DRAFT

Deltares

Final report Joint-Industry-Project Handbook Scour Protection Methods (JIP HaSPro)

Public after 31 August 2021

enabling delta life

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Summary (*in Dutch*)

Als funderingen van offshore windturbines in een zandige zeebodem worden geplaatst, zal door stroming en golven het zand rondom de fundering eroderen. Hierdoor kunnen grote ontgrondingskuilen ontstaan die een gevaar vormen voor de levensduur van de constructie. Ontwerpers van offshore funderingen moeten daarom altijd rekening houden met deze ontgronding door dit mee te nemen in het ontwerp van de fundering of door de ontgronding tegen te gaan. Voor dit laatste wordt een bodembescherming aangelegd om te voorkomen dat het zand wegspoelt, bijvoorbeeld door het storten van stenen of het plaatsen van matrassen rondom de fundering. Momenteel zijn er nauwelijks ontwerpformules voor bodembeschermingen en bestaan er geen richtlijnen. Door de industrie worden hierdoor voor vergelijkbare locaties soms zeer verschillende ontwerpen gemaakt met variërend succes.

“Joint Industry Project Handbook Scour and Cable protection methods (JIP HaSPro)” is daarom geïnitieerd door onderzoeksinstituut Deltares en certificeringsinstantie DNV GL, met als doel het ontwikkelen van een duidelijke, generieke en wetenschappelijke vergelijking van verschillende bodembeschermingsmethoden voor offshore wind funderingen en kabels op de zeebodem. Hiervoor is nauw samengewerkt met een groot aantal partijen uit de offshore wind industrie, bestaande uit energiebedrijven (Ørsted, innogy, Vattenfall, Scottish Power, EnBW, Shell, Equinor), aannemers (Seaway Heavy Lifting, Boskalis, Van Oord, Jan de Nul, DEME Offshore), leveranciers (Airgroup Industries, Maccaferri, Mibau Stema, NoRock&Co, SPT Offshore, SSCS) en een ingenieursbureau (COWI).

In dit project is de meest toegepaste methode, het gebruik van steenbeschermingen om ontgronding tegen te gaan, verder geoptimaliseerd. Daarnaast zijn er verschillende alternatieve concepten onderzocht waaronder kunstmatige vegetatie, blokmatrassen, schanskorven en dubbelwandige matrassen gevuld met ballast. Verder is er aandacht besteed aan het toevoegen van ecologische meerwaarde aan bodembeschermingen door het gebruik van kunstmatige rif-elementen die een schuilplaats vormen voor vissen en het toevoegen van oesterschelpen met als doel het herstel van de eens overvloedig aanwezige oesterriffen.

Voor dit onderzoeksproject is een groot aantal schaalmodeltesten uitgevoerd in de faciliteiten van Deltares, in zowel de kleine en middelgrote stroom- en golfbassins als op grote schaal in ’s werelds grootste golfgoot: de Deltagoot (zie figuur). Tijdens deze testen zijn de beschermingen rond verschillende funderingen op schaal nagebouwd om de werking en stabiliteit te testen onder invloed van golven en stroming.

JIP HaSPro project team bij de Delta Goot tijdens een grote-schaal test rondom een monopile fundering.

Alle deze testresultaten zijn gebruikt voor het maken van ontwerpformules en een softwaretool voor een conceptueel bodembeschermingsontwerp. Daarnaast zijn deze resultaten samen met de praktijkervaring en kennis van alle partijen uit het consortium gebundeld in een digitaal handboek en een “Recommended Practice” voor het ontwerp, construeren, installeren en onderhouden van een bodembescherming.

Contents

1 Introduction to JIP HaSPro

1.1 Introduction to scour and scour mitigation

Scour is the phenomenon of an eroding seabed around the base of a foundation, caused by the action of hydrodynamics (waves and currents). When a structure is founded in the offshore environment flow is diverted around it. This diversion is characterised by increased flow intensity and turbulence near the structure (see Figure 1.1). As a result, flow is capable of transporting sediment away from the structure leading to progressive scour hole development, until an equilibrium situation is reached. The expected scour depth depends on many different parameters, such as structural dimensions and shapes, seabed composition and the hydrodynamic climate.

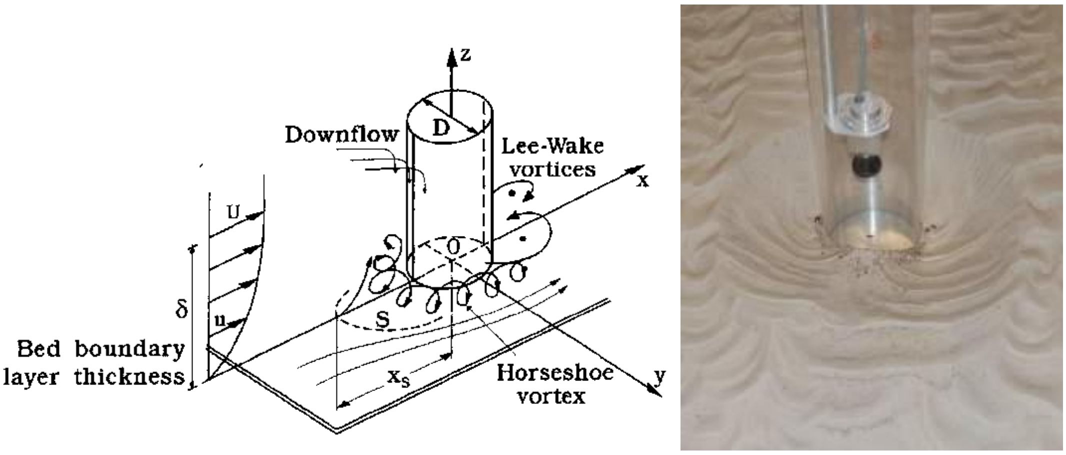


Figure 1.1 Left: Flow pattern of a current flowing around an unprotected cylindrical pile (Sumer & Fredsøe, 2002); Right: Scour hole development observed after the end of a scale model test with a transparent monopile.

If the scour hole development is severe, significant risks may be introduced for the integrity of the offshore foundation. A scour hole will lower the fixation level of the foundation leading to less lateral support from the soil and possibly to a vibrating response of the structure to the various loads it experiences. This has severe implications for the lifetime of the structure and therefore mitigation measures might be required.

Based on the predicted scour hole development, a designer may choose to protect the foundation by means of a scour protection or accept the scour development and possibly adjust the design of the foundation to be able to cope with the seabed level changes. If the designer chooses to protect the foundation against scour by installing a scour protection, then multiple strategies can be taken, differentiating between the moment of installation with respect to scour hole development and pile installation as well as to the type of scour protection applied. In any case, a scour protection needs be designed properly to be able to withstand the attack of waves and currents and possibly the migration of seabed features (e.g., sand waves) that are often present in sandy morphodynamic areas causing large scale changes in bathymetry.

1.2 Background

Before the start of this project, it was observed that there was limited guidance available on scour protections for offshore wind infrastructure in prevailing guidelines on design (e.g. DNVGL-ST-0126). As a consequence, very different scour mitigation strategies are chosen, even in neighbouring windfarms with almost similar boundary conditions and foundation concepts.

For each new wind farm, scour protections were designed and optimized by means of scale model tests. No guidelines existed how these tests should be executed and how scaling laws should be applied. All activities were done on a project-by-project basis, with hardly any generic research being performed.

One way of closing the knowledge gaps for problems that are widely felt within industry, but do not have a direct relation to Intellectual Property of the different companies is to create a Joint-Industry-Project (JIP's), in which the entire value chain is united. The knowledge and the experience present in the consortium is then used to set up a generic research programme. Deltares gained experience in the oil&gas industry, where JIP's were quite common. Since 2008 Deltares has been involved in JIP OSCAR, which focused on scour around spud can footings of jack-up drilling rigs. Hence the idea was born to explore the need for a JIP on scour protection methods for offshore wind infrastructure.

1.3 The start of the project

During the BlueWeek'15 organized by Deltares (20-22 April 2015, https://www.deltares.nl/en/events/blueweek-2015/) a full day meeting was organized to discuss the challenges regarding scour mitigation for offshore wind infrastructure that industry were facing. Both research institutes, certification and industry gave presentations, after which several polling questions were asked to the audience. An example of such a polling question is presented in Figure 1.2: "which type of rock protections should be considered in a Joint-Industry-Project". The response to this particular question resulted in a focus on single grading rock protections and scour protections installed in a highly morphodynamic environment (e.g. with migrating sand waves, such as in Borssele and Hollandse Kust wind farms).

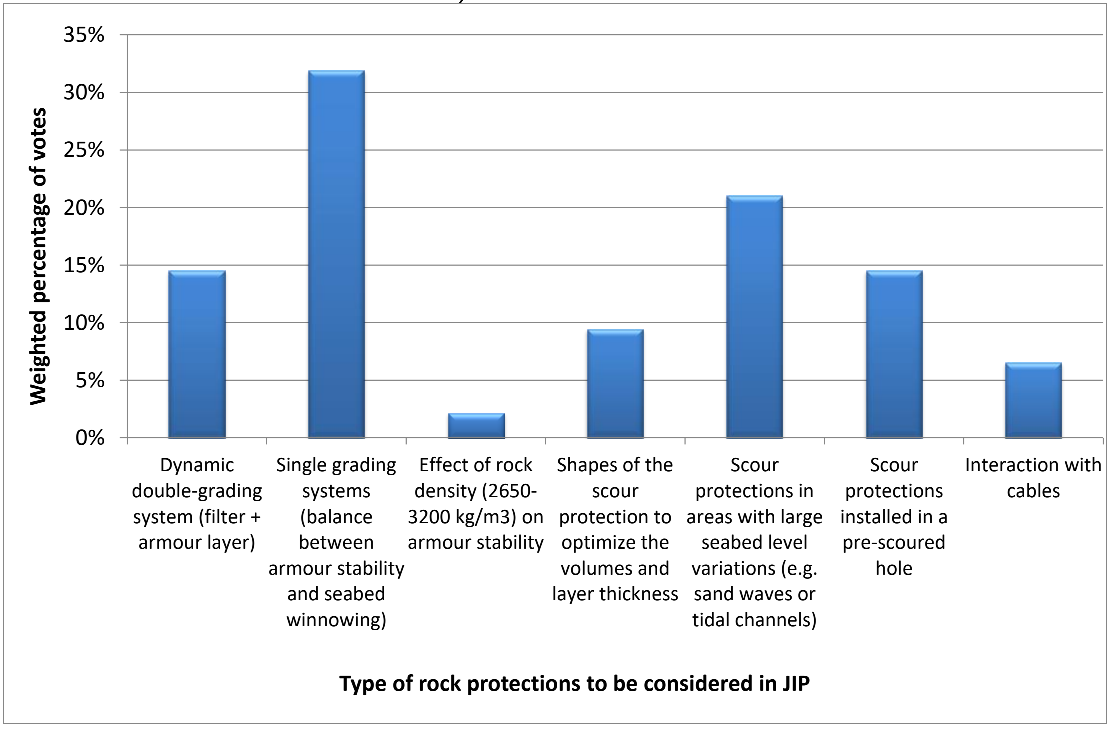


Figure 1.2 Example of stakeholder interview question during the BlueWeek'15 on which the scope of JIP HaSPro was based. This specific question resulted in the focus on single grading (very dynamic) scour protections and the focus on interaction between scour protection and morphodynamic seabed changes (representative for e.g. Borssele, Hollandse Kust (zuid) and Hollandse Kust (noord) .

1.4 Projects objective

The main objectives of JIP HaSPro are to:

- make a clear, generic and science-based comparison between different scour protection methods
- optimize existing scour protections methods (in terms of cost and material use)
- proving concepts of alternative scour protection methods
- generate recommendations/guidelines when and where to apply which method

This approach is based on the assumption that no scour protection method exists that works for all situations, which provides opportunities for several scour protection methods.

