DIFIS Consortium Members

Project FP6-516360 "DIFIS"

Double Inverted Funnel for the Intervention on Ship wrecks

Publishable Final Activity Report

DIFIS Concept for the Removal of Oil from Ship Wrecks - Hydrodynamic Scale Model Tests for Operational, Survival and Offloading Conditions and System Deployment

Hans Cozijn
MARIN, Offshore Department
Wageningen, the Netherlands

ABSTRACT

DIFIS (Double Inverted Funnel for the Intervention on Ship wrecks) is a concept developed to recover hydrocarbons from ship wrecks, even in very large water depths. The DIFIS concept is shown schematically in the sketch below (Fig. 1).

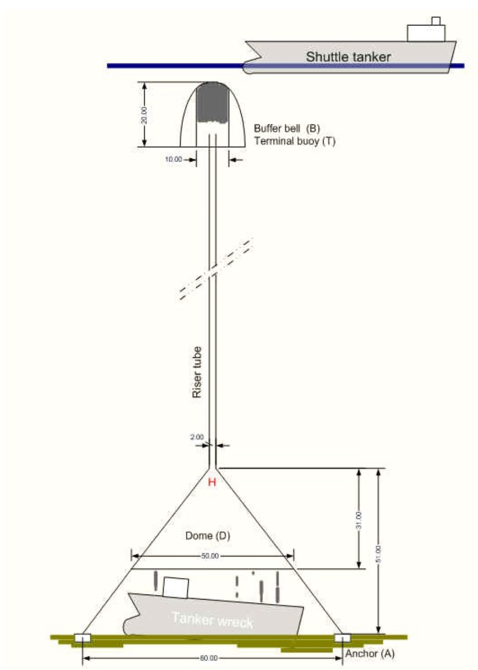


Fig. 1. Sketch of the DIFIS concept

The main components of the DIFIS system are the Dome, the Riser Tube and the Buffer Bell. The system is made of flexible and light components, enabling easy installation. It is completely passive and requires no intervention, except for inspection and periodic offloading of the collected oil. The DIFIS system is expected to be more effective and cost efficient than existing methods.

During the design of DIFIS, computer simulations and hydrodynamic scale model tests were carried out, investigating the system behaviour in operational and survival conditions, as well as during installation. An extensive series of model tests were carried out in MARIN's Offshore Basin, using unique modelling and measuring techniques. The results of these model tests are discussed in this paper.

More information on the DIFIS project can be found on the project web-site at http://www.difis.eu/.

KEY WORDS: oil removal; ship wreck; flexible structure; vortex induced vibrations; hydrodynamic scale model tests; system design; installation.

INTRODUCTION

DIFIS (Double Inverted Funnel for the Intervention on Ship wrecks) is a concept that was developed to recover hydrocarbons from ship wrecks, even in very large water depths. The concept consists of a Dome (to collect the trapped hydrocarbons from the wreck), a Riser Tube (to guide the collected oil towards the water surface) and a Buffer Bell (to collect and temporarily store the oil). The Dome is constructed of fabric material, while the Riser Tube is made of flexible pipe and high strength synthetic wire. The Buffer Bell is placed some 50 m below the water surface, where it is not affected by waves, and has sufficient buoyancy to tension the Riser Tube and to keep the entire system in its correct shape. Once it has been installed, the DIFIS system is completely passive and requires no further human intervention, except for inspection and periodic offloading of the collected oil. The DIFIS system is expected to be more effective and cost efficient than existing methods. Since the DIFIS system is designed to remain in place for a prolonged period of time, it needs to be capable of withstanding harsh environments. The DIFIS concept was also described by Andritsos et al. (2007) and Cozijn et al. (2008).

During the design process, computer simulations and scale model tests were performed to consider all necessary aspects. The focus of the present paper is on the unique series of hydrodynamic scale model tests that were carried out to investigate behaviour of the DIFIS system. The model tests were carried out in MARIN's Offshore Basin, in different environments of combined current, waves and wind. The scope of work included tests in operational and survival conditions, offloading tests, as well as system deployment tests.

In the following sections the working principle of the DIFIS concept is explained, the design of the main components is presented and the hydrodynamic scale model tests are discussed. Finally, some conclusions on the feasibility of the DIFIS concept are presented.

THE DIFIS CONCEPT

The DIFIS concept is a passive system to recover hydrocarbons from ship wrecks, even in very large water depths up to 4,000 m. It is a light and flexible structure, making it cost effective and relatively quick to install. The working principle of the concept relies on the hydrocarbons being lighter than water. The main components of the DIFIS concept are the Dome, the Riser Tube and the Buffer Bell.

The Dome is constructed of a fabric material, with a coating to repel oil. It covers the wreck and it is designed to collect the hydrocarbons leaking from the wreck and prevent them from escaping into open water. The Riser Tube is made of flexible PE pipe, combined with high strength synthetic wires. The purpose of the Riser Tube is to guide the oil and water mixture towards the water surface. The Buffer Bell is designed to collect and temporarily store the oil. It also acts as a separator, allowing water to flow out through its open bottom. The Buffer Bell is placed approximately 50 m below the water surface, where it is not affected by waves. It has sufficient buoyancy to tension the Riser Tube and to keep the entire system, including the Dome, in its correct shape. The Buffer Bell buoyancy also provides horizontal stiffness, to avoid excessive Buffer Bell offsets, caused by current.

SYSTEM DESIGN

In the following sections the main components of the DIFIS system are presented. The properties of the Dome, the Riser Tube and the Buffer Bell, as determined in the final design of the system, are discussed here.

Dome

In Fig. 2 below the lay-out of the Dome is shown. The image shows the 12 anchor blocks, to which Dyneema lines are connected. These lines are connected to the Dome Interface, which is shown in Fig. 3. The purpose of the Dome Interface is to connect the Dome and the Riser Tube and to transfer the axial tension in the Riser Tube to the mooring lines connected to the anchor points. The pre-tensioned mooring lines keep the fabric of the Dome in the correct conical shape.

