensional model tests including far-field scour effects resulted in a considerable reduction of required rock volumes of almost 40% from the conventional design volumes. The optimised scour protection design can be seen as a hybrid between the statically stable and falling apron principle.

Installation

The scour protection for the Sakhalin project was installed with the DP Flexible Fall Pipe Vessel *Rocky Giant*. Special care was taken when dumping the 60-400kg armour layer because of the ratio of fall pipe diameter versus rock size. In all, installation of the scour protection around the platform took just over 25 days.

Optimisation

The tests at the Canadian Hydraulics Centre that were undertaken for the Sakhalin project allowed the scour protection layout to be optimised with a 40% reduction in the volume of material required. The 3-dimensional model tests provided insight allowing for optimised placement of the material at those locations where scour was most severe. The adoption of a dynamically stable “sacrificial” protection layer proved to be a very cost-effective solution for a remote location such as offshore Sakhalin Island.

Malampaya

Boundary conditions

The Malampaya CGS was placed in approximately 43m water depth with a design wave height of 9.7m and an accompanying mean zero-up-crossing wave period of 8.9s (return period of 100 years). The maximum joint occurrence near-bed current velocity was estimated as 0.27m/s. On top of these a safety factor of 1.3 was applied.

Numerical computations indicated a maximum amplification at one of the corners of 2.5 times the ambient undisturbed current velocity and occurs within a narrow zone extending out-line to about 10m from the platform. The maximum amplification of the wave-induced flow is approximately 3 times the ambient and occurs approximately 2m from the corner.

Armour layer

The design of the Malampaya scour protection consisted of a light rock grading that can be considered as a dynamically stable scour protection. It was decided to install a 1m thick layer of small rock with a 2-10″ grading (maximum rock size of approximately 250mm) and with an outer slope of 1:3.

Horizontal extent

The horizontal extent of a dynamically stable scour protection and thus the total amount of rock must be large enough to ensure that the rock at the edge of the sill is stable. A structure introduces local turbulence due to the obstruction of the flow. The obstruction of the Malampaya CGS, however, is relative small because of the small height of 16m compared to the total water depth of 43m. Based on the numerical studies, a required scour protection extent was determined of 6m (perpendicular to the walls) of the CGS within 15m of the corners (parallel to the walls).

Installation

With Van Oord ACZ DP Flexible Fall Pipe Vessel *Rocky Giant* approximately 24,000 tonnes of rock was dumped to level the Malampaya seabed (D_{50}=18mm, average height of 1.4m). Directly after complete installation of the CGS the *Rocky Giant* placed the 3,000 tonnes crushed rock scour protection (2-10″ grading) around the structure, see Figure 7.