1.5 JIP HaSPro Consortium

In the JIP HaSPro consortium the entire value chain of scour protection methods is represented, see Figure 1.3.

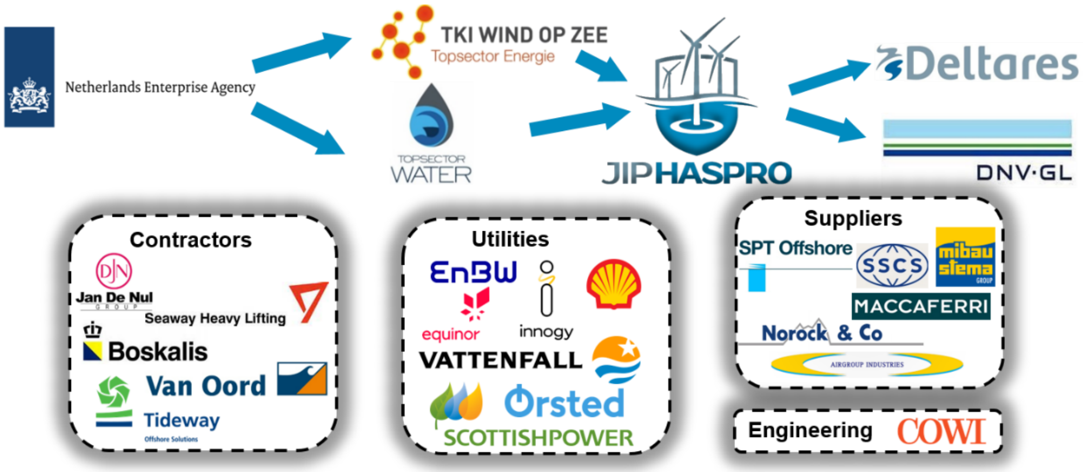


Figure 1.3 Project structure of JIP HaSPro with all project participants, involved top sectors and subsidy provider

Project communication

In order to inform each other and to discuss the scope and the intermediate results regular progress meetings were organized. Because of the large group size (and the related size of the meeting room facilities) and because of the fact that many of the progress meetings were coupled to a witness test of one of the scour protection tests, most meetings were held at Deltares in Delft.

Date	Meeting
Tue 29 Nov. 2016	Kick off Meeting at Deltares
Thu 9 Feb. 2017	1st Online Meeting
Wed 26 April 2017	2nd Progress Meeting + Witness Test *Alternative Protection Methods* in Atlantic Basin at Deltares
Fri 23 June 2017	3rd Progress Meeting + Witness Test *Rock Protection Methods* in Atlantic Basin at Deltares
Thu 26 Oct. 2017	4th Progress Meeting + Witness Test *Large-scale Tests* in Delta Flume at Deltares
Wed 22 Nov. 2017	Open Demonstration Events for TKI-WOZ-members and for IRO-Members
Tue 20 Mar. 2018	1st Workshop on *Ecological Framework for Scour Protections* at Van Oord, Gorinchem
Wed 25 April 2018	5th Progress Meeting at Deltares
Thu 13 Sept. 2018	6th Progress Meeting + Witness Test *Interface stability and flexibility* in Atlantic Basin at Deltares
Tue 7 May 2019	7th Progress Meeting at Deltares
Wed 8 May 2019	1st Work Group sessions on different chapters of the Handbook
Mon 24 June 2019	2nd Workshop on *Ecological Framework for Scour Protections* also with external stakeholders

Tue 26 Nov. 2019	8th Progress Meeting at Deltares
Wed 27 Nov. 2019	2nd Work Group sessions on different chapters of the Handbook
TBD (after COVID-19)	Meeting on Recommended Practice of DNV GL
TBD (after COVID-19)	Close out meeting at Deltares

Table 1.1 Overview of project meetings

Figure 1.4 Group photo of JIP HaSPro consortium taken during the 7th Progress Meeting on 9 May 2019 in Delft.

Steering Committee

Every participant was represented in the HaSPro Steering Committee; each member having one vote. The role of the Steering Committee was to:

- give advice (solicited or unsolicited) to the executing companies
- vote for decisions on project scope or project organization (within limitations of subsidy rules and awarded project plans)
- respond to questions by email in which the opinion of a participant is asked

It was decided early in the project that Steering Committee decisions were taken during the regular progress meetings, to allow for maximum transparency and to limit travel costs and CO_2 emissions. Although the composition of the Steering Committee changed throughout the project, its composition at the date of this report was:

Company	Steering Committee Representative
AG-Industries	Edwin Peters
Boskalis	Bart Mous
COWI	Nadia Genovese
Deltares	Tim Raaijmakers
DEME Offshore (formerly Tideway)	Connie Visser
DNV GL	Erik Asp Hansen
EnBW	Christian Weber

Equinor (formerly Statoil)	Gülin Yetginer Tjelta
innogy SE (formerly RWE)	Volker Herwig
Jan de Nul	Koen Schepens
Maccaferri	Marco Vicari
Mibau	Ricarda Godenau
Norock & Co	Truls Sverdvik
Ørsted (formerly DONG Energy)	Andreas Roulund
Scottish Power Renewables	Alberto Avila
Seaway Heavy Lifting	Vladimir Thumann
Shell	Erik van Iperen
SPT Offshore	Oene Jeljer Dijkstra
SSCS	Laura Bell
Van Oord	Irene Tönis
Vattenfall	Eleni Skoufaki

Table 1.1 Composition of JIP HaSPro Steering Committee on 1 May 2020

1.6 Cross-over between TKI-WOZ and TKI-DT

JIP HaSPro is a cross-over project between two different top sectors: Topsector Energy – TKI Wind op Zee and Topsector Water – TKI Deltatechnology. First, in June 2016 a R&D proposal was submitted at the TKI-WOZ R&D tender, which was ranked 1st and for which € 965.000,- subsidy was awarded to a consortium then consisting of 10 partners. When the project started in September 2016 more companies were interested to join the project. Moreover, the project consortium noticed two more important topics that could nicely be fitted in the scope of the existing project. These two topics were:

- Cable protections, in order to reduce the number of problems occurring at crossings with other infrastructure, such as pipelines and communication cables;
- Nature-inclusive scour protection designs, which were gaining interest from an ecological point of view. At that moment several studies were commissioned by Ministry of LNV..

Since these topics aligned with three of the Knowledge & Innovations Clusters of TKI Deltatechnology (part of Topsector Water), i.e. “Energy and Water”, “Sustainable use of estuaria, seas and oceans” and “Eco-engineering and nature-based solutions”, it was decided to make JIP HaSPro into a cross-over project between TKI-WOZ (Topsector Energy) and TKI-DT (Topsector Water).

The TKI-WOZ part of the project was executed with subsidy of the Ministry of Economic Affairs, National Economic Affairs Subsidy Schemes, Topsector Energy, executed by The Netherlands Enterprise Agency (RVO.nl). The TKI-DT part of the project was executed with subsidy of the Ministry of Economic Affairs, National Economic Affairs Subsidy Schemes, Topsector Water, executed by The Netherlands Enterprise Agency (RVO.nl).

1.7 Project deliverables

The individual project deliverables are introduced in the different sections of this report and listed with all reference details in Chapter 6. In summary, JIP HaSPro produced the main deliverables:

- 13 test reports on all considered scour protection methods and test programmes
- Handbook Scour Protection Methods
- Recommended Practice on “*Design of Scour Protection around Monopiles*” by DNV GL

- Ecological Framework addressing the most important legislative frameworks on marine ecology in relation to scour protections (design, installation, operation and decommissioning)
- Engineering Software Tool for Scour Protection Design, including User Manual
- Illustrative movie on the project

Scientific papers on the project results, which by the subsidy rules fall outside the project scope, are being written by the project consortium and will be published in 2021. New deliverables will later be added to this report.

More information on current and future project deliverables can be obtained Tim Raaijmakers (tim.raaijmakers@deltares). Please consider the confidentiality period which expires on 31 August 2021. Note that current (and future) members of the HaSPro Project Consortium have immediate access to the deliverables.

1.8 Knowledge dissemination during the project

During the project we communicated about JIP HaSPro in the following ways:
- Pitch about JIP HaSPro at TKI-WOZ Matchmaking Event, 15 February 2017
- Article "Offshore wind onder de loep" in De Ingenieur of 19 July 2017
- Article "Offshore wind industrie doet onderzoek voor windparken van de toekomst" in Breen Magazine of 1 August 2017
- Open Witness Test in the Delta Flume, with over 150 attendees from the TKI-WOZ and IRO-network on 22 November 2017
- Presentation on "Nature-inclusive design of scour protections" during BlueWeek'18 on 28 May 2018
- Presentation at Wind Days 2018 about JIP HaSPro project on 13 June 2018.
- Visit of Minister Cora van Nieuwenhuizen (I&M) tot he test programme of JIP HaSPro on 27 September 2018 https://twitter.com/MinIenW/status/1045355807293009920
- Stakeholder Workshop on Ecological Framework for Scour Protections, also attended by various policy makers on 24 June 2019.

A movie about the JIP HaSPro project is in the making.

1.9 Spin-off of the project and contribution to Offshore Wind in the Energy Transition

Already significant spin-off of JIP HaSPro has been achieved during the project. Some examples are mentioned here.

The 21 project partners of JIP HaSPro are already applying the new knowledge and test database in new offshore wind projects. As soon as the Handbook and Recommended Practice become publicly available, the entire industry can apply the HaSPro knowledge.

HaSPro intermediate results were also applied by Deltares in the Site Investigation Studies commissioned by RVO in order to provide useful guidance for scour mitigation strategies for the wind farm areas Hollandse Kust (zuid), (noord) and (west). For the latest studies also the topic of nature-inclusive scour protection designs was covered (please visit offshorewind.rvo.nl for the reports and webinars).

In terms of follow-up research, several spin-off research projects can be mentioned:

1. JIP ECO-FRIEND, in which by means of field pilots with nature-inclusive scour protections in GEMINI wind farm research is being performed on ecological effects / success and the most suitable monitoring methods;
2. ECO-SCOUR, in Van Oord and project partners will execute pilots with eco-friendly scour protections in Borssele Kabel V.
3. JIP CALM (Cable Lifetime Monitoring), which aims at reducing the number of cable failures, developing real-time monitoring techniques for cable burial depth and developing a smart Cable Routing Tool, which will facilitate (among others) that unfavourable locations and orientations of cable crossings can be avoided (on the basis of HaSPro knowledge on cable crossings).

The demonstration of the possibility to safely apply eco-friendly scour protection designs around wind turbines generated sufficient confidence to include this as a requirement in the new Wind Farm Site Decisions in The Netherlands. The Ecological Framework for Scour Protections at least initiated the discussion under what conditions scour protections can be considered artificial reefs.

For the alternative scour protection methods, interest is increasing for application in areas with very demanding conditions (e.g. typhoon- and earthquake-prone Taiwan), where the right rock gradings may not be available or will not be sufficiently stable.

1.10 Scour protection methods

In JIP HaSPro three main groups of scour protection methods:

1. **Loose rock scour protections**, in which the focus is on optimization rock gradings, layout dimensions and rock density and dealing with highly morphodynamic seabeds.
2. **Alternative scour protection systems** that can be installed with lighter equipment or even self-installable, while some systems could be more suitable for very severe hydrodynamic conditions (such as cyclones).
3. **Eco-friendly (or nature-inclusive) scour protections**, which especially in The Netherlands nowadays receive a lot of attention. These scour protection

Foundation types
Since the vast majority of offshore wind turbine foundations consists of monopile foundations (in The Netherlands even 100%), this project focused on this foundation type. Besides monopiles, also Suction Bucket Jackets have been investigated as an alternative foundation type for deeper water and larger turbines. Next to foundations, cable protections were studied in order to lower the number of cable failures at cable crossings or due to free spanning.