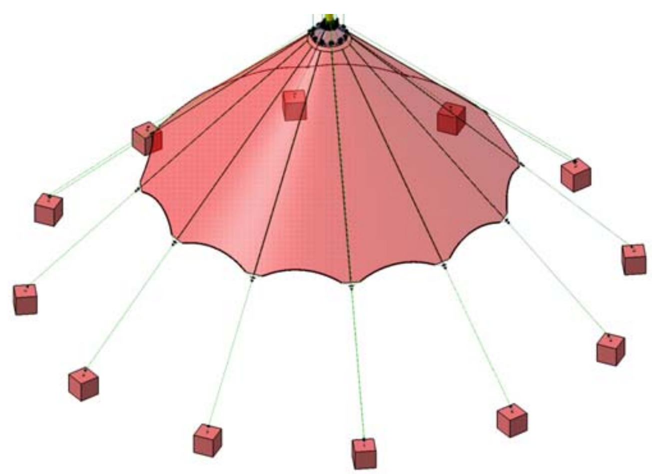


Fig. 2. Dome with anchor points

It is noted that the Dome Interface is a relatively heavy component in the DIFIS system, due to the magnitude of the transferred load. During the design of the DIFIS system Riser Tube pretensions between 1,000 and 2,000 tonnes were considered.

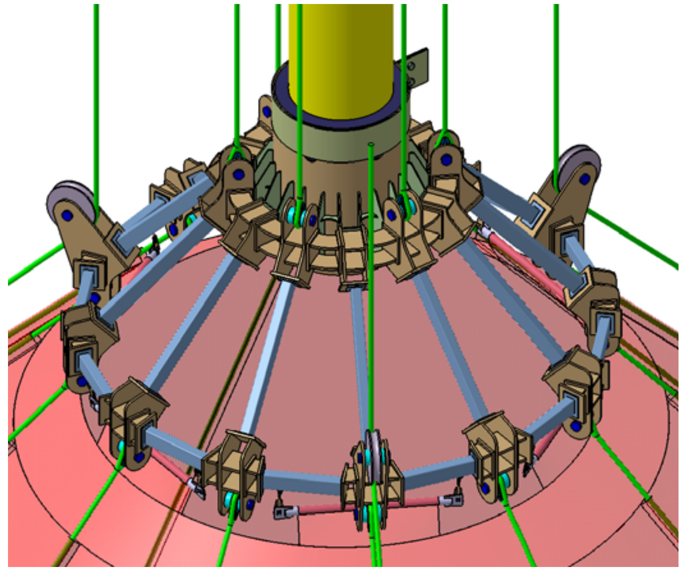


Fig. 3. Dome Interface, connecting the Dome and Riser Tube

The dimensions of the Dome are summarised in Table 1 below. The diameter of the Dome is sufficient to cover a significant section of the ship wreck. Larger diameters were considered during the design of the system, but practical considerations of the manufacturing process of the fabric Dome limit the diameter to a maximum of approximately 100 m.

Table 1. Dome main particulars

Designation	Unit	Magnitude
Dome height H	m	52.5
Distance above sea bed	m	40
Diameter D (at bottom)	m	105
Diameter D (at anchors)	m	185
Number of mooring lines	---	12

Riser Tube

The Riser Tube is manufactured of PE pipe sections and steel connectors. The PE pipe sections are slightly buoyant, but combined with the connectors a neutrally buoyant Riser Tube is constructed. The properties of the Riser Tube are listed in Table 2 below.

Table 2. Riser Tube main particulars

Designation	Unit	Magnitude
Diameter D	m	2.0
Section length L	m	50
Pipe mass M (per 50 m section)	tonnes	22
Pipe underwater weight (per section)	tonnes	-2
Number of axial lines	---	6
Axial stiffness EA	kN	2.0+E6

A length of Riser Tube is shown in Fig. 4, while Fig. 5 shows an example of a connector. The flange inside the steel connector, enabling the PE pipes to be stacked on top of each other, is also shown.

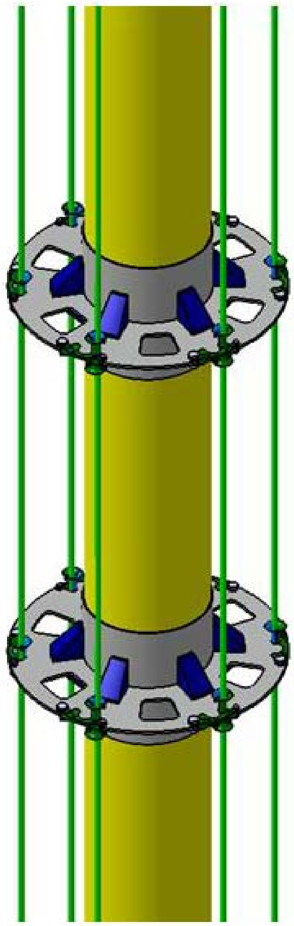


Fig. 4. Riser Tube section

It is noted that the PE pipe sections and steel connectors are stacked on top of each other and are not otherwise connected. The 6 Dyneema lines, placed around the pipe, carry the axial tension in the Riser Tube. In mechanical terms, these lines are therefore the connection between the Dome and the Buffer Bell.

