Foresight Study on the Physical Modelling of Wave and Ice Loads on Marine Structures

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Abstract

The measurement of wave and / or ice loads on coastal and maritime structures can play an important role in their final design. The number and range of man-made structures that are subject to these loads is increasing – from offshore oil and gas facilities, through ships and, renewable energy devices, to breakwaters, quay walls, bridges and tunnels. This paper summarises the results of a Foresight Study, available from www.hydralab.eu, which reviewed techniques for making physical model measurements of wave and ice loads on marine structures, summarised their weaknesses and outlined the advances in modelling techniques that the authors expect to see. The short-term developments that are expected include improvements in efficiency by the development of sampling schemes (so that shorter tests may be run) and the improvement of techniques for computing the low-frequency response of floating structures. They also include improvements in wave generation by improving techniques for producing focussed waves over varying bathymetry and in the presence of structures, improving shallow water wave generation using phase-resolving numerical wave models and developing novel forms of tsunami wave generation. We anticipate improvements in instrumentation, including the application of tactile pressure sensors to measure spatially-varying loads, the development of active (servomotor-based) transducers to reproduce non-linear responses and increases in the spatial coverage of optical and acoustic instruments. There will be improvements in access to data, including the sharing of meta-data over the semantic web and the transfer of data from remote experiments. The longer-term changes that are anticipated include (i) the development of composite models with full two-way coupling between numerical and physical models in real time, (ii) increased use of physical models with CFD, (iii) improved treatment of uncertainty, partly achieved through (iv) the provision of much more detailed datasets due to improvements in sensor size, resolution, sampling frequency and spatial coverage, (v) the development of the active laboratory, with many more computer-controlled non-linear devices, (vi) development of simulators to reproduce single phenomena (such as wave run-up or overtopping) in a controlled manner in the field and (vii) the development of more open science, with citations for publically-available data that can be found, described and downloaded over the web.

Key words
HYDRALAB, physical modelling, force, structure, foresight study

1. Introduction

Mankind has built structures in, around, under or over water since the days of the earliest piers, bridges and enclosed harbours (C 2,500 BC). From offshore oil and gas facilities, through ports, terminals, marinas, quays and breakwaters, to groynes, bridges and pipelines, the number and range of man-made structures that interact with the hydraulic environment is increasing. There is a long history of conducting experimental tests of the interactions between water or ice and structures. The 20th century saw the development of many of the great hydraulics and hydrodynamics laboratories that continue to use physical modelling as a design tool for river, coastal and marine structures. Indeed, the prevalence of hydraulics laboratories in Universities and Research Institutes across the world is testimony to the continued importance and influence of physical model testing in hydraulics today.

The study of wave or ice loads on man-made structures is an important sub-set of physical hydraulic modelling. Moreover, increasing development at the coast, the opening of new shipping routes in Arctic waters, the continued development of oil and gas facilities and the installation of shoals of renewable energy devices means that there is a continuing (and possibly even increasing) need for research and consultancy work on wave and ice forces on free-floating, moored and coastal structures.

The project HYDRALAB-IV has commissioned three Foresight studies into (i) water (including ice) and structures, (ii) water and environmental elements and (iii) water and sediments, each of which has developed a vision of how the physical modelling of water and the elements around it may evolve and has indicated the areas where the greatest changes are likely to occur. Each study has also identified what the possible consequences are for the development of our hydraulic laboratories, including instrumentation and facilities. All three foresight studies will be published on the HYDRALAB web site www.hydralab.eu.

This paper summarises the foresight study into water (including ice) and structures (Sutherland and Evers, 2013) concentrating on the changes in facilities, instrumentations and techniques that are envisioned in the short-term (perhaps five years and generally based on on-going developments) and long-term (perhaps 10-15 years) which are more speculative. Due to the focus of the laboratories involved, the study is mainly confined to coastal and marine structures, where waves or ice loads are of greatest concern. The Foresight study (Sutherland and Evers, 2013) also contains sections on the following topics, which are not summarized here:

- Review of topics, which introduces four main classes of problems, (i) ships in harbours, (ii) floating structures in deep water, (iii) response of fixed structures to waves and currents, and (iv) response of structures to ice. The issues that are of greatest importance are described for each class of problem. The section ends with some observations on the trends observed in the modelling of particular topics.
- Establishing the correct environment, which is split into two main sub-sections: (i) establishing the correct hydrodynamic environment and (ii) establishing the correct ice environment. The former includes methods for producing waves, winds and currents, a summary of standard measurement techniques (for measuring surface elevation and velocity) and a section on measuring the air content in breaking waves. The letter includes descriptions of how ice sheets are produced, the measurement of ice properties and the modelling of different ice conditions (such as brash ice and ice ridges).