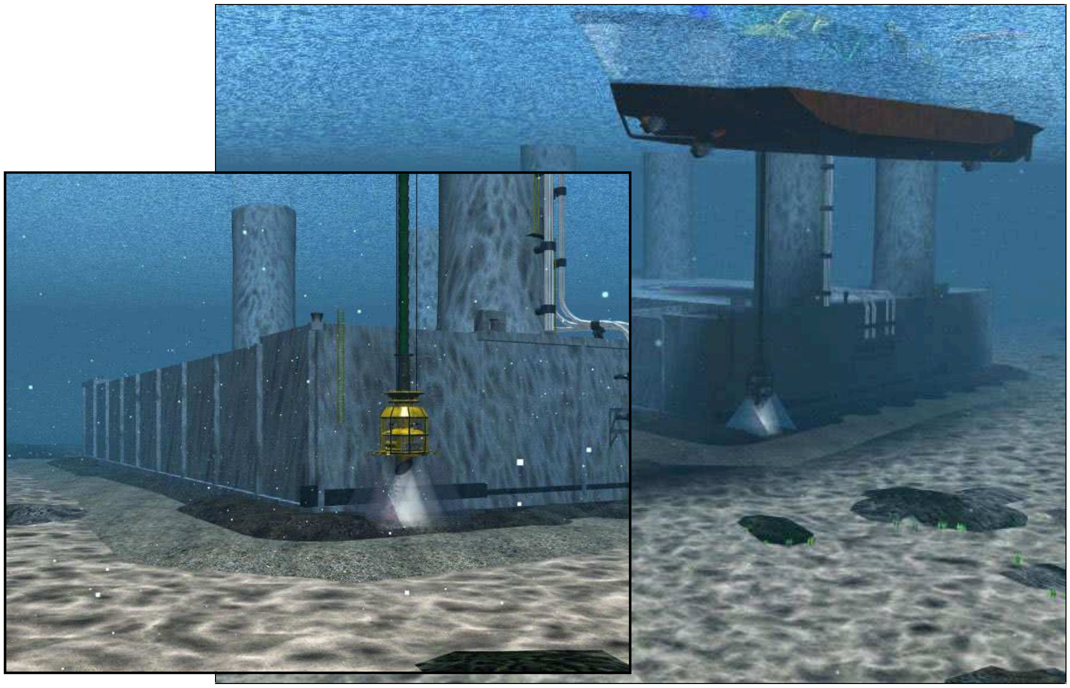

Fig. 7 – Flexible Fall Pipe Vessel dumping crushed rock around Malampaya CGS

Optimisation

The application of a dynamically stable scour protection instead of a conventional statically stable protection causes a significant reduction in installation costs. Application of heavy rock grading in marine conditions and very close to the structure is time-consuming and thus expensive. Small rock gradings can be placed accurately by means of flexible fall pipe vessels.

Storm surge barrier

In a detailed study for the design and construct project for the storm surge barrier in the "*Nieuwe Waterweg*", the entrance to the Port of Rotterdam, The Netherlands, Van Oord ACZ (as part of the so-called NIWAS combination of contractors) developed a new methodology for the design of the bottom protection. WL | Delft Hydraulics carried out various physical model test studies (1989) on, among other things, the stability of the NIWAS storm surge barrier bottom protection and the scouring behind it.

Although another concept than the one put forward by NIWAS for the barrier (and thus a different bottom protection) was finally selected, a similar (probabilistic) methodology was used for the final design of the ultimate bottom protection.

Boundary conditions

The "*Nieuwe Waterweg*" is a 17m deep shipping channel under tidal influence as well as one of the river Rhine delta outflows, see Figure 8. The stability of the scour protection must be guaranteed for an open barrier during extreme tide flow of 2.2 to 2.6m/s. The design condition, however, occurs when closing the sector doors: the rapid acceleration in the current can be considered as a concentrated jet leading to high turbulences. In the model tests measured maximum flow velocities during closing were in the order of 5 to 6m/s (when the gap between the doors is approximately 40m, during flood conditions). This extreme flow velocity reduces only from approximately 50m behind the barrier.

Fig. 8 – "*Nieuwe Waterweg*", entrance to the Port of Rotterdam

Design philosophy armour layer

Based on the two and three dimensional model tests (WL | Delft Hydraulics, 1989) a damage method was established that determined the amount of armour rock that was removed from its original section. The derived formulae contained the exposure time, the nominal rock diameter, the rock density, the head difference and certain location and geometry dependent coefficients. The main advantage of the derived damage method was that in this way the damage development of the armour rock in time could be estimated. It was also possible to carry out probabilistic computations. In addition a Shields based method was used for situations without an unambiguous damage pattern. With this procedure of probabilistic and deterministic computations the effects on the bottom protection of various different scenarios and strategies could be simulated, without having to carry out additional model tests.

Horizontal extent and falling apron

Based on the model tests, flow influenced factors for scour hole development were determined at various locations. Based on these the required horizontal extent of scour protection in the centre of the "*Nieuwe Waterweg*" was estimated for the riverside extent as 110m.

