Challenges in Deep Water Experiments: Hybrid Approach

An overview of challenges within hydrodynamic verification of deep-water offshore structures is given first. The role of model testing in the verification, as well as a range of relevant measured responses, are discussed. Various solutions for experimental verification of deep-water structures are considered. In particular, the combination of model tests with truncated set-up and computer simulations—the hybrid approach—is discussed. Two basic groups of hybrid methods are identified: Active (on-line) and passive (off-line). Most published works are on passive systems, of which a particular method is described. Case study examples with this procedure are reviewed and discussed, and future challenges are commented. [DOI: 10.1115/1.1464129]

Introduction

The oil industry is now increasingly concentrating their efforts and activities in connection with developing fields in deeper waters, ranging typically from 1000 m–3000 m. Such fields are presently located in various parts of the world, including the Gulf of Mexico, Brazil, West of Africa, as well as the North Atlantic/ Norwegian Sea. Traditionally, model testing has been involved in the hydrodynamic verification of new systems for oil and gas production systems, and preferably in laboratory basins which can accommodate the full depth of moorings and risers. A description of the role of model testing has been given in [1]. For ultra-deep waters, however, the modeling of a full-depth system becomes difficult since presently, no tank facility is sufficiently large to perform the testing of a complete FPS with compliant mooring in 1500 m–3000 m depth, within reasonable limits of model scale. This is illustrated in Fig. 1. Various procedures have been proposed and developed to meet this challenge. Most methods involve some kind of combined model tests at reduced depths with computer simulations—so-called hybrid methods. An overview of the challenges, as well as a review of some efforts made within the hybrid approach, are given in this paper. Comments on future challenges are finally presented. The presentation is to a large extent based upon recent works within the VERIDEEP Project [2], the Norwegian Deepwater Program (NDP) [3], and within the Deepstar program (for which an earlier overview of the mooring and riser activities was given in [4]).

The Challenges

Background: The Purpose of Model Test Verification. The main objective of hydrodynamic verification is to perform an independent check/control to confirm the level of critical response parameters of a concept design, in order to ensure that the floater system will fulfill the basic requirements to functionality and safety. Critical response parameters of the hydrodynamic verification process will normally be related to:

- Floater motions
- Mooring line tensions
- Riser tension and/or minimum bending radius
- Possible interaction (collision) related to moorings/risers/hull
- Relative wave motions, airgap
- Global structural loads
- Local wave impact loads, slamming

Experimental testing by means of physical scale models in a model basin, and with direct measurement of the critical response parameters, has been the traditional way of investigating the behavior of moored offshore vessels for many years, as described by ITTC [5]. This has been recognized as the most reliable tool for reproduction of realistic and extreme situations, including essential coupling effects between, e.g., the floater motions and nonlinear mooring line tensions. In particular, this can be important in cases with complex systems, where various kinds of dynamic and static coupling effects may occur, and especially if non-Gaussian statistics must be applied in the description. Also, the physical models may have the advantage compared to simplified numerical models that unknown phenomena and effects, not described by the theoretical models with their simplifications, can be discovered. (On the other hand, proper numerical models may in fact sometimes illustrate and enlighten the actual problem even better than experiments. Thus, the optimal solution is often a combined experimental/numerical study).

Model scales typically in the range 1:50–1:70 have been used for such testing, preferably including modeling of the complete floater system with moorings and risers (though a simplified modeling including a reduced number of equivalent risers are often used). Verification is required for the design conditions, where the survival cases normally are the most important, as these are crucial with respect to possible damage and breakdown of the system. Also, these are often the most uncertain cases with respect to the numerical computations of the design, due to nonlinearities, non-Gaussian statistics etc. In particular, this may typically relate to extreme offsets, mooring loads, and local wave impact loads...
(slamming) on the vessel. Also, for operational conditions, the verification of certain parameters may be needed, including check of response levels with respect to fatigue life.

Requirements and Alternatives in Deep Water Verification Experiments. Various verification methods are in principle possible:

- Physical model tests of complete system in a tank facility
- Outdoor model tests at sea or in lakes
- Field tests (full scale)
- Numerical computations (covering a range of types, from Monte-Carlo simulations to fully nonlinear numerical wave tank tests - CFD)
- Combination of model tests and computations (hybrid methods)

The actual choice may depend on several factors, such as the type of structure to be modeled, which are the most important parameters to be studied, the environmental conditions (depending on the location etc.), and others.