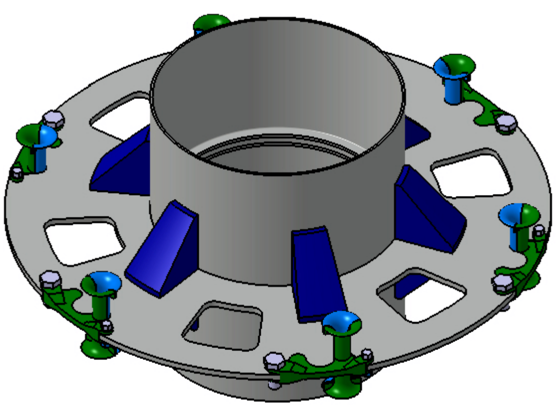


Fig. 5. Riser Tube steel connector

Buffer Bell

The lower part of the Buffer Bell is a steel ring, consisting of a number of box sections in an octagonal shape. This ring is designed to withstand the hydrostatic pressure and provides most of the Buffer Bell. The storage volume is covered by fabric material, similar to the Dome. Since this volume may be (partly) filled with oil, it also contributes to the buoyancy of the Buffer Bell. The shape of the Buffer Bell is shown in Fig. 6.

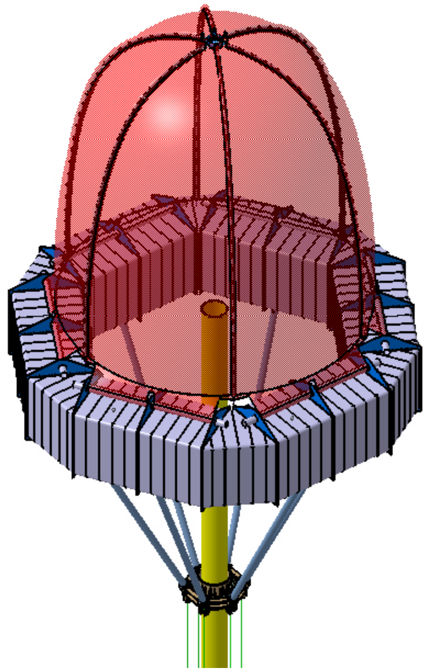


Fig. 6. Buffer Bell

The dimensions of the Buffer Bell are shown in Table 3 below. Different Buffer Bell sizes were considered, but a large Buffer Bell was found to be beneficial both in terms of operational cost (fewer offloading operations required) and system design (large buoyancy results in higher mean Riser Tube tension and a more stable system configuration.

Table 3. Buffer Bell main particulars

Designation	**Unit**	**Magnitude**
Height H	m	23
Diameter D	m	21
Maximum storage capacity V	m^3	6,250
Minimum buoyancy (full, heaviest oil)	tonnes	1,350
Maximum buoyancy (full, lightest oil)	tonnes	3,000

SYSTEM DEPLOYMENT

The development of the installation procedures and the design of the DIFIS components were closely linked. The specifications for the system design originated not only from the operational requirements, such as wreck size water depth, current conditions and wave conditions, but also from the developed deployment procedures. The shape and functions of the Dome Interface and the Riser Tube steel connectors, for example, were largely determined by the proposed installation method. In this section the step-by-step DIFIS deployment procedure is presented. The aim is not to give an in depth description, but rather to clarify the main steps in the installation procedure as background information to the hydrodynamic scale model tests discussed in the following sections.

In the system deployment of DIFIS the following steps are made.

1. Site survey - After localising the ship wreck the site is investigated using an ROV. The local water depth, bottom geometry, soil properties and current conditions are determined.

2. Placement of the anchor blocks - The (12) concrete anchor blocks are placed on the bottom using a work vessel with either a crane or a winch of sufficient capacity.

3. Launching of the Dome - The folded Dome (with Dome Interface) is transported on a barge. It is lowered into the water and brought alongside an Installation Vessel. Here it is connected to the (6) Dyneema lines and the first section of the Riser Tube.

4. Construction and lowering of Riser Tube - The Riser Tube is built section by section, each time placing a steel connector on top of the previous pipe section, after which another pipe section is added. As the length of the Riser Tube increases, the folded Dome is gradually lowered until it is close to the Ship Wreck.

5. Unfolding of the Dome - The Dome is unfolded using a set of Lifting Bags, connected to the Mooring Lines. The Lifting Bags are simultaneously released, after which they pull open the folded Dome. This is shown in Figure 7 below.

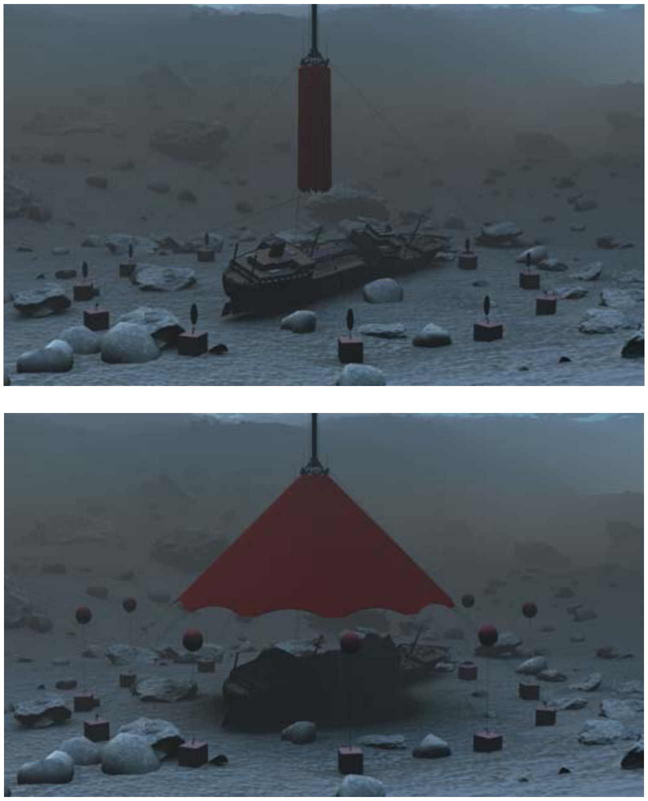


Fig. 7. Unfolding of the Dome above the Ship Wreck

6. Installation of the Buffer Bell - After the Buffer Bell is connected to the Riser Tube it is de-ballasted to provide sufficient top tension to the system. Finally, the system is disconnected from the Installation Vessel.