The model tests on scouring indicated furthermore that the application of a falling apron (or imperfect filter) at the edge of the scour protection parallel to the flow direction, had a significant reducing effect on the start slope and the eventual maximum scour depth (about 20 to 40%). Furthermore the deepest point of the scour hole was located further from the scour protection at approximately 25m from the edge. This principle was therefore applied along the caissons on both river-shores with a width of approximately 25m.

Filter layer

Due to the foundation construction works it was not possible to apply a geotextile or other mattresses in the vicinity of the barrier. Here a geometric closed filter (granular filter) was designed.

Optimisation

Due to the physical model tests and the derived damage method various different scenarios and strategies could be taken into account to design an optimal scour protection. The application of a falling apron in the areas with parallel flow gave a further reduction is required armour rock.

Figure 9 gives an overview of the NIWAS designed scour protection of the storm surge barrier in the "*Nieuwe Waterweg*".

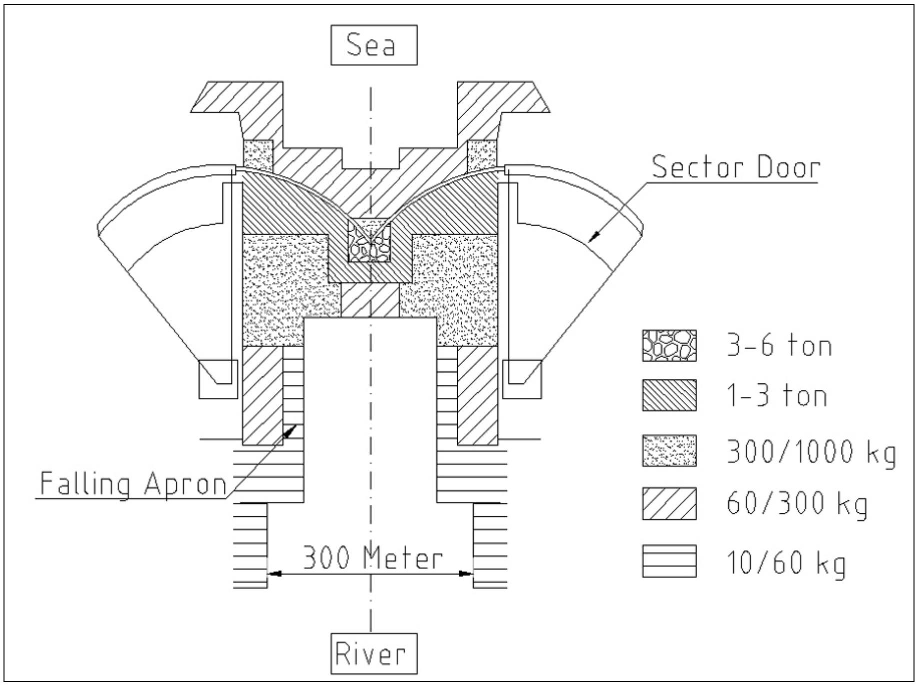

Fig. 9 – NIWAS scour protection

SUMMARY AND CONCLUSIONS

The global tendency that tenders for large marine infrastructure works must comprise both the final design as well as the ultimate construction and installation of the structures usually results in a decrease of the total construction costs, due to an optimal interaction between design and practical construction possibilities. In this paper practical examples have been described and discussed in support of this central idea.

Based on the given examples it is clear that the design of scour protection systems is not straightforward. Important factors are of course the local soil and hydraulic conditions and the structural dimensions. However, in order to achieve a competitive price the Installation Contractor must propose innovative design solutions. Although, in principle, innovative solutions can not be generalised, the following can be concluded from the given examples:

- A conventional design with a statically stable armour layer and normally designed filter layers is usually expensive;
- By applying the falling apron principle the required extent of the scour protection can be reduced significantly, especially when the soil is sensitive to liquefaction;
- A dynamically stable scour protection, combined with an adequate monitoring program can result in a cost-effective and feasible solution;
- Physical model tests are essential in the design of the scour protection: from these tests critical unexpected aspects can be identified but also cost-reducing elements might come out. Also, based on the model tests relations can be derived to study the effects of various scenarios and strategies.

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