1.11 Content of report

This report summarizes all activities that were executed in the framework of JIP HaSPro, combining both TKI-WOZ and TKI-DT scopes in one integrated project. Since the largest part of the project was centred around physical model testing of all scour protection concepts, Chapter 2 introduces the facilities, test programmes and measurement methods and illustrates how typically tests were prepared and executed. In Chapter 3, all considered scour protection methods are discussed, divided in three main groups, as introduced in the previous section: Section 3.1 describes scour protections consisting of loose rock, Section 3.2 discusses alternative scour protection methods and Section 3.3 elaborates on eco-friendly scour protections.

Chapter 4 describes the main software developments and deliverables, while Chapter 5 explains which guidelines were developed in this project. Finally, Chapter 6 lists all main project deliverables.

2 Physical model testing

A large part of this JIP consisted of the execution of physical model test programmes for the different foundation types and scour protection methods. Section 2.1 shows an overview of the different test programmes and facilities. Section 2.2 follows with illustrating the way tests were executed including the used measurement techniques.

2.1 Overview of facilities and test programmes

All physical model tests were executed in one of the Deltares' facilities which each their own specific strengths, described and visualised in Table 2.1. Quick and efficient laboratory tests were performed in the Scheldt flume, a long 1m wide wave-current flume with a glass wall, making it ideal for close-up observations of the stability of several scour protection methods. In the Atlantic Basin, tests could be performed on a slightly large scale on a sandy test section to better represent the interaction between the scour protection and the surrounding seabed. This 8.7m wide wave-current flume furthermore created the possibility to tests multiple scour protection layouts in parallel. A Unique physical model tests was performed in the Delta Flume, world's largest wave flume. In this 300m long flume, multiple scour protection methods could be tested on a much large scale, reducing scale effects to better represent real offshore conditions. These tests were very valuable within this project to validate the results on the small scale and to research processes that are difficult to scale down, such as the stability of shelfs, erosion of sediments trough the protection and realistic scour protection installation tests.

All wave flumes are equipped with a piston-type wave board which can generate all kind of waves from regular waves till an irregular wave spectrum to realistically simulate an offshore storm on the North Sea. Furthermore, all wave boards are equipped with Active Reflection Compensation technology to damp out reflected wave energy to better represent the offshore wave climate.

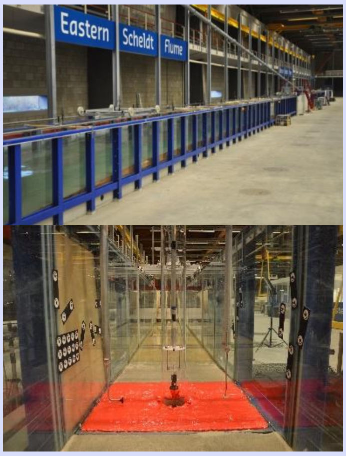
Scheldt Flume	Atlantic Basin	Delta Flume
• Model scale 1:30 to 1:50 • Tidal currents & waves • Fast cycle times: many exploratory tests	• Model scale 1:20 to 1:40 • Tidal currents & waves • Wide test section: efficient testing of multiple foundation • Mobile bed (sand)	• Model scale 1:1 to 1:10 • World's largest wave flume • Limited scale effect • State of the art, since Oct. 2015
		

Table 2.1 Deltares' facilities in which the physical model tests were executed

The different physical model test programmes that were performed within JIP HaSPro are chronologically summarised in Table 2.2. Within these test programmes, many potential failure mechanisms were investigated on various scales for the different scour protection methods around monopiles, cables and SBJ. Test started on the small scale in the Scheldt flume to efficiently perform proof of concept tests for the stability of mattresses and the sand tightness of artificial vegetation. Subsequently, tests were performed in the Atlantic basin for the external stability of loose rock scour protections and to test the interaction between the sandy seabed with the alternative scour protection methods. After knowing the scour protection behaviour and stability limits on the small scale, large scale tests were performed in the Delta Flume to reduce scale effects and to better predict the system's behaviour in the field. After the large scale tests, several other test programmes were executed focussing on washout of sediments trough a rock layer (also called interface stability or winnowing), the behaviour of a protection in morphodynamic areas (flexibility of a protection) and on several methods to improve the ecological value of scour protection.

Test programme	Facility	Foundation types	Period
Stability test alternative scour protections	Scheldt Flume & Atlantic Basin	Monopiles, Cables, SBJ	Mar – Jun 2017
External stability of loose rock	Atlantic Basin	Monopiles	Jun – Jul 2017
Large scale tests for loose rock, alternative and eco-friendly scour protections.	Delta Flume	Monopiles & Cables	Sep – Dec 2017
External stability of loose rock	Atlantic Basin	Cables	Jun 2018
Interface stability of loose rock (winnowing / washout of sediments)	Atlantic Basin & Scheldt Flume	Monopiles	Jul – Aug 2018
Flexibility and stability of loose rock	Atlantic Basin	Monopiles & Cables	Aug – Sep 2018
Eco-friendly scour protections	Atlantic Basin	Monopiles & Cables	Jan – Feb 2019

Table 2.2 Chronologically executed test programmes within JIP HaSPro, testing multiple scour protection methods in the three different facilities for monopiles, cables and SBJ.

2.2 Test preparation and execution

In preparation of the physical model tests, representative field scale conditions were defined for the structural dimensions, hydrodynamic conditions and soil parameters. This was done by considering the range of typical North Sea waves and currents and the trend towards larger wind turbines in deeper water resulting in larger foundations. The representative offshore conditions and structural dimensions were scaled down to the facility's model scale. Test were performed to protect monopiles, cables and SBJ. Special scale models were constructed to represent these foundations types (Figure 2.1). All structures are where possible build out of transparent material to use close cameras to record any scour protection deformation.

Figure 2.1 Several scale models of different foundation types from left to right: transparent monopile for small scale test, monopile scale model in the Delta Flume, SBJ scale model and cable protection

In preparation of each test programme, the tested scour protection systems were designed in close cooperation with the JIP participants. Special rock gradings were delivered by Mibau and Norock & Co and scale models for the alternative scour protection principles were designed and made together with the different suppliers (SSCS, Maccaferri, AG Industries, SPT Offshore). All these scale models were hand-made, considering scaling laws flexibility of the materials to show a similar behaviour on field and model scale.

Before each test, the scour protections were precisely installed according to the planned layout. Some visualisations of this scour protection installation process are shown in Figure 2.2.

Figure 2.2 Example of scour protection from left to right: installation of a rock berm, placement of gabions around the monopile in the Delta Flume and installation of a scaled loose rock scour protection in the Atlantic Basin.

Numerous measurement techniques were used to measure the achieved hydrodynamic conditions (instruments to measure wave height, current and water level) and the behaviour of the considered scour protections. Highlighted in this view, is the 3D-stereophotography technique to very accurately measure any deformation of the protections. These measurements are taken using a double-camera to quantify depth, and markers as a spatial reference. An example 3D result together with a picture of the measurement execution is show in Figure 2.3.

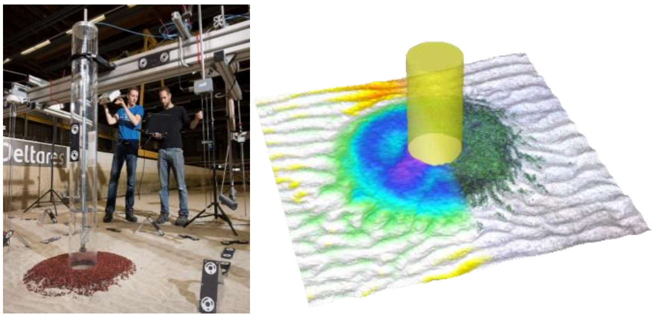


Figure 2.3 3D stereophotography technique measuring bathymetry

Furthermore, cameras from underwater and from inside the transparent elements of the structures were used to visually record the scour protection behaviour (Figure 2.4). Even in the steel monopile scale model in the Delta Flume, windows were places for visual observation. An example view of one of the internal camera's is shown in Figure 2.4. Besides nice video footage, these internal views also deliver quantitative results by using smart interface detection of the rock and sand layer height at the pile interface.

Figure 2.4 Underwater and internal cameras were used in all test programs to record the scour protection behaviour. From left to right: underwater camera in the delta flume, internal camera inside a transparent monopile foundation in the Atlantic basin, with the corresponding view from the camera on the protection. Smart image recognition is done to track the height of the rocks and sand layer at the pile interface.

3 Scour protection systems

This chapter will describe all scour protection systems for which physical model tests were performed within JIP HaSPro. For each concept, the following points will be addressed in the subsequent sections:

- The working principle
- Test campaigns in which the system was tested
- Results and learnings
- Recommendations for further research

3.1 Rock protections

Rock is currently widely used for scour protections. A large part of the physical model tests for loose rock scour therefore focussed on this scour protection method. Within these programmes, three main performance criteria were analysed (schematised in Figure 3.1):

- External stability: the top layer should be sufficiently stable under the design load;
- Interface stability: washing out / winnowing of sediment through the pores of the scour protection should be prevented;
- Flexibility: the scour protection should be able to handle edge scour and/or morphodynamic bed level changes.

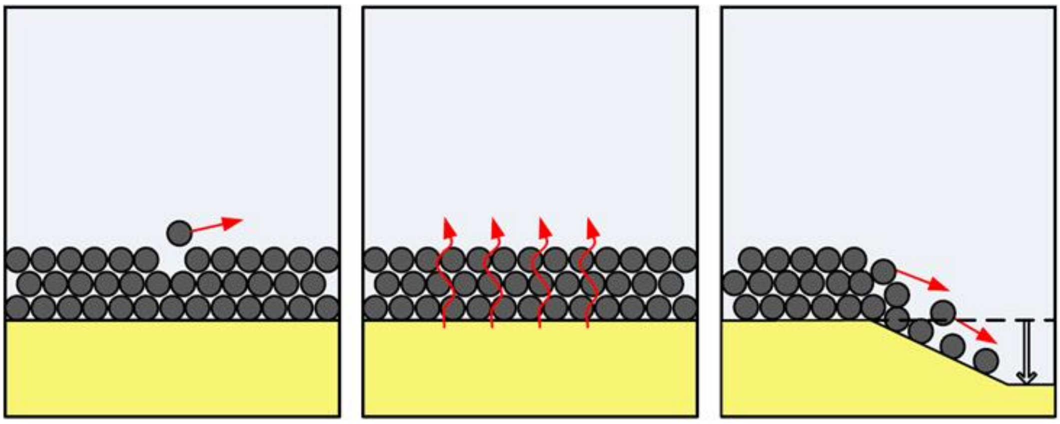


Figure 3.1 Schematisation of external stability (left), interface stability (middle) and flexibility (right).

3.1.1 External stability

Over the past years, Deltares has performed a large variety of physical scale model tests for several wind farms to investigate the stability of loose rock scour protections around monopile foundations. The external rock stability tests within JIP HaSPro focussed on filling in the current gaps of and verifying this existing database for monopile foundations and cable protections. Stability tests were for example performed for wider rock gradings and larger relative current velocity to extent the existing database.

External stability was tested in the Atlantic Basin and Delta Flume. During the Atlantic Basin test campaign, many different parameters were varied to test their influence on the scour protection deformation. These included for example the wave parameters, water depths, current velocity, rock size and rock density. An example test setup just before starting the first test in the Atlantic basin together with a photograph during testing is included in Figure 3.2. During testing, serval typical deformation patterns were observed. An example of such a pattern is shown in Figure 3.3 with typical rock erosion and deposition areas for the monopile in the Atlantic Basin and flattening of a rock berm caused by wave action in the Delta Flume.

Figure 3.2 Breaking wave during in the test section for loose rock scour protections (left) and four scour protection layouts just before testing.