- Sate of the art in modelling techniques. This section is split into two main areas: (i) Model construction and (iii) Measuring and analysis techniques for modelling the forces on structures.
- Shortcomings, where limitations in our present methods are discussed.

2. Short-term developments

Improvements in techniques are anticipated over the next few years, although it is likely to take several more years for some of these techniques to achieve wide-spread use. The anticipated short-term advances are described in the sub-sections that follow. They have been arranged into four categories: improvements in (i) the efficiency of testing, (ii) wave generation, (iii) instrumentation and (iv) access to data.

2.1. Improvements in efficiency

2.1.1. Sampling schemes

Long test series of several thousand waves have to be run in order to determine the response of a structure to high return period events. Davey et al (2008, 2010) applied an importance sampling technique to decrease the duration of a test run (overtopping over a vertical breakwater) by a factor of two to five. The development of other sampling schemes would allow shorter test series to be run for a wider range of structures and responses. Advances will come through the application of techniques to new cases and comparisons between different approaches.

2.1.2. Quadratic transfer functions

Moored ships or other floating structures respond around their natural modes. The drift velocity of a free-floating body can be approximated by a simple model based on the equilibrium between the drift forces and drag forces. The drift forces are calculated from the second order quadratic transfer functions (QTFs) at zero frequency, taking into account their variations with the velocity through the wave drift damping (le Boulluec et al, 2008). Drag forces are tuned by a drag coefficient and a development of the square velocity. Side by side interaction involves precise modelling of the berthing lines and fenders (Lécuyer et al, 2012). Incremental advances are expected that will allow the calculation of QTFs to be undertaken more easily and with greater accuracy, while application of different methods to the same case(s) will point to the strengths and weaknesses of each approach.

2.2. Wave generation

The ability to generate accurate representations of realistic sea states is a pre-requisite for many tests, so equipment manufacturers and facility operators are always looking to improve their wave generators. Three areas where wave generation is expected to improve within a few years are described below.

2.2.1. Coupling of Boussinesq model to wave paddle in shallow water

Waves are typically generated in relatively deep water and then propagate up an artificially steep slope to an area where the bathymetry is realistic and can produce the desired wave characteristics at the structure. A smaller geometric length scale could be used in the same facility (or a smaller facility could be used at the same scale) if waves with the correct non-linear characteristics could be generated in intermediate to shallow water depths. Zhang and Schäffer (2005) originally coupled a Boussinesq wave model and a wave paddle to account for linear dispersion and shallow water non-linearities. Local wave phenomena – evanescent modes – are also taken into account so the elevation at the moving paddle can be computed. There is renewed interest in developing this approach for three dimensional sea states and different wave models.

2.2.2. Generation of tsunami-like waves

Most piston paddles are limited in their ability to generating realistic tsunami waves by their stroke. One way to address this is to construct a flume with a long stroke. Wedges and landslides have also been used. Another approach is to use a pneumatic tsunami generator (Rossetto et al, 2011) which can generate controlled and stable simulation of extremely long waves led either by a crest or a trough (depressed wave). This pneumatic tsunami generator has been improved by the use of a computational fluid dynamics (CFD) model to test potential improvements, with only the best improvements being constructed and tested in the laboratory. More use of CFD models in the design of equipment and experiments is to be expected (see also Section 3.2).

2.2.3. Focused wave generation

In order to design safe and economic floating and non-floating structures along the coast and offshore, it is essential to model freak waves and other extreme wave patterns. This can be achieved in the laboratory using wave focusing techniques. Most of these use a linear back transformation from the target wave to the paddle, so non-linear effects and the effects of varying topography are neglected. Self-correcting techniques (Chaplin, 1996, Schmittner et al., 2009, Hofland et al. 2010) have proved promising in correcting for non-linear effects over a flat bathymetry. Fernández et al. (2013) have developed a self-correcting technique that uses a second order wave profile as the target signal at the focal point, is efficient and has been tested in a numerical wave tank for constant and variable water depth. The testing of such approaches to a range of non-linear applications over varying bathymetry in the laboratory and numerical wave tanks will increase confidence in the use of these techniques.