Some of the alternatives are briefly discussed in the following.

Ultra Small Scale Testing of Complete System. As discussed earlier, the first alternative (complete system modeling) is considered to be the most direct, independent method for the verification. Considering the size of existing model testing basins, the use of very small scale ratios will be necessary if testing of complete systems shall be made for deep-water systems. The situation is illustrated in Fig. 2 where, as an example, the available full scale depth versus model scale is shown for the Ocean Basin at MARINTEK. Details will certainly be different in other laboratories, depending on the basin depth, the current generation system etc., but the overall simple message will be the same: the maximum scale is determined by the available depth and vice versa. For use of ultra small scales, one has to assure that the uncertainty of results is within certain acceptable levels, and there is a need for quantification of these uncertainties.

Important issues for choice of model scale and resulting accuracy of results will be:

- accuracy related to model construction, geometry, and mass particulars
- response levels, accuracy of instrumentation, possible influence of instrument probes, and cables on test results
- generation of environmental condition, repeatability in basin
- hydrodynamic load regimes and viscous scale effects, especially in relation to the increasing importance of current loads and damping of the mooring and riser systems.

The ultra small scale alternative has been investigated in [6], including a case study with an FPSO tested in scale 1:170. Comparisons to identical tests in scale 1:55 were made. A similar study was made with a semisubmersible in [2], where tests in scales 1:55, 1:100, and 1:150 were compared. The experience from these studies shows that model testing in ultra small scales down to 1:150–1:170 is in fact possible, at least for motions and mooring line forces of FPSOs and Semi’s in severe weather conditions such as those offshore Norway. Particular care was needed during the planning, preparation and execution of these model tests, since the required accuracy is at a level considerably higher than for conventional scales.

For floating systems not requiring a large footprint area on the bottom, such as TLPs, tests in deep pits [7] may be an alternative. It is, however, difficult to generate a specified current all over the depth range in that case.

Outdoor Testing. Testing in fjords or lakes may in certain cases be a relevant alternative to basin tests, and presently may be the only one, without having to compromise on scale and system simplifications. Two different examples are reported in [8] and [9]. The main problem of Fjord-testing is of course that the environmental conditions given by nature are non-controllable (although one should try to measure what they are, at least) and can therefore not be used on a routine basis as a verification tool. By use of technical facilities at sea (floating dock, wavemaker, top-end actuator, etc.), it may be possible to improve this situation.

For research projects, and for use as reference check (benchmark test) of the numerical computations of specific details, fjord-testing can be a very attractive alternative if the actual on-site environmental conditions can be measured.

Hybrid Methods. It seems that the most realistic alternatives at hand will require the use of hybrid testing or hybrid verification in some form. Given this situation, the main challenge of deep-water verification will be to apply model tests and numerical computations in such a manner that a reliable verification is still performed. This provides that the critical system parameters can be verified at an acceptable level of accuracy and should be seen in conjunction with other uncertainties involved in the design of the system. Reliability analysis can be used to quantify the effect of the uncertainties. Ultimately, the accuracy of the verification process must be reflected in the selection of the level of the safety factors of the design. Of course, for the sake of cost reduction, a reduction of these factors is desirable.

If a truncation is being considered, important issues are:

- when to choose a truncated system
- selection of criteria for system truncation
- degree of system truncation in relation to coupling effects of floater and under water systems
- possibility of equivalent mooring and riser modelling
- selection of system truncation and model system versus need for extraction of empirical hydrodynamic data for use in numerical computations (hybrid verification), such as slow drift information (excitation and damping).

Another important issue, for both model tests and computations, is the very long natural surge/sway periods of deep-water systems and the impact on procedures and methods for providing the statistical results of the verification.

For hybrid verification, the complete modeling is replaced by a combined process, which in itself introduces an uncertainty gap: How do we know that the final simulations give the same results as would have been obtained from a complete model test? And how do we choose the proper model scale and the proper truncated set-up, in order to reduce these uncertainties? A schematic illustration of how the uncertainty of the verification process depends on the model scale as well as the degree of truncation, respectively, is given in Fig. 3. This figure shows qualitatively how a large scale model (i.e., a small scale factor λ) can lead to

![Fig. 2 Available depth in MARINTEK’s Ocean Basin](image-url)
large uncertainties due to truncation, and a small scale (i.e., a large \( \lambda \)) can lead to uncertainties due to small models. Thus there is, in principle, an optimum scale range where the total uncertainties are smallest. One should also avoid that the final simulations in a combined procedure are simply a reflection of the original design calculations, in stead of an independent verification process.