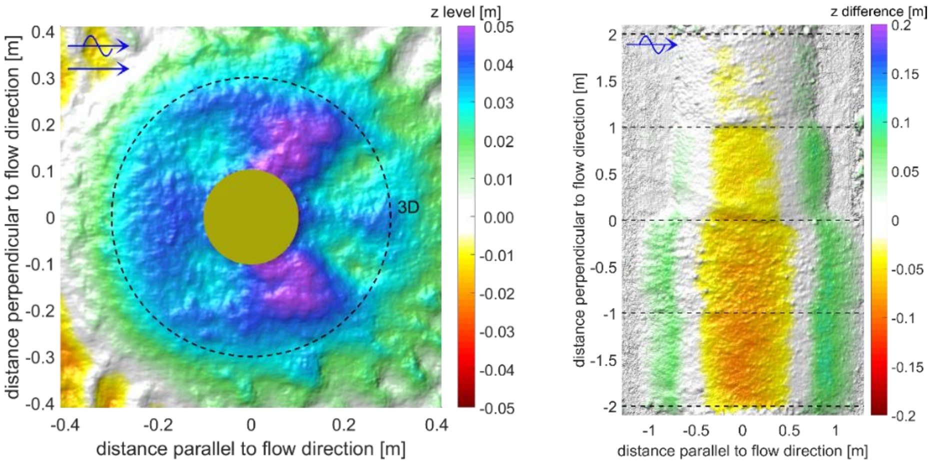


Figure 3.3 Example deformation pattern for a monopile rock protection from the Atlantic Basin and 4 different rock gradings in a rock berm tested in the Delta Flume.

All rock stability tests focussed on quantifying deformation as function of the hydrodynamic and structural parameters for monopile foundations and cable protections. The main result of these rock stability tests is an extensive test database on scour protection deformation for many different structural and hydrodynamic parameters. From this, design formulae can be derived to be implemented in a conceptual design tool for scour protection designs (see Section 4.3).

Within JIP HaSPro many tests focussed on single storm events. It is currently not well understood how multiple consecutive storms effect the scour protection deformation. For further research, we therefore recommend to better quantify the cumulative effect of multiple storms on a scour protection layout. Furthermore, field validation cases can be very valuable to better validate the physical model test results.

For further information the reader is referred to the test report on external stability of loose rock scour protections for monopile foundations and cables (Deltares, 2019d, 2019i, 2019j).

3.1.2 Interface stability

A scour protection should be sufficiently sand tight to prevent the suction removal of sediment through the pores of the scour protection (called winnowing). Traditionally this was guaranteed by applying geometrically closed filter layers, which made sure that the sediment could not pass through the pores of the scour protection. For offshore applications often use is made of geometrically open filters, which means that sediment can entrain into the filter and potentially escape into the water column through the pores of the protection. For such designs winnowing is prevented by ensuring sufficient layer thickness is present to reduce the hydrodynamic load at the seabed.

Tests were performed on a large scale in the Delta Flume, focussing on the interface stability during waves-only conditions and the scale effects of winnowing. A second test programme was performed in the Atlantic Basin, which is equipped with a sediment bed. The (scaled) Delta Flume tests were repeated in this test programme, in order to further investigate the scale effects on a smaller scale. Furthermore, additional current-only tests were performed to investigate the winnowing potential in tidal conditions. The third and final test programme was performed in the Scheldt Flume. Focus of this test programme was on winnowing during current-only and storm (waves and current) conditions, and on determining equilibrium winnowing scour depths during these conditions.

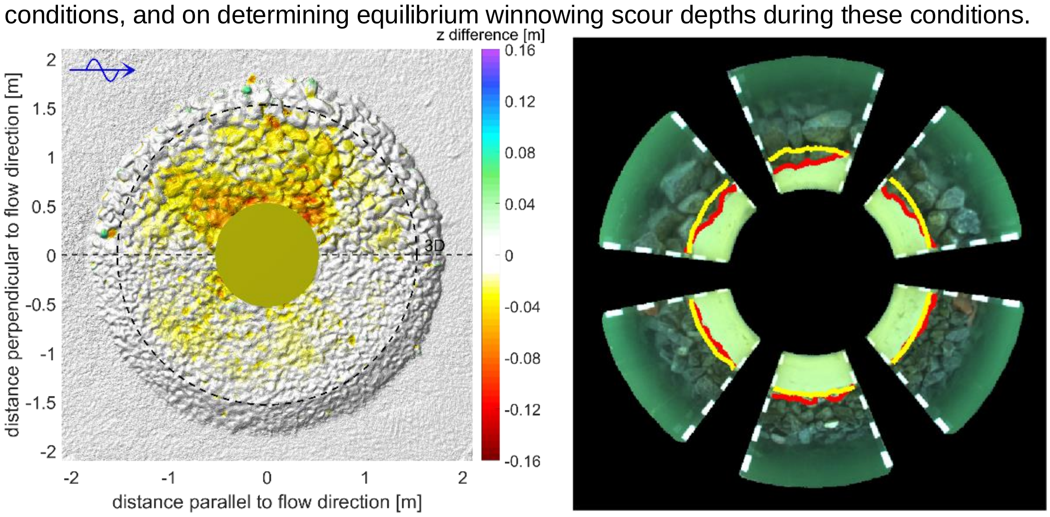


Figure 3.4 Deformation developed due to washout of sediments close to the monopile during the Delta Flume tests. Left shows the result of the 3D measurement and right shows the sediment lowering at the pile interface, captured from the internal camera inside the monopile.

Within this project we improved the understanding of this process for which only little was known by specifically investigating the combination of a foundation, waves and currents. Based on the results, we intend to include this winnowing process in the new scour protection design tool (Section 4.3).

Because of the complex scaling of sand to laboratory scale, we recommend for further research to support and validate the scale model results with large-scale experiments / field data to specifically address the combination of currents and waves on the winnowing potential (which was only tested in the smaller scale facilities).

For further information the reader is referred to the test report on interface stability of loose rock scour protections (Deltares, 2019h).

3.1.3 Flexibility

Wind farms are increasingly built in more challenging locations with larger migrating morphodynamic features requiring a scour protection to cope with bed level changes. Excessive undermining of the edges of a scour protection could lead to progressive failure of the entire system. To prevent this, a scour protection should be sufficiently flexible at its outer edges to cope with bed level changes of the surrounding seabed (e.g. bed level lowering due to a migrating sand wave). This is typically achieved by sacrificing the material at the outer edge of the protection as a falling apron: the material rolls down the slope of the edge scour hole, stabilising it against further erosion (see Figure 3.5 Photo and underwater camera images showing the falling apron behaviour around the edge of a protection as a result of bed level lowering in a physical model test setup.). Within this JIP the existing test database was systematically extended to better understand the behaviour of loose rock scour protections in areas with bed level lowering.

Figure 3.5 Photo and underwater camera images showing the falling apron behaviour around the edge of a protection as a result of bed level lowering in a physical model test setup.

Estimating the rock volume that is needed to form the falling apron at the protection edges is an important design parameter for such a scour protection. Through physical model testing knowledge was obtained about the geometry of the falling apron that forms under different hydrodynamic conditions and different scales of bed level changes. The side slopes of the falling apron tend to be steeper under current-only conditions, turning into milder slopes with increased wave action. The slope angles together with the rock layer thickness on the slopes can be used to predict and design the required additional extent of a scour protection to be able to cope with bed level changes.

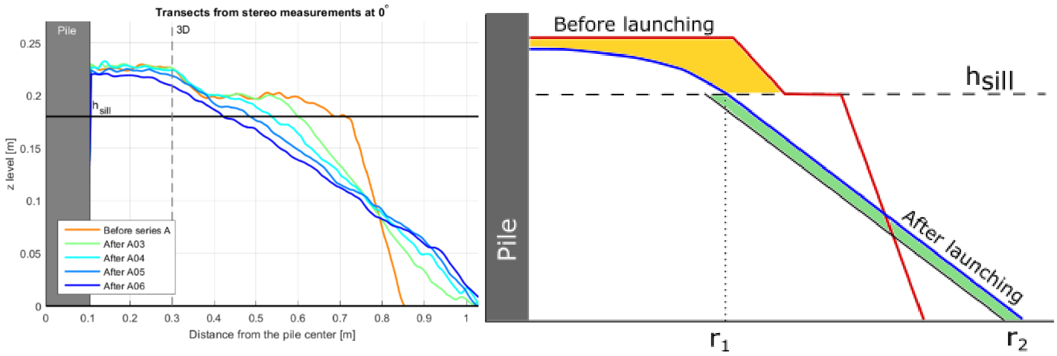


Figure 3.6 Measured falling apron slopes as developed under increasing storm severity (left) and a schematic image showing the required rock volume to cover the slopes around a protection after falling apron launching (right).

Based on the knowledge gained within this JIP, this process can be incorporated in a conceptual design tool for scour protection design. It is recommended to further research this topic by validating the falling apron behaviour with field measurements in order to exclude any scale effects.

For further information the reader is referred to the test report on flexibility of loose rock scour protections (Deltares, 2019f).

3.2 Alternative scour protection solutions

3.2.1 Introduction

Besides scour protections of loose rock, in JIP HaSPro also several alternative scour protection systems were investigated. Some of these systems are already applied for different applications in hydraulic engineering works, while others are tested for the first time in HaSPro or even developed within the framework of JIP HaSPro.

3.2.2 Artificial vegetation

An artificial vegetation scour protection (also referred to as a frond mat) functions similarly to the natural marine vegetation, which is known for its ability to reduce near-bed flow velocities and retain sediments, while being light, permeable and flexible. A front mat consists of a flexible frame populated with a uniform dense field of artificial vegetation (usually made of polypropylene). A grid of frond mats placed around an offshore structure is easy to install (no heavy equipment or large volume transport necessary), requires little maintenance and can even promote build-up of sediment under favourable conditions. Frond mat scour protection system has already been applied around various offshore structures; however, its use is hampered by the lack of systematic research into the design rules and lack of reliable evidence of the effectiveness of this type of scour protection. The tests in JIP HaSPro were proof-of-concept tests, with a focus on understanding the role of different design parameters in preventing scour.

Scale models of artificial vegetation scour protection have been tested in the Scheldt Flume around monopile foundations and in the Atlantic Basin around both monopiles and suction bucket jackets (SBJs) in March - June 2017, see Table 2.2. The scale models were made of poplypropylene strips with various thicknesses and densities in order to resemble fronds with a range of physical properties. Scheldt Flume tests made use of a simplified layout with a local sand section, and a large number of tests was performed to understand the influence of the vegetation stiffness and population density on scour development under current-only, wave-only and wave-current conditions. Based on that, two layouts with the most promising performance were designed and tested in the Atlantic Basin, where the large mobile bed allowed us to model processes of scour development and sediment accretion within the fields of fronds. Figure 3.7 presents an example of the tested layouts at a monopile in the Scheldt Flume (left), at a monopile in the Atlantic Basin (centre) and at an SBJ in the Atlantic Basin (right). Subsequently, these medium-scale tests were validated through the large-scale tests that were done in the Delta Flume in September - December 2017, where tests were carried out with very limited scale effects.

Figure 3.7 Artificial vegetation scour protection tested at a monopile in the Scheldt Flume (left), at a monopile in the Atlantic Basin (centre) and at an SBJ in the Atlantic Basin (right).

The physical model test results have clearly indicated the influence of vegetation stiffness and population density on scour development around the monopiles and SBJs. Overall the artificial vegetation scour protection has proven to be an effective measure to limit scour, however, its effectiveness strongly depends on the physical properties of the frond mat. Based on these results, we were able to formulate recommendations for the optimal frond mat design, where vegetation with different bending stiffness shall be used in different parts of the frond mat, depending on the proximity to the structure.

For further research we recommend to gain further understanding in the other design parameters of frond mats, such as ballasting that is required to keep the frond mats in place on the seabed, and the environmentally-friendly materials that the flexible fronds can be manufactured from. Overall, close study of future field experiments is also very important, since the complexity of the frond mats cannot be fully represented on a small scale in a laboratory environment, leaving some uncertainty in the quantitative results due to the scale effects.