2.3. Improvements in instrumentation

2.3.1. Spatial variation of pressure

Traditionally, pressure measurements are conducted using an array of pressure transducers placed in the middle of the structure where the maximum pressures are commonly assumed to occur. In recent years the number of pressure sensors typically used has increased, with deployments of 16 to 32 becoming more common, due to advances in computers, data acquisition and sensor technology. Total forces are calculated by integrating the point measurements by assuming uniform pressure distribution between the sensors. For more complex studies the pressure distribution is significantly less well known and the calculated resultant force may vary quite considerably from the actual force (Alderson and Allsop 2007). Hence, there is a requirement to develop pressure measurement systems with high spatial and temporal resolution. This is already occurring through the application to hydraulics of technologies developed elsewhere and these developments are likely to continue. Two examples are given below.

Matrix based tactile sensors, such as those by Tekscan (2003) are attractive when there is a need to measure the pressure distribution with very high spatial resolution. A sensor consists of two thin sheets, which have electrically conductive electrodes deposited in varying patterns (Figure 1 left). The intersection of these rows and columns creates a sensing cell called a 'sensel'. The resistance of each sensel varies inversely with applied load. Stagonas et al. (2011) achieved simultaneous mapping of the horizontal and vertical distribution of wave impact pressures at the face of a vertical seawall in a small scale model, while Ramachandran et al (2013) present results from tests in a large-scale wave flume (Figure 1, right) and experiments have also been conducted on ice loads on a model lighthouse.

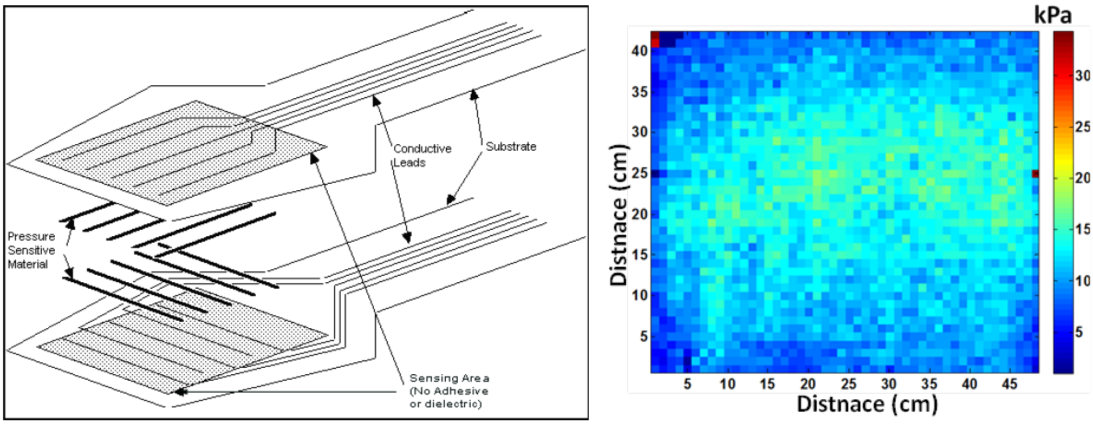

Figure 1: Sensel arrangement (Tekscan, 2003, left) and spatial distribution of wave impact pressure (right, courtesy of Forschungszentrum Küste)

Tactile sensors have a lower sampling frequency than pressure sensors and only 8 bit digital output (0-255 scale) which lead to uncertainties in the results. For example, the 48 column by 42 row sensor user by Ramachandran et al. (2013) has a scanning rate of 680 Hz, which is not sufficient to entirely capture the peak impact pressures resulting from breaking waves. Further, simultaneous measurements of lower hydrostatic and impulsive peak pressures become quite challenging due to the lower output resolution (8 bits system). It may be several years before we see the size, sampling rate and resolution that would see tactile sensors acquiring a clear advantage over pressure sensors.

An alternative innovative approach to the development of pressure sensor arrays is to adopt the small sensors used by divers (of order 5mm in each direction). Eight have recently been deployed in a ring around a 70mm diameter cylinder. The test section was constructed using a 3D printer – another innovative technique which will be used more frequently in the future.