The hybrid approach is discussed in more detail in the following chapter.

**Hybrid Approach**

**Overview of Procedures**

*Truncated Systems with Mechanical Corrections Only.* The simplest approach with a truncated system is the one without computer assistance at all, that is, all connections to the full depth system is put into passive mechanics of the model test set-up itself, by means of springs, masses and mechanisms connected to the floater. Although static characteristics can be modeled quite well by this method, such as demonstrated in [10], it has been found that it is very hard to combine with a proper line dynamics and floater damping reproduction [11-13]. If and when such issues are of less or no significance, however, the procedure may be considered as an alternative.

*Truncated Systems with Off-Line Numerical Simulations.* Various procedures have been described for combining a passive truncated test set-up with a subsequent off-line computer analysis. Some examples are given in [2,11,14,15]. The actual procedures proposed reflect, to some extent, the purpose of the model tests. Thus, if the purpose of the experiment is to study a particular effect only, the main focus of the physical modeling is on that particular detail, while other details are modeled in the computer. For example, tests can be run with a single mooring line for a study on line dynamics, or with the vessel moored in a very simple spring system only for the study of vessel hydrodynamics. On the other hand, if the aim is to observe the behavior of the total system, one will try to model as much as possible in the laboratory, including, for example, individual mooring line models although they will be truncated. In the latter case, the purpose of the tests will be to check and calibrate the numerical program on the whole system, including the vessel and lines/risers, on the reduced depth system, and using relevant information in an extrapolated version of the numerical model. There may also be intermediate cases, where lines/riser systems are modeled to some extent in a realistic way, but where the main focus is still on the floater.

Thus it is essential to have in mind what is going to be verified. Is it: \( a) \) The computer program, \( b) \) Details of the vessel (or of other parts), or \( c) \) The complete system? In the future, procedures with even closer integration between experiments and computer simulations are expected, including the active (on-line) combination described below. Then it will become important to sort out what will be the new information obtained from use of the combined procedure, and what will be just a reflection of the input to the computer program. The more advanced the available computer programs are, the more new information can be expected from the computations. But they will have to be extensively verified, for example against a range of experiments, before that.

*On-Line Equivalent Systems.* Active hybrid model testing systems make use of real-time computer-controlled actuators replacing the truncated parts of moorings and risers. This must be able to work in model-scale real time, based on feedback input from the floater motions. Thus mooring line dynamics and damping effects are artificially simulated in real time, based on a computer-based model of the problem. System identification from single mooring lines model tests can be used as input to the computer model. A feasibility study with such a system used on a 1:80 scaled FPSO model moored in a relatively shallow water basin has been described in [16,17]. Another system which might be used in a deep water basin has been described in [7].

A complete model test verification system based on these ideas is a challenging, but interesting task for future considerations. It requires powerful computers, as well as well advanced and very accurate control systems. The motion range required in 6 degrees of freedom for actuators simulating very deep cases may be another limiting factor. One should also take into account an evaluation of the question: How intelligent does the computer model have to be for hydrodynamic verification purposes? It is expected that significant developments will take place in this field in the future.

*Selection and Design: Truncated Passive System.* In order to reduce the uncertainties related to an off-line extrapolation of test results from a truncated to the full-depth systems, one should strive at obtaining the same motion responses of the floater as would result from the full-depth mooring. The truncated mooring system should preferably have a similarity to the physical properties of the full-depth system. In practice, the design of the test set-up may follow the following rules, given in succession of recommended priority:

- Model the correct total, horizontal restoring force characteristic
- Model the correct quasi-static coupling between vessel responses (for example, between surge and pitch for a moored semisubmersible)
- Model a representative level of mooring and riser system damping, and current force
- Model representative single line tension characteristics (at least quasi-static)

To the extent that these requirements may not be fully obtained, the philosophy of the procedure is that the numerical simulations shall take care of the effect of the deviations between the full-depth and the truncated system.