For further information the reader is referred to the report describing artificial vegetation scour protection as tested in the Scheldt Flume, the Atlantic Basin and the Delta Flume (Deltares, 2019b).

3.2.3 Concrete block mattresses

A block mattress consists of a matrix of concrete blocks connected to each other (usually with a polypropylene rope or a geotextile). Concrete block mattresses are available in various shapes and sizes, dependent on the manufacturer but also on the application. Block mattresses are characterised by their flexibility (ability to follow different shapes), permeability (open to water), relatively small height (compared to rock protections) and the fact that they are relatively easy to remove. However, they also generally require precise installation. Because of these characteristics, block mattresses are very common as protection of hydraulic boundaries, such as river beds, embankments, flow outlets, etc. On the current offshore market block mattresses are mainly used for stabilization of offshore cables. As a scour protection (either at a monopile or over cables) block mattresses have found very limited application yet.

The concrete block mattresses have been tested in the Scheldt Flume and the Atlantic Basin from March – June 2017, see Table 2.2. The difference between the basins is the presence of a mobile sand bed in the Atlantic Basin. In both basins the test conditions included, current-only, wave-only (regular and irregular) and current-and-waves (storm conditions). The scale model block mattresses were applied around a monopile and over a cable section. Together with Maccaferri a dedicated block mattress design and layout was developed, and scale model were manufactured accordingly. To ensure a precise and consistent shape of the blocks, they were not made from concrete but from aluminium (which has approximately the same specific density). Coloured patches were added to track the movement of the mattress. Figure 3.8 presents an example of the tested layouts in the Scheldt Flume (left) and Atlantic Basin (right).

Figure 3.8 Concrete block mattresses tested in the Scheldt Flume (left) and Atlantic Basin (right).

Throughout the physical model tests the block mattress has shown it is very effective as cable protection/stabilisation. Block mattresses furthermore proved to be flexible enough to follow bed level lowering around the protection (edge scour and/or morphological changes). As a scour protection special attention should be given to the transitions, either with other mattresses or at the pile face, as sand can move easily through the gaps if the transitions are not covering the bed sufficiently (see the lowering at the pile face in Figure 3.8-right).

For further research we recommend investigating the possibility of manufacturing dedicated shapes. At a monopile the mattress should be able to follow the curvature of the pile to ensure a sand-tight interface between the pile and the mattress. Hereby the installation accuracy should also be kept in mind. For further information the reader is referred to the Test report on Concrete block mattresses (Deltares, 2020).

3.2.4 Gabion mattresses

A gabion mattress is a series of steel wire mesh cells filled with rocks. Gabion mattresses are available in various sizes, dependent on the manufacturer but also on the application. They can furthermore be implemented with a geotextile, which can easily be attached to the wire mesh. Gabion mattresses are characterised by their flexibility (ability to follow different shapes), permeability (very open to water) and the use of relatively small (easily available) rock. Moreover, they allow for dedicated shapes and the inclusion of shell material, which improves their ecological potential. However, they generally require precise installation. Gabion mattresses are very common as protection of hydraulic boundaries, especially in high flow velocity conditions or under wave attack. Main (hydraulic) applications are river banks, channel linings and flow outlets. As an offshore scour protection (either at a monopile or over cables) gabion mattresses have found very limited application yet.

The gabion mattresses have been tested in the Scheldt Flume, the Atlantic Basin and the Delta Flume from March – June 2017 and September – December 2017, see Table 2.2. In the Scheldt Flume the gabion mattresses were applied over a cable and around a monopile and the test conditions included, current-only, wave-only (regular and irregular) and current-and-waves (storm conditions). In the Atlantic Basin the gabion mattresses were applied around a monopile (see Figure 3.2-left) and the test conditions included current-only, wave-only (regular) and current-and-waves (storm conditions). In the Delta Flume the gabion mattresses were applied over a cable and around a monopile and some of the gabions were partially filled with oyster shells, see Figure 3.2-right. The conditions in this flume consisted of wave-only conditions. Like the block mattresses a dedicated design and layout was developed with Maccaferri, which was optimized during the test campaigns.

Figure 3.2 Gabion mattresses tested in the Atlantic Basin (left) and a gabion mattress partially filled with oyster shells that was tested in the Delta Flume (right).

Throughout the physical model tests the gabion mattress has shown its potential as a scour protection around monopiles and as a cable protection/stabilisation. If provided with sufficient thickness the tests showed that the mattress can be sufficiently stable. Moreover, the mattresses proved to be sufficiently flexible to follow changing bed shapes. To prevent scour around a monopile, dedicated shaped mattresses and very accurate mattress installation are required to prevent sand washing out at the pile interface.

The tests clearly show the potential for this system. For further research we recommend developing a dedicated shaped mattress that is easily manufactured and installed. It should also prevent any gaps between the mattresses and/or the pile face and the mattresses. Systematic testing of this design should be performed to determine a design formula for the required thickness as a function of hydrodynamic parameters. For further information the reader is referred to the Test report on Gabion mattresses (Deltares, 2019g)

3.2.5 Ballast-filled mattresses

Figure 3.9 Ballast-filled mattresses tested in Delta Flume as a scour protection around a monopile (left) and at a cable (right).

Working principle

A ballast-filled mattress is an innovative scour protection method and consists of an impermeable (air- and watertight) outer layer, with an empty compartment in between, which can be filled with a certain substance. The top and bottom sides of the mattress are typically held together by means of threads, which increases the overall stiffness of the mattress. The method is loosely based on conventional air mattresses but are filled with a heavier substance (for instance water, bentonite, slurry, etc.) to keep it on the seabed and protect against scour. This method is still in the conceptual design phase, so there is no prototype. Possible advantages of this method are mainly related to its simplicity during installation and removal and makes it especially interesting for temporary foundations. Additionally, due to the impermeability of the mattress this method yields a significantly lower protection layer, which in turn reduces the potential for edge scour and hence the required protection extent.

Test campaign

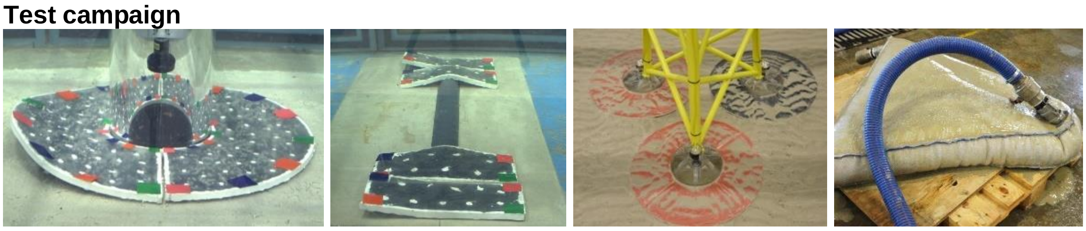


Figure 3.10 Ballast-filled mattresses tested in Scheldt flume (a,b) Atlantic Basin (c) and Geohal (d).

Ballast-filled mattresses were tested in Scheldt Flume (around monopiles and cables), Atlantic Basin (around monopiles and SBJ) and Delta Basin (around monopiles and cables) for a wide range of environmental conditions. The tests were focused on mattress stability, flexibility and winnowing potential near the pile face. Next to the dimensions and the density of the filling substance, the mattress stiffness is one of the main design parameters for this method. A stiff mattress will have more resistance against uplift than a flexible mattress. On the other hand, the flexibility of the mattress determines the ability of the mattress to follow edge scour or different bed shapes. Mattresses of varied stiffness were tested for stability and flexibility in the performed test campaign. Mattresses tested in Delta Flume were delivered by Airgroup Industries. Finally, additional tests were performed to assess the filling procedure for various types of coating and spatial thread configurations.

Results and learnings

Based on the test campaign it was seen that ballast-filled mattresses have potential as a scour protection method. Mattress flexibility is needed to arrest potential undermining and stiffness to resist uplift forces. This calls for an optimization of the method's design parameters.

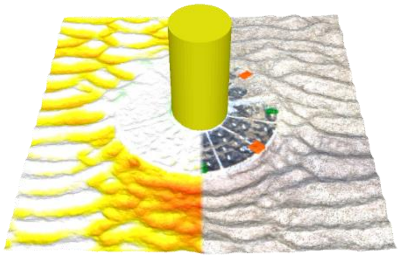


Figure 3.11 Stereophotography measurement of a ballast-filled mattress protection.

Recommendation for further research

Based on the performed test campaigns, future research could focus on estimating the required (field scale) bending stiffness of the mattress for the various scour protection applications; the bending stiffness is also related to the degree of filling. This would require systematic scour testing for realistic field conditions and validation with field data.

Further reading: Test reports on testing the Ballast-filled mattress stability and filling procedure (Deltares, 2019c, 2019e).

3.2.6 Innovative scour protection installation using self-installable frame

During the large-scale test programme in the Delta Flume, several installation tests were performed for ballast-filled mattresses and artificial vegetation using the self-installable frame developed by SPT Offshore. With the self-installable frame, a scour protection can be lowered to the seabed where it automatically unfolds to cover the soil and prevent scour. After installation, the self-installable frame is brought back to the surface to be reused.

The installation system consists of several winches on top of the monopile to control the movement of two rings with distance holders around the monopile. Hooks around the lower ring carry the scour protection system that is to be lowered to seabed. At the seabed, the mattresses automatically unhook such that the protection unfolds. The upper ring (which is not present in a real installation test), brings the scour protection back up to the waterline. To efficiently execute multiple tests, the flume was accessed with a boat to re-attach the protection to the hooks.

Figure 3.12 Monopile in the delta flume with the self-installable frame.

In close cooperation with SPT Offshore, installation tests were successfully performed under several operational wave conditions, showing a proof of concept for the system. During these tests, special attention was given to the lowering of the frame trough the water surface and the unfolding process at the seabed.

Based on the test results, further improvements can be made to the self-installable system, such as reducing the clearance between the rings and the monopile. For future research we recommend to further design and perform physical model testing to make the system ready to be applied offshore.

For further information the reader is referred to the test report about the scour protection installation tests (Deltares, 2019a)

Figure 3.13 First unfolding tests together with the JIP participants (left), accessing the flume with a boat to re-attach the scour protection (middle) and unfolded system in a drained flume (right).

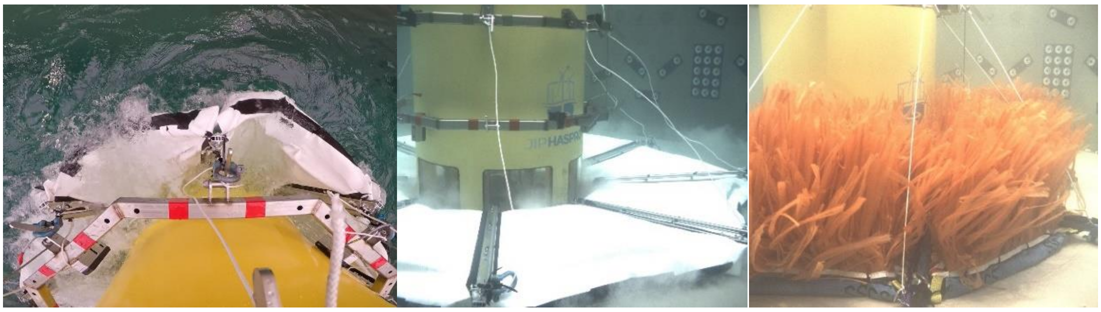


Figure 3.14 Lowering of the system through the water surface, system unfolding for ballast filled mattresses and artificial vegetation from an underwater view.