2.3.2. Active transducers

One aspect of floating structure physical modelling which has seen little change in decades is the representation of model elements (such as mooring lines and fenders) with nonlinear responses to applied loads. For such elements it is common practice to include an item of known stiffness e.g. a coil spring or length of metal, which gives a linear response to the applied load. The modeller can combine linear responses, through the introduction of stops, to better replicate the real non-linear system. This approach becomes increasingly complex to implement and tune where the load response is highly non-linear, such as in the buckling and recovery of a fender at high loads or the rapid irreversible extension of mooring lines prior to breaking.

An active transducer in the form of a servomotor will be capable of reproducing any elasticity curve on a physical model. The control capabilities of modern servomotors connected to programmable logic controllers allows for the accurate monitoring and control of both the torque being developed by the servomotor and the position of the servomotors shaft (Figure 2). Assuming a linear relationship between the requested and delivered load, it is possible to adjust the torque of the servomotor dependent upon the shaft's position which essentially allows the replication of any elasticity characteristic likely to be required on a physical model. With changes in the hardware attached to the servomotor this system should be capable of modelling any part of a model for which precise deflection or extension under load is important.

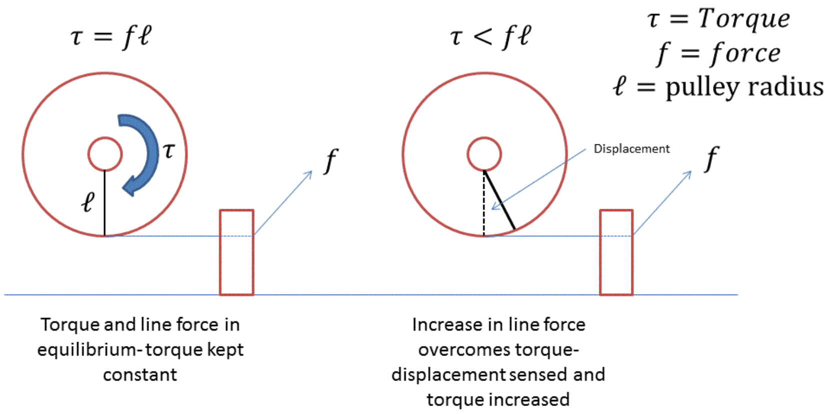

Figure 2: Principles of an active transducer, illustrated by a mooring line

2.3.3. Optical or acoustic measurements of water surface

Physical models usually give the best description of non-linear wave processes, but this information cannot presently be obtained from the basins and flumes at the same spatial resolution as numerical models. However, in the last decades a number of techniques have been developed whereby surfaces can be measured quickly and accurately. Stereo photography using digital CCD cameras can give a digital representation of a surface area after some post-processing. Laser scanners are used to scan 3D topographic data with more than 100,000 points per second and have been used for wave measurement in the field and in the laboratory (e.g. Blenkinsopp et al, 2010; Allis et al 2011). Range cameras (for instance used in the XBox game computer) can directly measure distances at about 10,000 points using a CCD chip that measures the phase of reflected infrared light. However, making these techniques robust for the hydraulic laboratory will require some work. The data processing must become fast and reliable (comparable to the development of numerical techniques), and the water surface must be visualized in an easy, not-too-intrusive, way. If these obstacles are overcome, it seems likely that we will be able to measure the water surface using these techniques relatively soon. This may lead to new analysis methods and parameters.

2.3.4. Extension of optical / acoustic kinematics measurements to 3D volumes

The development of acoustic and optical measurement techniques for measuring kinematics has led to improved understanding of the flows around structures. The extension of these techniques from measuring at a point to measuring profiles and eventually to measuring volumes will lead to increased information being obtained, which will inform our understanding of the reflection, refraction and diffraction of waves and flows around structures.

2.4. Improvements in access to data

There are two main stages to ensuring that data can be re-used: finding a data set and transferring it. Ensuring that the data can be found and identified as useful and trustworthy by scientists and engineers who were not involved in collecting the data implies an increased use of meta-data. Within HYDRALAB (www.hydralab-eu) methods are being developed to share the meta-data collected on some projects over the world wide web. File-based data transfer is sometimes inefficient but offers a well utilised and simple structure for sharing data from a variety of sources.