*A Particular Implementation.* A particular two-step (passive) hybrid verification procedure was developed and investigated through the VERIDEEP project [2], and was also applied in the NDP project [3]. Similar ideas have been suggested in [11]. The principle is illustrated in Fig. 4, and can be summarized as:

1. Design truncated set-up (according to above guidelines)
2. Select and run a proper test program with representative tests for the actual problem
3. Numerical reconstruction of the truncated test (coupled analysis); for calibration and check of computer code
4. Numerical extrapolation to full depth (coupled analysis)

For the computer simulations, coupled analysis is generally recommended. A program system established for this purpose, and

**Fig. 3** The balance between uncertainties related to truncation and to small scales (i.e., large scale factors)
which has been applied in the examples reviewed later on in this paper, is the RIFLEX-C system. Here the motions of the large-volume floater and the dynamics of the slender-body lines and risers are integrated in a time-domain finite element (FEM) analysis. This takes into account mooring line induced slow-drift damping [19] as well as the corresponding nonlinear line dynamics. An example of a part of such a model is shown in Fig. 5. A comparison to experiments, including empirical calibration, has been presented in [20]. The role of coupled analysis in the numerical studies of deep-water systems has been discussed in [21].

If the time domain coupling is definitely considered non-significant for the problem, a non-coupled alternative might be considered.

In the present approach, the numerical reconstruction (step 3) is carried out by a detailed reconstruction of the actual time series recorded during the tests, using the measured wave record as input. This may in many cases be a non-trivial operation, with accurate system identification and tuning of parameters such as slow drift forces and damping of the vessel.

Special nonlinear signal analysis processing may be needed, such as the quadratic analysis described in [22] and applied in [23]. The calibration may be sea state dependent, so that the test program should include a range of conditions (although the number of final full-depth simulations may be higher than the actual model tests). The calibration and check of the computer code also includes a check of the nonlinear dynamics and corresponding drag effects on the mooring lines, at the actual reduced depth.

**Review of Examples from Case Studies.** A case study with a semisubmersible platform in 335 m water depth was run as a part of the study in [2]. Some details were also presented in [20]. The mooring consisted of a catenary system with 12 lines, and 8 risers were also modeled. A conventional model scale of 1:55 was chosen. Full-depth tests as well as tests with truncation at 167.5 m were run. Thus results from use of the numerical extrapolation could be directly compared to full depth tests. The moderate water depth, 335 m, was chosen in order to be able to run a full depth test in such a scale, since the aim of the tests was mainly to investigate the method, rather than to study an ultra-deep water case. Results comparing line tensions in the truncated and full-depth systems, for measured as well as numerical simulations, are presented in Fig. 6. It is seen that the numerical extrapolation agrees reasonably well with the full-depth measurements—the significant increase in line dynamics from half to full depth is clearly reproduced. A slight under-prediction of the line dynamics in the most extreme conditions (a 100-year North Sea storm) was observed, probably caused by the neglect of forces from water particle velocities.

As a part of the calibration of this numerical model, drift coefficients and damping were empirically estimated from the experi-
ments. Significant deviations from potential theory (using WA-MIT [24]) were observed, which can be explained by viscous effects on the columns [23,25].

The same semisubmersible floater was later used in another case study in 3000 m water depth [3]. The mooring now consisted of a 16-line steel rope catenary system. In this case, model tests were run in scale 1:150 with a system truncated at 1100 m. Thus two additional challenges were now included: An ultra-small scale in combination with ultra-deep water. A photograph of the physical model is shown in Fig. 7, while the full-depth and truncated moorings are shown in Fig. 8. Mooring line characteristics are presented in Fig. 9 (upper), with examples on line tensions from a 100-year Norwegian Sea storm shown in Fig. 9 (lower). A benchmark study of an 1100 m system truncated at 550 m was also included, since the small scale now allowed a full depth test at 1100 m as well. The results compared reasonably well, as for the 1:55 study above. However, the results indicate that the scale 1:150 is at the lower limit for use in a hybrid procedure. If truncations have to be done anyway, one might consider scales around 1:125 – 1:100 or larger, depending on the actual case.