7. Periodical offloading and inspections - Once installed the DIFIS system is completely passive and requires no human operator. Offloading operations are scheduled and periodic inspections take place to ensure the integrity of the system.

HYDRODYNAMIC SCALE MODEL TESTS

Model tests were carried out at a scale of 1:60 in MARIN's Offshore Basin, which has state-of-the-art capabilities for modelling of current, waves and wind. The basin measures approximately 40 x 36 m, with an adjustable water depth to a maximum of 10.2 m. The basin properties are discussed in detail by Buchner, Wichers and de Wilde (1999).

Test Set-up and Scale Models

The DIFIS system, being a large and flexible structure, resulted in a unique test set-up in the Offshore Basin. Figure 8 shows an underwater photograph of the test set-up used in the Operational Tests, Survival Tests and Offloading Tests.

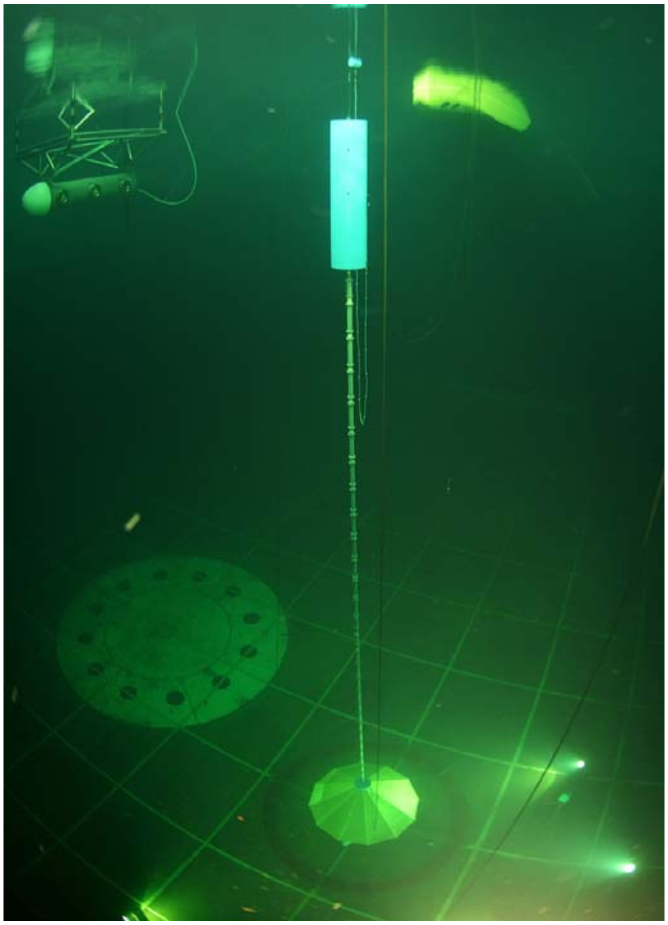


Fig. 8. Test set-up in MARIN's Offshore Basin

The photograph shows the Dome model near the basin bottom, at a depth of 10.2 m, the Riser Tube model of more than 5 m length and the

Buffer Bell model, which (according to the DIFIS system preliminary design) still had a cylindrical shape. At the water surface the hull of the DP Shuttle Tanker for offloading can be seen.

The following models were constructed at a scale of 1:60.

- Dome
- Dome Interface
- Riser Tube
- Buffer Bell, including Offloading Hose and Surface Buoy
- DP Shuttle Tanker
- Installation Vessel
- Lifting Bags

The properties of the above components, as determined in the system preliminary design, were accurately represented at model scale, both in terms of geometry and in terms of inertia and mechanical properties.

Instrumentation

During the model tests motions, loads, accelerations and thruster RPMs were measured, using different types of instrumentation. The motions of the ship models were measured by an optical motion measurement system (Krypton), which uses a set of infra-red diodes on the model and 3 cameras in a housing on the basin carriage. With this contactless measurement system accuracies of better than +/- 0.5 mm or +/- 0.1 deg can be achieved. The motions of the Buffer Bell were measured using a special version of the same system, dedicated for underwater measurements. The underwater photograph in Fig. 9 shows the Buffer Bell model with diodes and the top of the Riser Tube (left), as well as the underwater housing for the 3 measurement cameras (right).

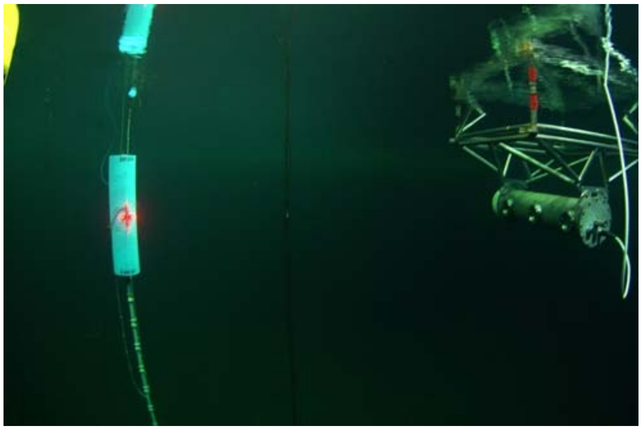


Fig. 9. Buffer Bell with underwater motion measurement system

Tensions in the Mooring Lines and Offloading Hose were measured using ring-shaped strange-gauge transducers. In addition, the tension in the Riser Tube was measured at 3 locations, using strain-gauge transducers. Accelerations on the ship models and at the Dome Interface were measured using piezo-type accelerometers. Finally, the DP Shuttle Tanker thruster RPMs were measured using pulse counters.