3. Long-term developments

The short-term developments in the previous section indicate a trend towards specialisation in more complex, nonlinear phenomena, resolved at smaller scales. In this section, we propose changes that are likely to occur over a longer timeframe (perhaps 10 – 15 years) These technological developments will require innovation to bring us to a higher level of knowledge, which will allow physical modelling of wave and ice interactions with coastal and marine structures to remain a central part of the design and verification of these structures for many years to come. They have been split into four main sections covering improvements in techniques, instrumentation, facilities and openness.

3.1. Improvements in techniques

3.1.1. Development of composite models

Composite modelling involves the combined use of more than one modelling tool (commonly a physical model and a numerical model) to address a complex problem (Gerritsen et al. 2011, Gerritsen and Sutherland 2011, Sutherland and Barfuss, 2011). One type of composite model is a hybrid model - where a physical model and a numerical model are run simultaneously and pass information between themselves in real time. True hybrid models (with two-way exchange of information) are rare and most test set-ups allow the sequential running of models and the one-way flow of information. The reasons for this include the difficulties in (i) running a numerical model synchronously with the physical model, (ii) passing information between models and (iii) getting the physical model to respond to the input from the numerical model. These difficulties are gradually being overcome, opening the realistic possibility that within a few years the full two-way coupling of numerical and physical models in real time will be achieved.

The starting point may be to use active transducers in a physical model, where the non-linear characteristics of the mooring line (for example) may be determined in advance. To advance from there, new technologies must be employed. For example, the reproduction of part of a mooring line may require an active transducer that varies its position, as well as its force/extension characteristics. That may require the use of a numerical model to calculate far field effects outside the physical model, with an active mooring line mounted on actuators at the interface between the physical and numerical models. Another potential development would be of a hexapode (6 dof motion mechanism) to enable the study of multi-parametric loads in relation to motions, eg full added mass or damping matrix. Two plates and 6 actuators have already been used by IFREMER to simulate the motion of a sea state.

3.1.2. Learning from CFD

The development of Computational Fluid Dynamics (CFD) model code has put us in a position where CFD wave flumes and wave basins are being developed. This will draw the physical and CFD modelling communities together as both communities will be addressing similar problems, such as nonlinear wave generation and the absorption of reflected wave energy at the wave maker. The physical modelling community must be prepared to monitor developments in CFD and look for ways to implement the most promising approaches.

3.1.3. Treatment of uncertainty

The increases in the volumes of data being collected and an improved awareness of risk (and hence uncertainty) are likely to lead to improvements in methods to define the uncertainty in measurements. Techniques will be developed to put uncertainty limits on measurements and to use measurements with uncertainty. It is common practice to compare predictions to measurements by assuming that the measurement is error-free. We will move towards analysis procedures that take into account the error in measurements.

Increases in spatial and temporal resolution, plus the increasing ability to measure over profiles or within volumes will lead to an increased capacity to measure the properties of turbulent flow fields. This is likely to lead to a better understanding of the role of turbulence and we will start to address more thoroughly questions such as: when is turbulence important and how do we characterise it?

3.2. Improvements in instrumentation: towards the active laboratory

Sensors will reduce in size, increase in resolution and increase in sampling rates. The development of physical modelling facilities has already benefited tremendously from the increases in computer speeds, which has allowed more devices, such as wave paddles, to be controlled at higher speeds than before. The recent development of Ethernet technology (which can communicated over 1,000 channels at 1,000 Hz) has meant that communication speeds around the laboratory are substantially higher than could be achieved using RS232 or other cables.

The use of non-intrusive optical and acoustic methods will become more common and will cover larger areas. For example we may expect to see the use of optical techniques to measure surface elevations over a high-density spatial array of points at sampling rates of tens of Hertz. New materials, such as ferrofluids and other coatings, will be developed to measure shear stress, so that maps of shear stress distributions that vary in time over a surface will be produced.

The development of active transducers for mooring lines has been described above, while the active absorption of reflected waves (Schaffer and Klopman, 2000) is included in many modern wavemaker systems. Other potential applications of the active technology to the modelling of floating structures include breakaway tests (of the snapping of a mooring line) render recover and constant tension winches, fenders, static and dynamic wind and current loading. Modern high performance embedded PC’s are capable of running control logic for multiple servomotors with a cycle frequency measured in kHz, so several devices can be operated simultaneously alongside traditional wave gauges and other instruments. In the future we are likely to see laboratory set-ups featuring many more active systems (each with its own control loop).