A similar, but simpler version of the procedure was applied in [26]. In this case, an FPSO moored in 3000 m water depth was investigated with the purpose to verify the mooring design. The work was run as a case study in the investigation of methods. The vessel hydrodynamics data available from an earlier study on 350 m depth were imported into a numerical, coupled analysis model of the full-depth system. In particular, drift coefficients and damping coefficients of the vessel were empirically found from the experiments, see Fig. 10. The observed deviation from the WA-MIT [24] model is in this case assumed to be due to bow effects in large pitch motions.

Both of the above mentioned 3000 m system studies showed that most of the offset was determined by current forces on the
mooring lines (risers were not included). Furthermore, the mooring line induced damping of the vessel was very high, especially in current where it was over critical.

Deep water moorings are often designed with polyester taut mooring rather than steel ropes. This may reduce the dynamic effects that are often leading to particularly nonlinear line loads and resulting slow-drift damping. However, the dynamic effects of taut mooring in very deep waters may still be significant, and should not be neglected in general.

In conclusion, the experience so far with the present hybrid verification procedure is technically positive, while there is still room for improvements in the practical implementation. Due to the coupled analysis applied here, rather heavy computations are also involved. But it is expected that due to the rapid developments in this field, such methods will play a role in future verification of deep-water concepts. The further developments and challenges are commented in the following chapter.

Further Challenges

Design of Truncated System. There is a need for an efficient methodology in the design of the truncated system, e.g., apply an optimization technique to establish a truncated system with required properties. The method has to reflect:

- uncertainties regarding model scale versus uncertainties introduced by the gap between full-depth system and truncated system
- the importance of interaction effects between mooring/riser system and floater motions
- which loading effect is more important, e.g., wind, wave, current, etc.
- retain the possibility to explore unknown effects

There is also a need for general guidelines or a guide to help set the criteria to the requirements that the properties of the truncated system have to fulfill. These requirements are dependent of the system (and site) in hand and have to be evaluated from case to case.

A survey on important effects in general with regard to floater types, mooring types and loading will be helpful to set adequate requirements.

Parameter Estimation. In the future, the experimental estimation and interpretation of vessel hydrodynamics (drift forces etc.), and other system characteristics such as properties of single lines, can be made more efficient and robust, and there is also a potential with regard to improved accuracy. Accurate estimates set requirements to model test measurements and arrangement, i.e., consistent separation of load effect measurements from risers and moorings. More efficient use of non-linear time-domain analysis in the system identification process can also be achieved. Improved load formulations for e.g., viscous wave drift forces on large-volume structures in the presence of current should also be considered.

Challenges in Numerical Simulation. Development of optimal integration between experiments and computer simulations. This includes, for example, efficient and practical procedures in transferring data from laboratory measurements to numerical simulations and vice versa for result interpretation and comparison

- Faster and more efficient computers and algorithms
- Efficient algorithms for time domain wave kinematics (viscous drift forces and local wave loading on individual mooring lines and risers)
- Evaluate the use of coupled versus un-coupled analysis approach. Un-coupled approach has to be verified by coupled analysis.
- Improved mathematical formulation of floater force models in general, especially for drift forces in large waves.

Other Challenges.

- Assessment of uncertainties in hybrid verification
- Alternative station-keeping systems (DP-assist or full DP)?
- Assessment of needs in real-time hybrid testing
- Development of mechanics and software needed for real-time hybrid testing
- Further development of guidelines/recommended procedures.

Concluding Remarks

The challenges in carrying out model tests of deep-water offshore structures have been investigated. With laboratory basins available today, truncation of systems will definitely be needed if depths more than approx. 1200 m are to be considered, also if scales are reduced to around 1:150. Even smaller scales may introduce problems with accuracy and repeatability, although improvements can be done in that area, and for certain models, scales larger than 1:100 are recommended. The hybrid approach, which is a combination of model tests at reduced depth with computer simulations, is then likely to be the most relevant tool.

A brief overview of developments carried out at various laboratories has shown that there are basically two groups of hybrid methods: Active (on-line) integration, and passive (off-line) integration. Most activities have been in the latter area, although there are continuously a development within both. A particular off-line procedure has been reviewed. The results from case studies are promising, showing that carefully designed truncated set-ups combined with a coupled-analysis computer tool can reproduce results obtained with full-depth set-ups. There is a need for further developments in order to obtain an efficient tool for routine use.

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