Environmental Conditions

In hydrodynamic scale model tests for deep water, an accurate modelling of the environmental conditions is essential, as indicated by Buchner, Cozijn, van Dijk and Wichers (2001). The loads resulting from current, waves and wind, and the system response to those loads, are important factors in the design. The environmental conditions considered in the DIFIS project were described in the system functional specifications, see Andritsos et al. (2007), and represented conditions in different relevant locations in European waters.

In the model tests described here the current modelling is particularly important, since the entire DIFIS structure is below the water. In the Offshore Basin a current profile, representative of the current conditions at the location of the Prestige wreck, was modelled. In addition, also higher and lower current velocities were calibrated. In Fig. 10 an example of one of the calibrated current profiles is shown.

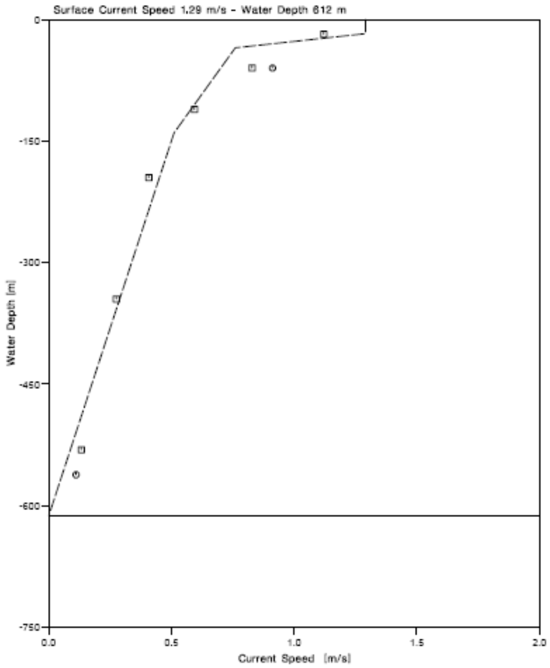


Fig. 10. Example of a calibrated current profile

Another important aspect was the effect of waves (especially long period swells) on the motions of the Buffer Bell. In Fig. 11 an example of one of the calibrated wave spectra is shown.

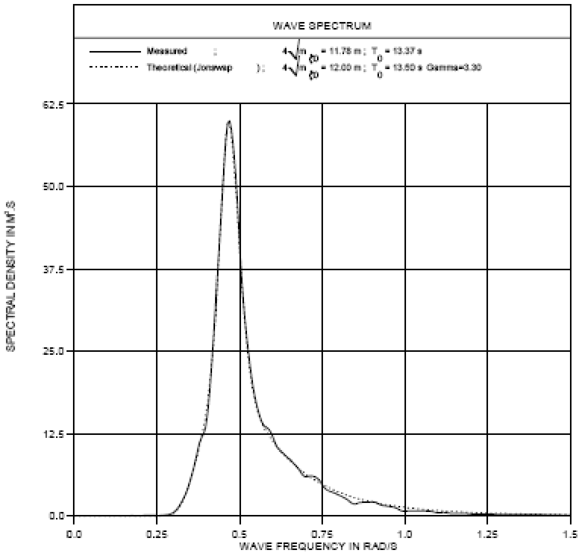


Fig. 11. Example of a calibrated wave spectrum

In the Offloading Tests and Deployment Tests the focus was more on the waves and wind, since these result in motions of the DP Shuttle Tanker and the Installation Vessel.

Operational and Survival Tests

The test programme for the Operational Tests and Survival Tests included tests in current only, to investigate the system VIV response, as well as tests in combined current and waves, to determine the system motions and loads.

VIV Response The Buffer Bell model used in the hydrodynamic scale model tests had a cylindrical shape, which corresponded to the preliminary design of the DIFIS system. Current flowing past the Buffer Bell will cause alternating vortices to shed from the back of the cylinder, resulting in an oscillating transverse force. The shedding frequency depends on the velocity of the current. The large transverse oscillating motions occurring when the shedding frequency is near the natural frequency of the structure are called Vortex Induced Vibrations (VIV) or Vortex Induced Motions (VIM). As described in detail by de Wilde (2007) and Liu, Cheng, de Wilde, Burke and Lambrakos (2009) for free standing risers, the VIV response is generally presented using the reduced velocity U_r, which is defined in Eq. 1 below.

$$U_r = U / T \cdot D \quad (1)$$

In which U is the velocity of the incoming current, T is the natural period of the transverse motion and D is the Buffer Bell diameter. In Fig. 12 the (dimensionless) VIV response of the Buffer Bell A/D is plotted as a function of the reduced velocity U_r.

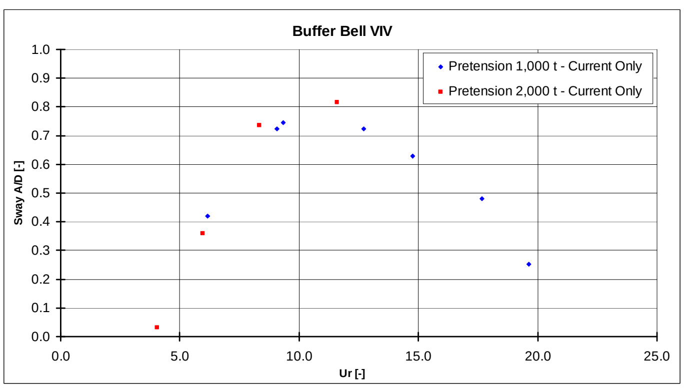


Fig. 12. Buffer Bell VIV response in current only (Ur vs. A/D)

The above graph shows different U_r ranges for the Buffer Bell with 1,000 tonnes buoyancy (blue) and 2,000 tonnes buoyancy (red), because the same range of current velocities U was used, but the natural period T is different for both cases. The results show little or no VIV response for U_r < 5 and U_r >20. The maximum response is found around U_r = 10, indicating a response at oscillation mode 1 with possibly higher modes participating, see also de Wilde (2007).