3.3. Facility developments

Advances in wave generation and data collection are likely to continue in incremental steps. The mechanical designs of common wavemaker types (piston and flaps) are likely to remain substantially the same as they are today, with the development of new generation techniques for tsunamis adding diversity to the portfolio of options. Wave generation software will improve, including developments for focussed waves.

Both wind generation and current generation methods are relatively simplistic, with little control over changes in the spatial distribution or time-variation of wind or currents in many facilities. The cost of control systems has dropped significantly, so the development of spatial variations in wind or current fields may therefore come from the installation of many, smaller capacity pumps or fans, rather than through the manipulation of the output from a single unit.

Hydraulic and geotechnical engineering are generally taught separately at universities and their research studies have also been conducted separately. Geotechics plays an important role in dike erosion (driven by wave overtopping) and also in the response of offshore foundations (such as wind turbine monopoles) which are excited by wave impacts. Greater links between hydraulic and geotechnics research will be developed to address these (and similar other) issues. This is likely to require specialized (or hybrid) facilities.

Whether or not the strength of a coastal structure can be modelled at small scale depends on the structure considered. Materials like grass on clay cannot be modelled easily on a smaller scale. Thus one can only perform tests of the materials on real dikes, or on parts moved to a large (or prototype) scale facility like the Delta Flume (Netherlands) or the GWK (Germany). Recently, simulators of a single process, such as wave overtopping, have been constructed in order to undertake controlled tests in the field (van der Meer et al, 2012, Steendam et al, 2013). Both wave run-up and overtopping simulators could be used to generate forces on a structure.

3.4. Open Science

An era of more open science is emerging, comprising: open source software, open software architecture, open access to data, open access publication and open collaboration (or networked science). There has been a rise in the use of open source numerical model codes and open software architecture, which can incorporate component models from different code bases using an interface standard such as OpenMI (http://www.openmi.org/). Meanwhile the importance of open access to public sector research has been recognised by the EC (2011) and there is a commitment to increasing access to data and publications within the EC's Horizon2020 research programme. Technologies for allowing open access to data from experiments are also being developed. Moreover, we are in an era of increasingly open scientific collaboration using the web.

The move towards open science is on-going but faces many difficulties. Nielsen (2011) predicts that it will only take place when we learn to value openness and the sharing of models and data as much as our publication and citation records. This will be assisted by the development of methods to assign a Digital Object Identifier, or DOI to datasets. DataCite (http://datacite.org/) for example, allocates DOIs that link to a public web page with meta-data about the associated dataset and a direct link to the data itself. This allows a dataset to receive a citation in a paper or report. The allocation of DOIs to quality physical model datasets will support researchers by helping them to find, identify and cite these datasets with confidence. The inclusion of citations to data in the metrics produced by organisations such as the Web of Science would increase the citation records and h-indices of researchers who produce much-used datasets, which would change the culture of science to recognise the importance of sharing data.

It therefore seems highly likely that DOIs will start to be allocated to hydraulic datasets that are collected as part of research projects and that making data publically accessible will become a more common requirement of research organisations (such as the European Commission). This will lead to the development of shared datasets, which will help to create a free market in data, which every member of the community has equal access to. This will require protocols and standards to be developed, published, accepted and used. There will, for example, be benefits to enhancing the richness of information about shared data. This extra information will enable any interested party to judge the suitability and quality of the data. In order to do this we need to develop (and ideally consolidate) metadata standards and ontologies. Scientists and engineers will have to get used to the routine generation and use of metadata.

There is likely to be a move towards the standardisation of data, which is tending to occur at two levels: the structure of the data and its technical implementation. Definitions of data structure are independent of the file encoding. For example, ISO19115 outlines the data structure of spatial metadata with its XML encoding given in ISO19139. The supporting (use and discovery) metadata can be given in separate files to the values themselves. This is exhibited in formats such as CSML, NetCDF and XDMF, which offer a binary file type (such as HDF5) for high volumes. Also, directives such as INSPIRE provide a legal and technical framework for data interoperability. It includes specifications for the data, discovery, use and download services and is aimed at making the finding, using and sharing of data easier across the EU. However, for any practitioner wishing to offer a dataset to the wider community, the set of standards on offer is incomplete, overlapping and highly esoteric.

There is a role here for impartial, international organisations, such as International Association of Hydro-Environment Research and Development (IAHR) to provide repositories of (or links to) datasets that can become the de-facto standard for benchmarking tests.