3.3 Eco-friendly scour protections

3.3.1 Introduction

When it comes to the environmental impacts of wind farms, most attention is usually paid on negative effects such as noise impacts on mammals and collision threat to seabirds. Recently, growing interest is also shown in possible positive environmental impacts of wind farms. The steel structures of offshore foundations together with the scour protections, introduce hard substrates which can act as habitats for marine species in otherwise sandy seabed areas, in which wind farms are commonly built for practical reasons. In addition, a wind farm acts as a protected marine area, due to the limitation of pressure activities like fishing. Scour protections have thus the potential to become successful artificial reefs and in some cases a key for the restoration of habitats of umbrella species, which have been lost in the past due to overexploitation, such as the flat oysters in the North Sea.

There are already numerous concepts of nature-inclusive design that are aimed at optimizing the ecological functioning of wind farms. These concern either adjustments to conventional scour protections consisting of loose rock (e.g., by integrating the so-called “ecologically-enhanced units” in their vicinity), or alternative eco-friendly scour protection concepts (e.g., gabions with packed shells and rock, and concrete block mattresses consisting of favorable material composition and surface texture). In JIP HaSPro many of those ecological concepts were tested for the first time with regards to their stability and interaction with the seabed and scour protections for typical offshore conditions. Furthermore, new concepts were developed and tested as a result of the cooperation between ecologists working across the offshore wind sector and participating in the project’s consortium.

Note that in JIP HaSPro only the technical aspects of eco-friendly scour protections are considered. It still has to be investigated in field experiments whether these scour protections will have the intended ecological effect. This is part of follow-up projects such as JIP ECO-FRIEND.

3.3.2 Artificial reef elements

Figure 3.15 Eco-friendly scour protections with various artificial reef elements tested in Delta Flume.

Working principle

Artificial reef structures typically consist of concrete reef elements (such as reef balls and pipes) that are 3d-printed or cast onshore and later deployed in the offshore environment. When integrated in a scour protection they have the potential of enhancing reef growth and biodiversity by providing structural complexity and shelter from flow for mobile species of various sizes (e.g., Atlantic Cod). Their dimensions and geometry are determined by the stability requirements and the size of the target species. For pilot studies, reef balls have already been deployed in wind farms (e.g., Luchterduinen) but not integrated in scour protections, to mitigate possible risks on erected infrastructure.

Test campaign

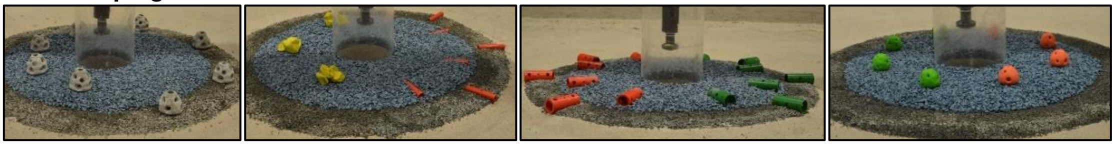


Figure 3.16 Eco-friendly scour protections with various artificial reef elements tested in Atlantic Basin.

In JIP HaSPro, several tests were performed at a medium and large scale (1:40 and 1:5) primarily focused on the stability of various artificial reef structures (reef balls, pipes, large rock clusters, and solid reef balls), when these are integrated in a reshaping scour protection both around a monopile and a cable. The tests covered a wide range of offshore environmental conditions -including a mobile seabed- and design parameters (e.g., unit dimensions, placement layout, and embedment depth).

Results and learnings

Based on these tests, indicative stability limits were produced for some of the most widely considered nature-inclusive design concepts. A general finding of the test campaign is that the stability of artificial elements significantly improves with increasing distance from a monopile face and in some cases with embedment depth in the scour protection rock. Additionally, this test campaign produced first insights on the related risks for the integrity of scour protections and the collision threats with offshore foundations. Based on stability and risk considerations, cable locations are deemed as the most favorable locations in a windfarm to integrate ecofriendly units in a scour protection.

Recommendation for further research

A next step is an in-depth research on the effects of artificial reef structures on the integrity of offshore infrastructure such as scour protections and steel foundations.

3.3.3 Introduction of calcareous material

Working principle

Some species are more likely to grow where materials that have specific favorable chemical properties exist. This is the case for the keynote umbrella species in the North Sea, European flat oysters (Ostrea edulis), whose larvae is known to preferably settle on chalk-rick hard substrates. Therefore, introducing loose shell material or limestone rock in the scour protections is deemed to have potential for supporting the life cycle of the species. Depending on the site conditions this can be combined with the provision of a kickstart oyster population e.g., by deploying oyster cages. There are numerous pilots in the North Sea, focusing on oyster reef restoration. Challenges for introducing shell material are related to sourcing, stability due to low weight and burial under sand waves and mega-ripples.

Figure 3.17 Eco-friendly scour protections with loose shell material tested in Delta Flume (fully covering a cable protection) and Atlantic Basin (installed in patches around a monopile) for JIP HaSPro.

Test campaign

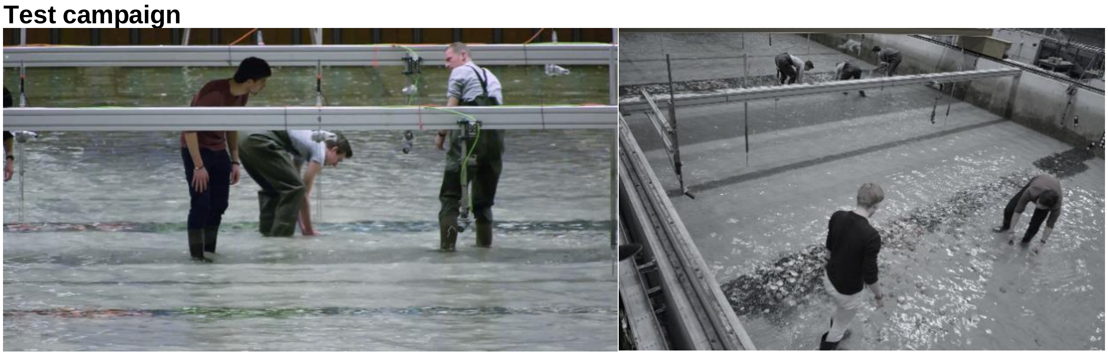


Figure 3.18 Restoring the various shell test sections in Atlantic Basin in preparation of a current-only test, after a wave test series is finished. Photographs are taken during a working session with participants of the JIP HaSPro consortium.

In JIP HaSPro, several tests were performed to assess the stability of shells for a wide range of offshore environmental conditions including waves, currents and a mobile seabed. The test campaigns additionally included various types and sizes of shell material, gabions with shells and even models of flat oysters prepared in the lab (see Figure 3.19). Shells were integrated in scour protections at both monopile and cable locations (see Figure 3.17), but also placed directly on the seabed. For most tests, instead of scaling down the shell dimensions, only the hydrodynamic conditions were scaled properly to allow for testing with the natural recycled shell material.

Figure 3.19 Preparation of shell material for the test campaign. Left to right: pictures show cleaning of empty shell material, painting and sorting of shells according to size and finally preparation of oyster models in the lab.

Results and learnings

Based on the results from the test campaign, insights are gained for the stability of various shell types and sizes. A general finding from this test campaign is that shell stability is likely to improve significantly when shells are sprinkled on the scour protection and have a comparable size with the underlying rock, as opposed to forming a separate top layer. This allows shells to “hide” from flow in the rock crevices but also remain present at the top layer where they can be accessible to species.

Recommendation for further research

Validation of test results against field data taken from pilot studies in North Sea.

Further reading: Test reports on Eco friendly scour protections tested in Delta Flume and Atlantic Basin (Deltares, 2019k, 2019l)

4 Software deliverables

4.1 Designing Delta Flume test setup using Virtual Reality

JIP HaSPro was the first project in which offshore scour protection tests were performed in the new Delta Flume, the world's largest wave flume. Since at this large scale test execution is rather costly and mistakes are more difficult to correct without causing significant delays and cost overruns in the project, it was decided to first develop the test setup in Virtual Reality. An already available 3D model of the Delta Flume served as the basis. Next, all considered test setups were constructed in the Delta Flume VR environment. Participants wearing VR glasses could "enter" the Delta Flume, while a test was being executed, which would obviously not have been possible in reality. The different test setups could then be selected, and potential issues could be noticed before materials were ordered and the actual models were constructed. The Virtual Delta Flume and the HaSPro test setups are not official HaSPro deliverables and can be used for demonstration purposes.

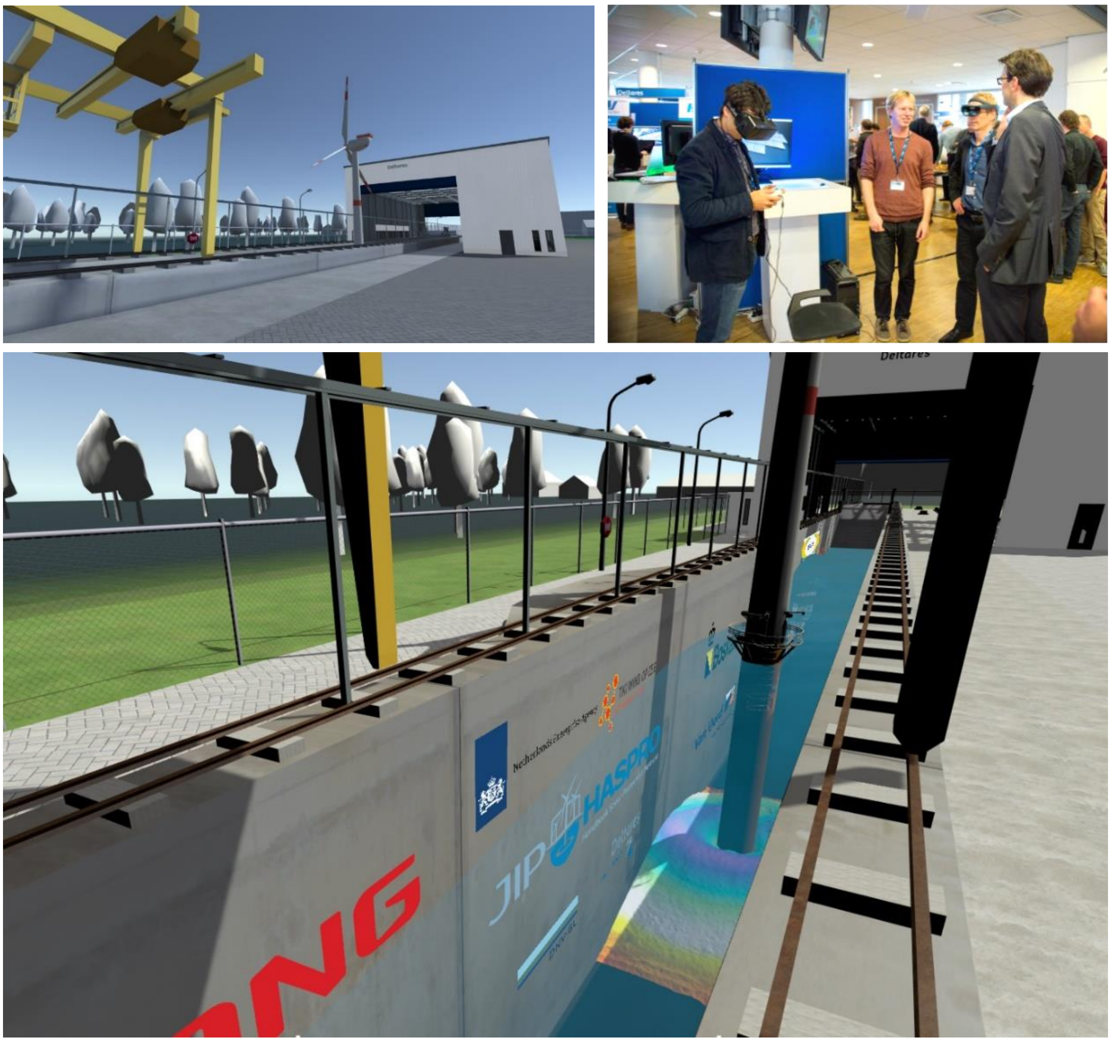


Figure 4.1 (Top left) Test setup in Delta Flume in Virtual Reality (wind turbine in real scale); (top right) project participants are exploring the test setup in VR; (bottom) monopile scale model with a scour protection on top of a sand wave (3D bathymetry measurement was scaled up from a small scale experiment).