Motion Response in Waves Although the Buffer Bell is located some 30 m below the water surface, long-period swells may still affect the structure. In the model tests environmental conditions of combined current and waves were considered, including survival conditions with long period swells. The Buffer Bell motions measured in the tests were presented in the form of motions RAOs and Buffer Bell contour plots. An example of such a contour plot in the xz-plane, plotted every 120 seconds Buffer Bell in survival conditions (H_s = 12.0 m, T_p = 13.5 s) is shown in Fig. 13.

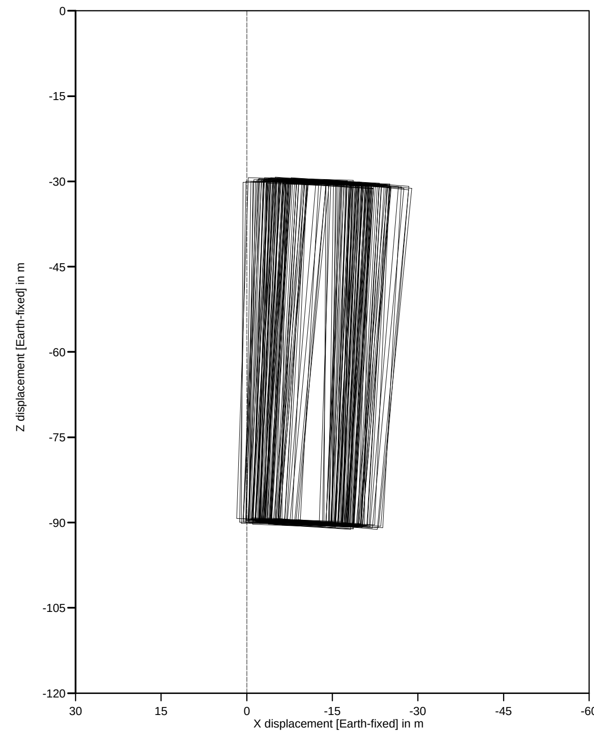


Fig. 13. Buffer Bell contour plot (side view) in survival conditions

In the model tests with the 1,000 tonnes buoyancy Buffer Bell larger tension variation were observed in the Riser Tube, compared to the 2,000 tonnes buoyancy cases. In a few cases the Riser Tube was close to compression, indicating that a 2,000 tonnes Buffer Bell buoyancy is to be preferred. Furthermore, it was noted that the relatively high axial tension of the Buffer Bell, causes the Buffer Bell vertical motions to be largely transferred to the Dome Interface, causing tension variations in the Mooring Lines of the Dome.

Offloading Tests

The offloading operation is only foreseen in operational environments, since a Shuttle Tanker will not be able to connect to the Buffer Bell in survival conditions. The test programme for the Offloading Tests therefore included operational conditions of combined current, waves and wind. In the Offloading Tests a DP Shuttle Tanker model, which is shown on the photograph in Fig. 14, was included in the test set-up.

Fig. 14. DP Shuttle Tanker model M8649

The Shuttle Tanker model was equipped with a DP system, enabling it to maintain its own position using two main propellers and rudders and two bow tunnel thrusters. Its only connection to the Buffer Bell is through an Offloading Hose, which is used for transfer of the stored hydrocarbons. It is noted that the Shuttle Tanker is not moored to the Buffer Bell or to the seabed.

The results of the Offloading Tests included measured motions of the Shuttle Tanker and Buffer Bell, as well as tensions in the Riser Tube and Mooring Lines. Also the tension in the Offloading Hose was measured. In addition, top view contour plots (plotted every 120 s) of the Shuttle Tanker and Buffer Bell were made. An example of these plots is shown in Fig. 15 below.

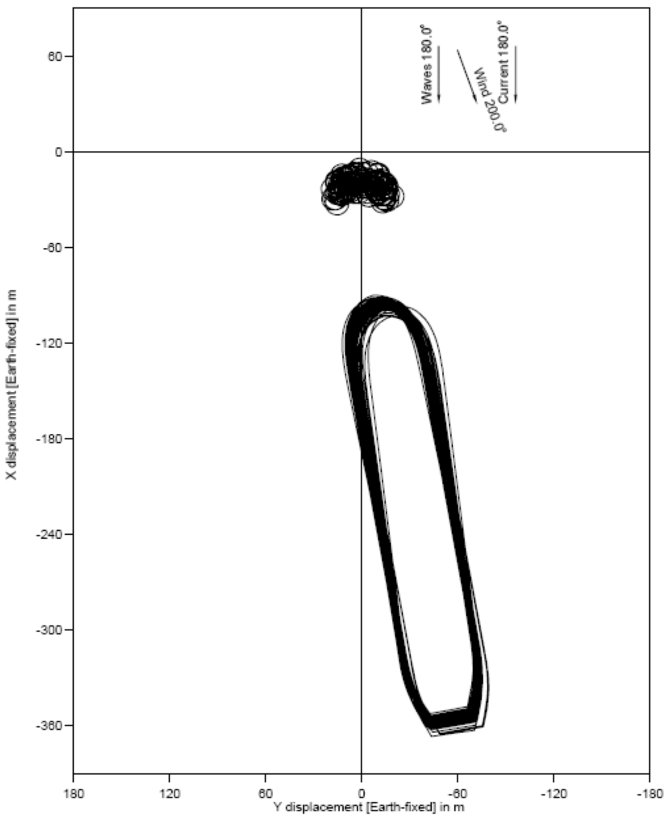


Fig. 15. Example DIFIS and DP Shuttle Tanker top view contour plot

The results of the Offloading Tests showed that the performance of the DIFIS system was not affected by the presence of the Shuttle Tanker. The motions of the Buffer Bell and the tension in the Riser Tube and Mooring Lines were the same as in the tests without Shuttle Tanker.