4. Conclusions

Physical modelling has been the foundation of hydraulic and hydrodynamic studies for the past century and a half, particularly when it comes to the analysis of forces on structures and their interactions with waves, currents or ice. The complex, nonlinear phenomena involved in these interactions have been reproduced in the laboratory by increasingly sophisticated techniques for the preproduction of environmental conditions. The techniques used to measure the hydraulic, hydrodynamic and ice conditions and the resulting forces on structures have also improved immensely during this time. This has always meant that the most detailed studies of wave, flow and ice interactions with structures have been carried out in the laboratory, where conditions are controlled and experiments can be repeated. Field measurements, although more expensive and less controlled, have also played an important part in establishing knowledge about these interactions.

Improvements in numerical models, particularly computational fluid dynamics (CFD) codes, mean that these can now be used to determine forces on structures in relatively simple flow cases. CFD codes are being used at research organisations to model more and more complex structures and flow cases, such as waves breaking over structures. As the number of cases modelled increases, and more knowledge is gained in how to apply these models, they will be able to undertake more and more studies that previously could only be undertaken by a physical model. This does not, however, signal the end of physical modelling. Rather, it is likely to signal the start of a new era where numerical and physical modelling are used in collaboration to address complex problems. There is a range of ways in which physical and numerical models can be combined (Sutherland and Barfus, 2011) including:

- Traditional nesting where a detailed physical model site within a regional numerical model;
- Numerical modelling can assist in the design of physical models;
- Numerical pre-modelling can provide information about potential problems associated with the theoretical design or proposed design changes to a structure, thereby reducing the number of physical modelling configurations that need to be tested.
- Modelling the model can allow a numerical model to be calibrated or corrected using the physical model results. The calibrated or corrected numerical model is then available to undertake additional model runs that would be too time consuming in a physical model or were only considered after the physical model has been decommissioned.

Clever combinations of physical and numerical modelling will be used in the design and testing of complex structures subject to extreme conditions for many years to come.

Laboratories have developed active feedback systems for absorbing re-reflected waves at wave paddles over the last twenty years (Schaffer and Klopman, 2000). The concept of the active transducer has now been extended to the reproduction of non-linear mooring lines. The same concepts and control systems could be applied to other phenomena, such as the snapping of a mooring line, constant tension winches, fenders or static and dynamic wind and current loading. Therefore we are likely to see the development of laboratories with many more active control systems.

The increases in computer power, the development of Ethernet technologies for transferring data and the shrinking of electronics mean that physical models have been able to make more and more detailed measurements at finer resolution and higher frequencies. This has allowed more detailed investigations of increasingly complex phenomena to be undertaken. This trend will continue and new measuring techniques will be developed, allowing physical measurements at a greater spatial density. We anticipate the use of more remote sensing (optical and acoustic). The improved spatial and temporal resolution of measurements will allow more detailed analysis of complex (often turbulent) phenomena; provide more data to validate numerical models and drive their development; allow the design of structures to be refined more than ever before; and generate unprecedented volumes of data.

The increased volume of data being generated will provide opportunities for this community and create additional obligations (especially when funding organisations begin to require open access to data as well as publications). Greater value will come from the sharing and re-use of data. This will require organisations to ensure that their data can be understood and read by others and comes with sufficient supporting information to indicate its quality. This is likely to drive moves towards common standards for meta-data and data and increased use of semantic web technologies for data discovery (although there is never likely to be a single standard for data). In an era when more data sets are public, we are likely to see a rise in data driven modelling and may gain benefits from the re-analysis of multiple data sets (as occurs in medicine, for example) which may reveal more information than any single data set. These developments will require this community to engage more with software developers.

Physical modelling of the interactions between structures and waves, flows or ice will continue to develop and will remain a core component of studies in this field for decades to come. There will be an increased focus on non-linear phenomena, as numerical modelling takes over more of the modelling of shallow water flows and non-broken waves. There will therefore be an increasing emphasis on smaller spatial and temporal scales and on working with CFD models.

The increasing specialisation in testing equipment and facilities makes it likely that there will be a reduction in the number of facilities with the capability to undertake the most advanced testing. There will therefore be a continued, and potentially increasing, demand for access to these facilities from regions and countries that do not possess such facilities. There is therefore a clear role for international funding organisations, such as the European Commission, in coordinating the access to and development of the largest facilities, in order to meet these needs.

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