4.2 3D Experimental Database Viewer

In all combined HaSPro test programmes hundreds of test results were obtained. Every individual test result consisted of a three-dimensional before and after measurement on a 1x1mm resolution. In order to make this extensive database available and easily accessible for all the participants, a 3D experimental database viewer was (further) developed. This software was programmed in C# by S&T Vision and is optimized for 3D visualisation of large datasets. The software allows for direct comparison between different tests and for exporting images. Some screen shots of this software are presented in Figure 4.2.

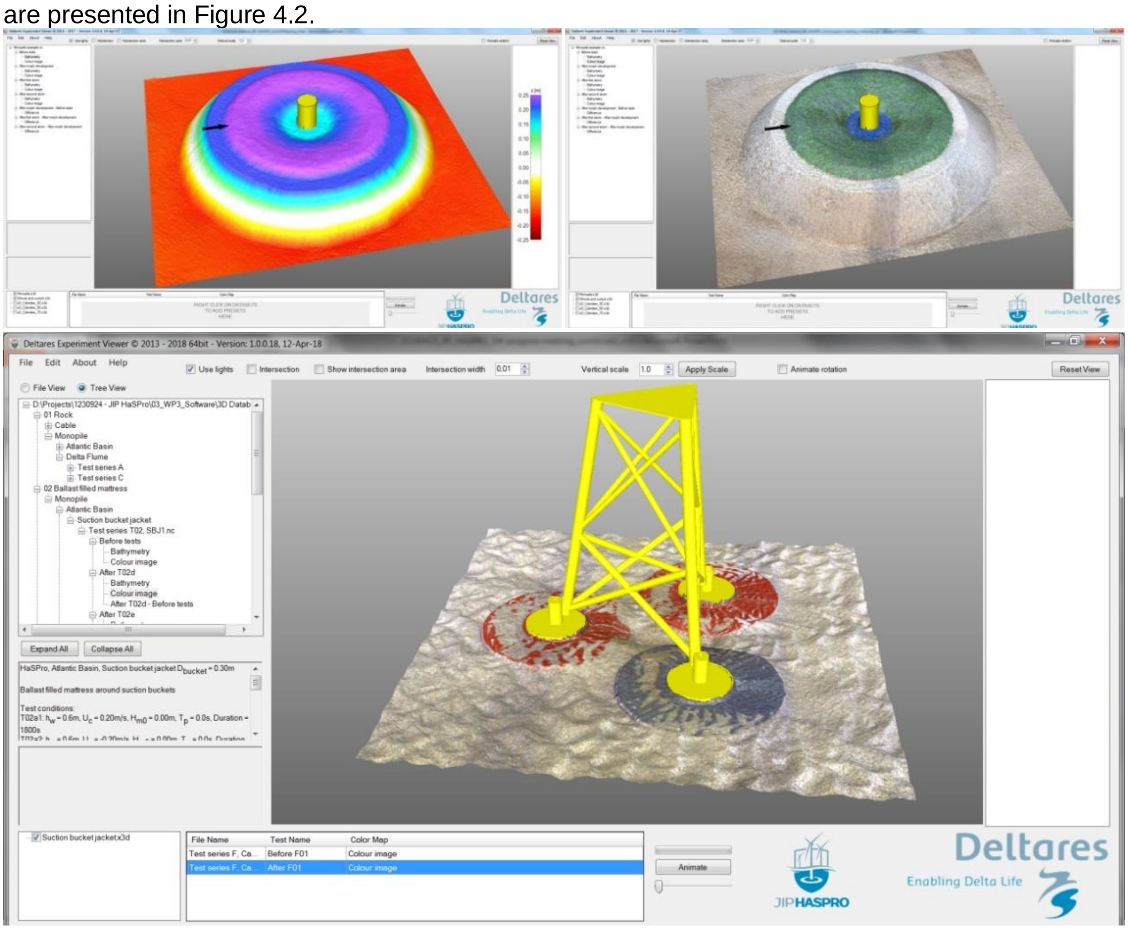


Figure 4.2 Screen shots of 3D Experimental Database Viewer: (top) a "before"-measurement of a test setup in which the interaction between a scour protection and a morphodynamic seabed was tested; (bottom) an "after"-measurement of a test with ballast-filled mattresses protecting a Suction Bucket Jacket against scour.

The Database Viewer is not an official HaSPro deliverable and is not protected by a confidentiality period or software license. Therefore, this software can also be made available to visualize 3D laboratory data that is obtained in other (consultancy / research) projects. The HaSPro database with 3D test results, however, is confidential.

Besides the "full" Database Viewer, also a smaller, portable version was developed which can be used on mobile phones as well as in Augmented Reality mode (see Figure 4.3). In this latter mode, a 3D test result can be shown right before you, for instance on your meeting table, allowing for direct discussion and interpretation of the test results.

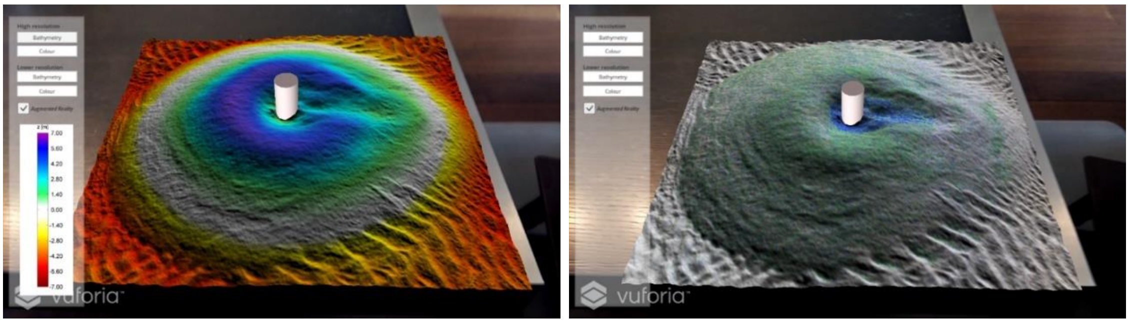


Figure 4.3 Visualizing test results using Augmented Reality allowing for interpretation of test results at the meeting table using only your mobile phone.

4.3 OSCAR – an Engineering Tool for Scour Protection Design

To allow for easy and validated application of the new knowledge on scour protection design gathered in this project, an existing engineering tool was extended for the use of offshore wind infrastructure. This software tool is “OSCAR, the Scour Manager”, which was developed for scour development around spud cans of jack-up drilling rigs (within the framework of JIP OSCAR). In JIP HaSPro scour protection design for monopiles and cable crossings was added to this software.

In OSCAR, all computations are based on empirical design formulae predicting scour and deformation patterns in scour protections. The software allows both for assessing individual events such as design storms and for assessing time series of boundary conditions, which can be used to investigate cumulative deformation due to e.g. sand wave migration and/or edge scour development and/or multiple subsequent storm occurrences. Computations for single conditions take no longer than a few seconds; for longer time series they may take up to a few minutes.

The OSCAR software tool takes the designer in 5 steps through the design process:

STEP 1: Input

1a: Structure & Soil

Available structures:

- Monopile: vertical cylindrical structure
- Pipeline or cable: horizontal cylindrical structure
- Three spud can designs for jack-up installation vessels (varying in shape)

1b: Hydrodynamics: waves and currents

Characteristics:

- Direct wave input or wind-induced wave growth
- Direct current input or schematized tidal currents
- Currents can be specified at different depths
- All hydrodynamic parameters have the option to import a time series instead of a single value

1c: Scour protection characteristics

Characteristics:

- Loose rock scour protections: single and double gradings
- Grading can be specified by rock sizes (D_{15}, D_{50} and D_{85}) and rock density
- Protection layout can be specified by extent, height and side slope for each protection layer

In Figure 4.4 two screen shots of the input menus are shown.

STEP 2: Hydrodynamics

- Hydrodynamic parameters, such as seabed mobility, Keulegan-Carpenter number, relative velocity etc, are computed and visualized
- Sensitivity analysis for variation in input parameters

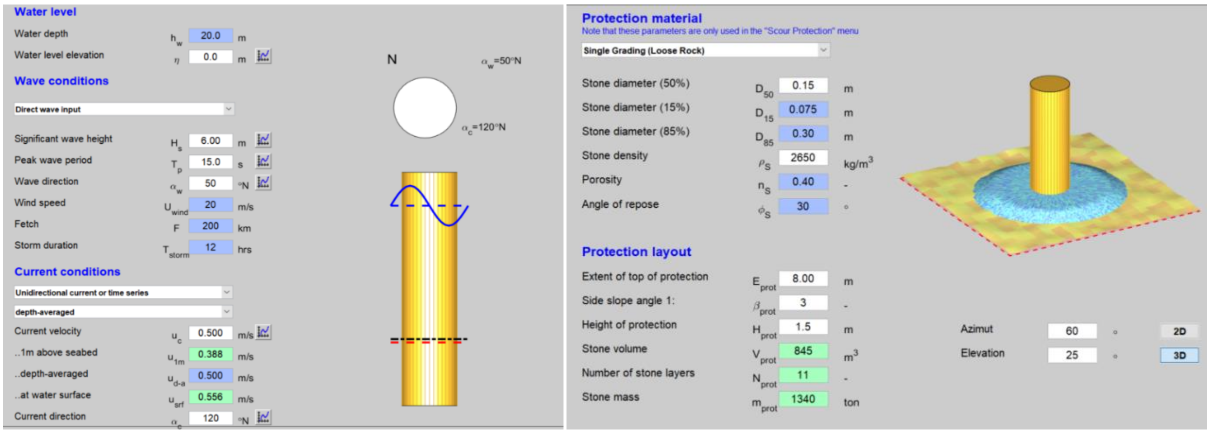


Figure 4.4 Two screen shots of the OSCAR scour protection design tool

STEP 3: Scour Prediction

- Scour parameters, such as equilibrium scour depths and characteristic time scales, are computed and visualized
- Sensitivity analysis for variation in input parameters
- Scour development in time is computed and visualized

STEP 4: Scour Protection

- Scour protection parameters, such as rock mobility, deformation volume and characteristic number of waves are computed and visualized
- Sensitivity analysis for variation in input parameters
- Deformation of the protection in time is computed and visualized

STEP 5: Output reports

- Overview lists of parameters and graphs can be selected for Steps 1 to 4
- Automated output reports can be generated in png- or pdf-format (see Figure 4.5 for an example of a part of the output report)
- These output reports can be added to design memo's

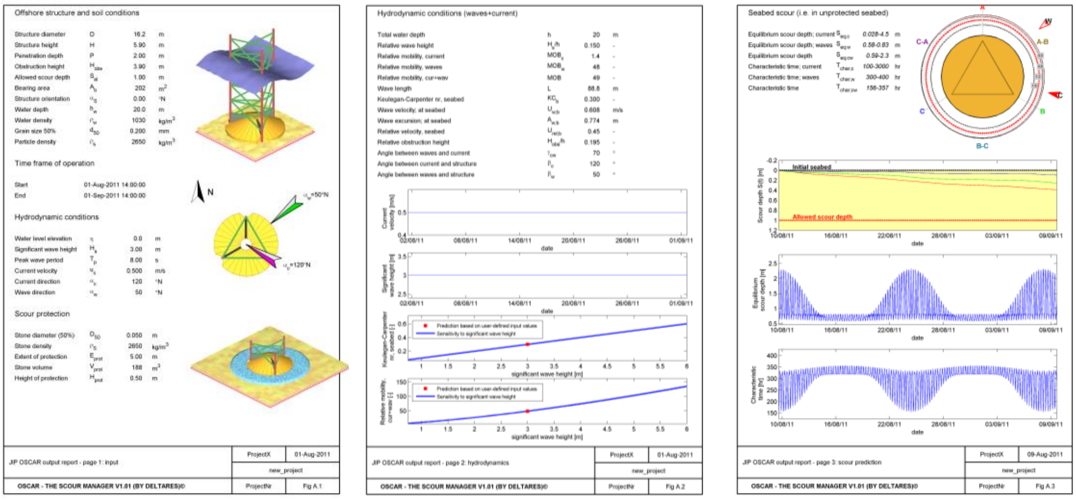


Figure 4.5 Example of (part of the) output report of the OSCAR engineering tool

The Engineering Tool remains exclusively available to HaSPro Consortium Members until 31 August 2021. In this period the software will be tested on the design of scour protections in real projects, bugs will be removed and required improvements will be made.