Deployment Tests

The test programme for the Deployment Tests included stationary tests and dynamic tests. The purpose of the Stationary Tests was to obtain reliable statistic data of certain specific phases in the installation process. The objective of the Dynamic Tests was to test the mechanical process of the actual unfolding of the Dome.

Stationary Tests The stationary tests concerned 3 hour tests modelling a number of specific stages of the deployment process. An example of such a test set-up is shown in Fig. 16.

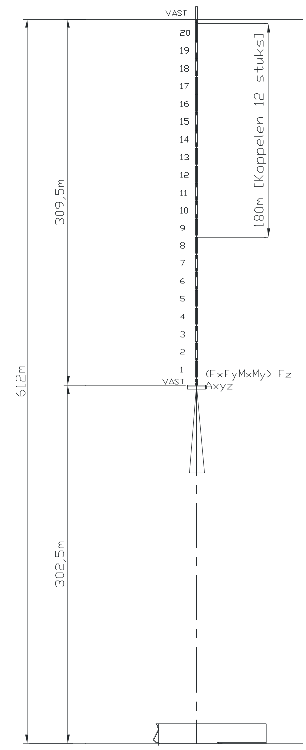


Fig. 16. Test set-up for the Deployment Tests (stationary)

During the stationary tests was statistically reliable data was collected of a number of different intermediate steps in the installation process. The data included Dome Interface motions and Riser Tube tension variations, as well as motions of the Installation Vessel. Furthermore, the tests were intended to confirm the feasibility of the DIFIS system deployment. The results showed no unexpected or instable behaviour during any of the investigated steps. Furthermore, the load variations in Riser Tube and Installation Wires were relatively small during system deployment.

Dynamic Tests During the dynamic deployment tests the Dome was unfolded (under water) by opening the remote-controlled release mechanism, after which the Lifting Bags were free to pull on the Mooring Lines. The Dome correctly unfolds, both in calm water conditions and in current. The unfolding sequence is shown in the photographs in Fig. 17 on the last page of this paper, which are stills from the underwater video recordings made during the tests. In addition, the test scope included tests in damaged conditions, in which it was shown that with 1 or 2 Lifting Bags failing the Dome could still be unfolded.

FUTURE DEVELOPMENTS OF THE DIFIS CONCEPT

During the DIFIS project the first ideas of the concept were developed into a complete design of the system, included engineering of all components and calculation of cost, as well as the development and scheduling of the deployment and operational procedures. Part of the work performed is presented in this paper.

With the DIFIS design ready, the next step would be the development of a proto-type and its application in a pilot project. This next step will give important information on practical application of the DIFIS concept. At this moment, plans are made to initiate a follow-up project to consider these aspects.

CONCLUSIONS

The scope of work of the DIFIS model tests in MARIN's Offshore Basin included Survival Tests, Operational Tests, Offloading Tests and Deployment Tests. Based on the results of these model tests the following conclusions were drawn.

Survival and Operational Tests

1. The overall behaviour of the DIFIS system in operational and survival conditions meets the expectations; the concept appears to be feasible. No unexpected or instable behaviour was observed in the operational and survival conditions.

2. In current the Dome shape remains intact. Only minor deformations of the Dome can be observed.

3. The Buffer Bell motions are limited, both in operational and survival conditions. This confirms that the Buffer Bell is sufficiently far below the water surface.

4. In waves, the tension in the mooring lines of the Dome showed larger variations than expected. This aspect needs to be addressed in the final design of the system.

5. For further evaluation of the DIFIS system in operational and survival conditions an extrapolation of model test results (in a water depth of 612 m) to actual water depths of up to 4,000 m is required.

Offloading Tests

6. The overall behaviour of the DIFIS system during offloading meets the expectations; the offloading operation is feasible.

7. The presence of the DP Shuttle Tanker does not influence the performance of the DIFIS system. The Buffer Bell and Riser Tube are not affected.

Deployment Tests

8. The overall behaviour of the DIFIS system during the deployment meets the expectations; the investigated stages of deployment are feasible. No unexpected or instable behaviour was observed during the stationary tests.

9. The dynamic deployment tests showed that the Dome correctly unfolds, both in calm water conditions and in current.

10. For further evaluation of the DIFIS system deployment an extrapolation of model test results (in a water depth of 612 m) to actual water depths of up to 4,000 m is required.

ACKNOWLEDGEMENTS

The design and development of the DIFIS system, including its deployment procedures and cost calculations, were carried out in Project FP6-516360 "DIFIS", which was partly funded by the European Commission. The contribution from the EC is greatly acknowledged. In addition, the author would like to thank all project partners (being MARIN, SENER, Ifremer, CEA-List, Cybernetix, Sirehna, ISI and Consultrans) for their contributions to the DIFIS project and the material provided to prepare this paper.

REFERENCES

Andritsos, Fivos (JRC), Konstantinopoulos, Panagiotis A, Charatsis, Konstantinos J. (ISI), Derdas, Christos, Mazarakos, Dimitris and Kostopoulos, Vassilis (Patras University), "Recuperation of Oil Trapped in Ship-Wrecks: the DIFIS Concept", *International Symposium on Maritime Safety, Security and Environmental Protection*, SSE 2007, Athens, Greece.

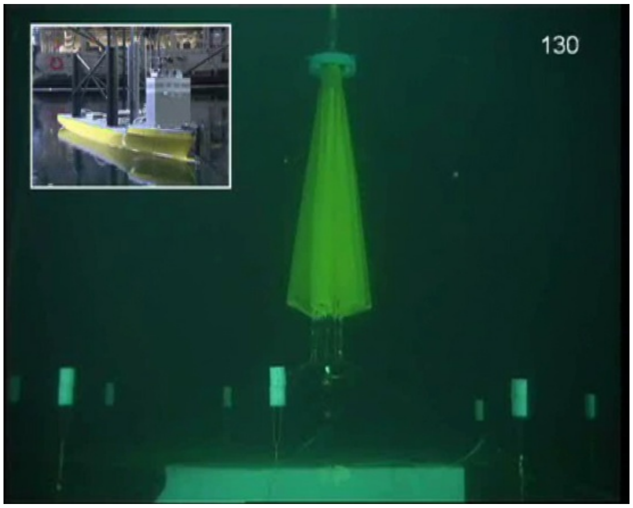
Buchner, Bas, Cozijn, Hans, van Dijk, Radboud and Wichers, Johan (MARIN), "Important Environmental Modelling Aspects for Ultra Deep Water Model Tests", *Deep Offshore Technology Conference*, DOT 2001, Rio de Janeiro, Brazil.

Buchner, B., Wichers, J.E.W. and de Wilde, J.J. (MARIN), "Features of the State-of-the-art Deepwater Offshore Basin", *Offshore Technology Conference*, OTC1999-10841, Houston, TX.

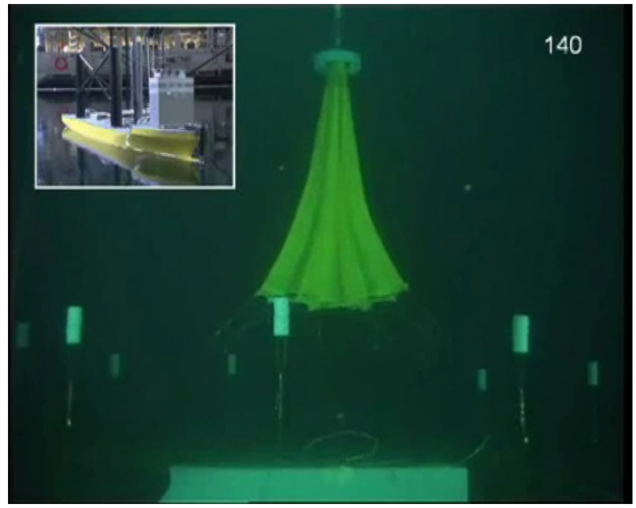
Cozijn, J.L. (MARIN), Andritsos, F. (JRC), Konstantinopoulos, P.A., Charatsis, K. J., Derdas, C., Mazarakos, D. Kostopoulos, V., (ISI), Hoornstra, D., Arnedo Pena, A. Candini, L., Ametler, S. (SENER), Fidani, A., Castex, A., Delauze, M. (Cybernetix), Drogou, J.F., Lévèque, J.P., Davies, P. (Ifremer), C.Montandon, C. Geffard, F. (CEA-List), Pecot, F. (Sirehna), Estrada, V. (Consultrans), " Recovery of Oil Trapped in Ship-Wrecks: the DIFIS Concept", *International Oil Spill Conference*, IOSC 2008, Savannah, GA.

Liu, Nicole, Cheng, Yongming (Technip), de Wilde, Jaap (MARIN), Burke, Roger and Lambrakos, Kostas F.(Technip), "Time Domain VIV Analysis of a Free Standing Hybrid Riser", *Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering*, OMAE 2009, Honolulu, HI.

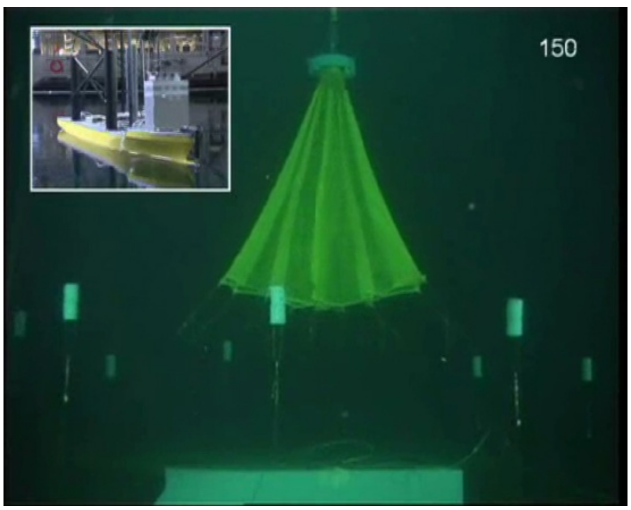
Wilde, J.J. de (MARIN), “Model Tests on the Vortex Induced Motions of the Air Can of a Free Standing Riser System in Current”, *Deep Offshore Technology Conference*, DOT 2007, Stavanger, Norway.



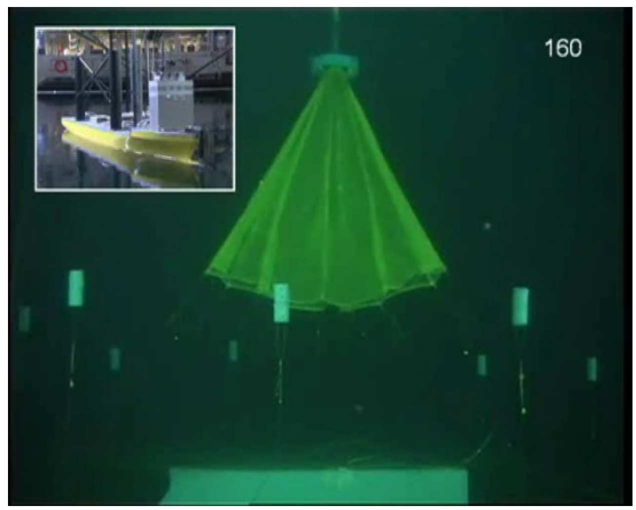
T = 130 s



T = 140 s



T = 150 s



T = 160 s

Fig. 17. Still images from the video recordings made during the Deployment Tests (dynamic tests)