Further reading: User Manual OSCAR – Offshore Scour and Remedial Measures

5 Guidelines

5.1 Handbook Scour Protection Methods

In a joint effort, a digital handbook for scour and cable protections is being prepared together with all consortium partners. In this handbook, all obtained knowledge from this project is aggregated such that it can be used as a guideline to design, construct and maintain a scour protection. It starts with a description of the different scour mitigations strategies of which an example is included in Figure 5.1. The subsequent chapter will focus on the design of loose rock scour protections in which the knowledge from the loose rock scour protection tests is used.

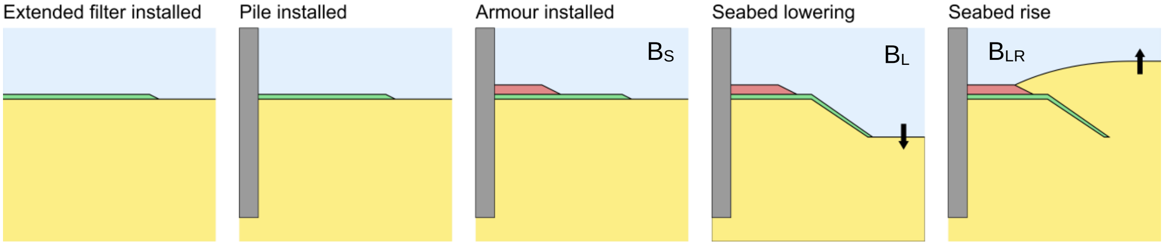


Figure 5.1 Example scour mitigation strategy showing the installation sequence and possible lowering or rising of the seabed during the lifetime.

Besides scour protection design, several other topics are dealt with in the handbook. Four handbook chapters were written by different workgroups in which input and experiences were shared between all consortium partners. These chapters cover the following topics:

- **Offshore rock gradings**: explaining different types of gradings, together with their specific requirements, testing methods and production process.
- **Installation of rock protections**: Covering the installation equipment and vessels, installation sequence, interfaces with for example cables, survey specifications and installation tolerances.
- **Operation and maintenance**: About when to survey your protection during the lifetime , how to deal with non-conformances to the design and several examples of surveys from the field.
- **Innovative scour protection systems**: Addressing the four alternative scour protection systems and the nature-inclusive designs, together with information about potential failure mechanism, design consideration, installation method and maintenance.

For further information the reader is referred to the handbook for scour and cable protections (JIP HaSPro, 2020)

5.2 Recommended Practice by DNV GL

At present, limited guidance on scour protection design is available in Standards or Recommended Practices. The well-known *DNV GL-ST-0126 Support Structures for Wind Turbines* contains 1 page on “*Scour and scour prevention for offshore structures*”, briefly addressing both the option to protect and not to protect the structure against scour.

The new Recommended Practice (RP) by DNV GL, developed in the framework of JIP HaSPro, presents a self-contained procedure for designing a site-specific scour protection around monopile foundations. Site specific design means that the design is based the local ocean design parameters (waves, current, tides etc) and local design seabed parameters (water depth, bathymetry activity, grain size etc).

The RP specifies general principles and methods for the design of riprap scour protections around offshore monopiles for wind turbines, to be used in combination to the referenced standards. The objectives of this recommended practice are to:

- provide an internationally acceptable set of recommendations that fulfil the requirements of the referenced standards for the design of a scour protection around offshore wind turbines;
- serve as a reference document between project stakeholders, to agree and align the methods for the design of the scour protection around offshore wind turbines;
- serve as a guideline for designers, suppliers, purchasers and regulators;
- specify procedures and methods for the analysis of scour protections subject to DNV GL certification

An important aspect in this RP is the definition of failure as the basis of a scour protection design. In many cases it is not specified how much lowering, erosion or deformation may be allowed, which is however required to design and evaluate a scour protection.

The table of contents are presented in Figure 5.2. The RP is aligned with other DNV GL RP.


PROPOSAL no.: 2019-xxx

Writing guidance:
Please use the DNV GL structure and style manual prepared by Rules and Standards.

RECOMMENDED PRACTICE

DNVGL-RP-0XXX

Design of Scour Protection around Monopiles

DECEMBER 2019

DRAFT

Chapters	Content
Chapter 1	Introduction
Chapter 2	Objective
Chapter 3	Scope and Application
Chapter 4	Codes
Chapter 5	References
Chapter 6	Definitions
Chapter 7	Site Conditions
Chapter 8	External Stability
Chapter 9	Internal Stability
Chapter 10	Scour protection width & height
Chapter 11	Survey
Chapter 12	Scour protection model tests
Chapter 13	Operation and Maintenance

Figure 5.2 Overview of contents of Recommended Practice by DNV GL.

5.3 Ecological Framework for nature-inclusive design

Wind farms and scour protection are placed in a natural environment that are considered to have an ecological value, and the associated hard substrate of scour protection typically attracts species due to the creation of a new habitat. From an ecological perspective, this can either be desirable or not, depending on the ecological developments resulting from the new hard substrate and the baseline ecosystem in place. In the upcoming tender requirements of wind farms in the Dutch North Sea there is requirement to consider and include nature in the design. In order to consider the interaction of scour protection with the natural environment from an early, in a way that is aimed to be beneficial for the natural surroundings, the ambition is to include nature into the consideration of the design of scour protection: “Nature Inclusive Design”. To this end an Ecological Framework for Nature Inclusive Design has been developed as part of JIP HaSPRo. The framework is aimed to help industry parties to optimally develop nature inclusive design in scour protection and include guidelines from relevant legislation and ecological considerations. Furthermore, it can aid national governments to further shape their existing legislation around requirements for ecology in wind farms, as well as the requirements for decommissioning.

The development of the framework was part of a participatory process, in which international stakeholders from scientific backgrounds, government and industry have come together to both discuss required components for a framework. This was done during 2 workshops, the first of which was aimed at developing ideas and an initial framework for nature inclusive design, and the second of which focused on the review of a draft framework and further considerations. Both the output from the workshops, as well as an in-depth literature review and review of existing policy and legislation have led to the development of an Ecological Framework for Nature Inclusive Design. Following the development of a wind farm from the design phase, to construction and operation and finally decommissioning, the framework describes the relevant legislation to consider, steps for execution of each phase and the resulting output of each phase. A simplified summary of the framework is provided in Figure 5.3.

Further reading: Ecological Framework of Nature-inclusive Design of Scour Protections.

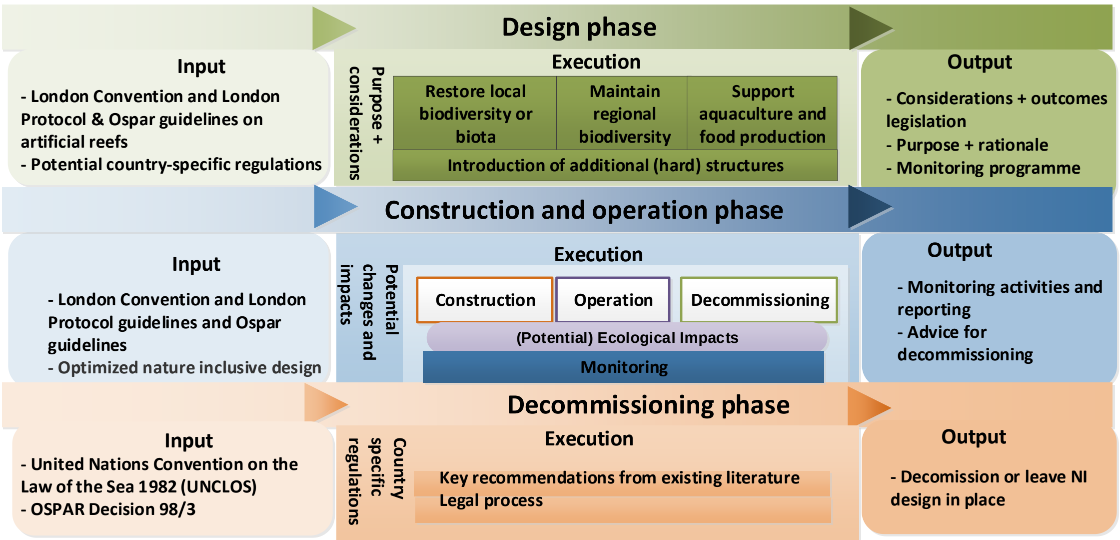


Figure 5.3 Schematized overview of the three phases and its components of the Ecological Framework

6 Project Deliverables

Deltares. (2019a). JIP HaSPro - Innovative scour protection installation tests using self-installable frame. Test specification and factual test results. Ref: 1230924-004-HYE-0011.

Deltares. (2019b). JIP HaSPro - WP2 Artificial vegatation. Test specification and test results. Ref: 1230924-004-HYE-0007.

Deltares. (2019c). *JIP HaSPro - WP2 Ballast-filled mattress. Test specification and test results. Ref: 1230924-004-HYE-0008.* Retrieved from

Deltares. (2019d). *JIP HaSPro - WP2 External stability loose rock scour protection. Test specification and test results. Ref: 1230924-003-HYE-0001.* Retrieved from

Deltares. (2019e). JIP HaSPro - WP2 Filling tests of ballast-filled mattress. Test specification and test results. Ref: 1230924-004-HYE-0009.

Deltares. (2019f). JIP HaSPro - WP2 Flexibility of loose rock scour protection. Test specification and test results. Ref: 1230924-003-HYE-0002.

Deltares. (2019g). *JIP HaSPro - WP2 Gabion mattress. Test specifications and test results. Ref: 1230924-004-HYE-0006.* Retrieved from

Deltares. (2019h). JIP HaSPro - WP2 Interface stability loose rock scour protection. Test specification and test results. Ref: 1230924-004-HYE-0003.

Deltares. (2019i). JIP HaSPro - WP5 Loose rock cable protection. Test specification and test results: Delta Flume test programme. Ref: 1230924-033-HYE-0001.

Deltares. (2019j). JIP HaSPro - WP5 Loose rock cable protections. Test specifications and test results: Atlantic Basin test programmes. Ref: 1230924-033-HYE-0002.

Deltares. (2019k). JIP HaSPro - WP6 Ecological Aspects - large-scale model tests. Test specification and test results. Ref: 1230924-037-HYE-0002.

Deltares. (2019l). JIP HaSPro - WP6 Ecological Aspects - Test specifications and factual test results: Atlantic Basin test programme. Ref: 1230924-037-HYE-0003.

Deltares. (2020). JIP HaSPro - WP2 Block mattress. Test specification and factual test results. Ref: 1230924-004-HYE-0010.

JIP HaSPro. (2020). Handbook Scour and Cable Protections.

Sumer, B. M., & Fredsøe, J. (2002). *The mechanics of scour in the marine environment*. Singapore: World Scientific.

Deltares is een onafhankelijk kennisinstituut voor toegepast onderzoek op het gebied van water en ondergrond. Wereldwijd werken we aan slimme oplossingen voor mens, milieu en maatschappij.

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