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ASSESSING THE HYDRAULIC RESPONSE OF STRUCTURES TO WAVES AND ICE

BY JAMES SUTHERLAND

Laboratory measurements 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. However, the capabilities of numerical models are increasing and they have displaced physical models in certain areas, so physical modelling cannot afford to stand still. In order for hydraulic laboratories to remain competitive, we must develop our equipment and techniques to improve the services we offer.

A Foresight study conducted as part of HYDRALAB-IV (Sutherland and Evers, 2013) 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. Meanwhile, the members of the joint research activity *Hydraulic Response of Structures* (HyReS) have been developing techniques in three main areas:

1. Wave generation – so that a selected time series of waves can be generated;
2. Optimizing the wave sequences at the structure being tested; and
3. Improving techniques for modelling, measuring and interpreting the responses of structures to waves and to ice.

This article summarises some of the main developments made by HyReS partners between 2010 and 2014.

Wave generation

Wave generation using a phase-resolving numerical model

If we can generate nonlinear waves in shallow water, we can conduct tests at larger scales, minimising scale effects and improving accuracy, or we can run the same scale of test in a smaller facility. However, as waves enter shallow water, their shapes evolve from near sinusoidal into skewed (sharp wave crests separated by broad, flat troughs) then into asymmetrical forms (pitched-forward shapes with steep front faces). Hansen et al (2014) have been implementing techniques to drive wave paddles using input from a phase-resolving Boussinesq numerical wave model, so that the waves are generated in shallow water with the required skewness and asymmetry.

The Boussinesq model reproduces wave shoaling and outputs wave flux and surface elevation at a point in shallow water where the wave paddle will be situated in the physical model. Horizontal velocity is determined from flux and the displacement of the water is determined from velocity. The paddle position time series is created by applying a paddle transfer function and is then used to drive the wave paddles in the physical model.

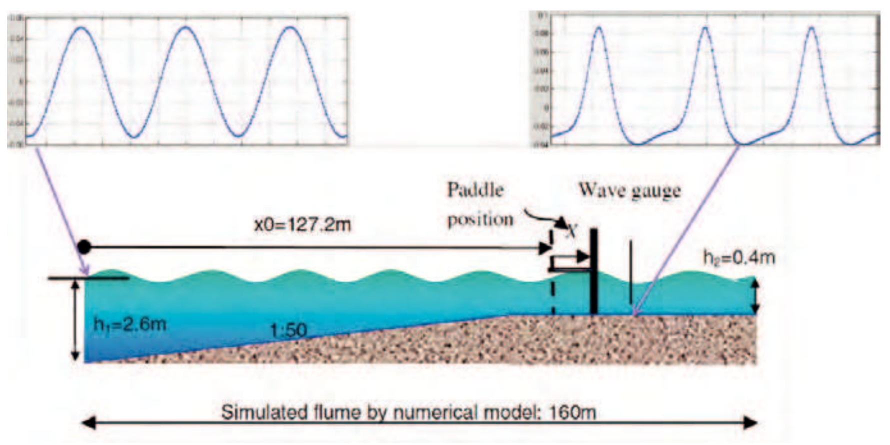

Figure 1 - Numerical wave flume showing waves generated in deep water, passing information to a wave paddle and providing a shallow water time series to compare to the physical model

The theory was tested using 2D flume and 3D basin tests, where surface elevations from numerical and physical models were compared a few metres from the wave paddle position (Figure 1). The coupling method was shown to be a robust and reliable wave generation method, capable of reproducing advanced 3D effects over a wide range of wave parameters.

Tsunami wave generation

Tsunami waves have caused significant destruction to coastlines during the last decade. The generation of tsunamis in the laboratory is particularly difficult as they have a very long period and require a very large stroke (peak to peak displacement of the wave paddle). In practice, most ‘tsunami’ waves generated in laboratories have actually been solitons: a representation of a single wave crest only. HR Wallingford has worked on improving a pneumatic tsunami generator using a OpenFoam CFD model of the test setup. The new design includes a taller and shorter cross-section to reduce sloshing and help in the reproduction of steep leading edge waves. It also features a smoother inlet profile to reduce head losses. A revised tsunami generator was built and tested in a wave flume, where it reproduced N-waves and measured tsunami traces.

Propagation and optimisation of wave time series

Sampling schemes

In order to determine extreme loads, long physical model test series are often run to produce many independent extreme events, to which a statistical distribution can be fitted. Hofland et al (2014) has been investigating how to decrease the duration of repeated physical model tests, while still reproducing the same distribution of extreme values. In cases where it is the highest waves that cause the extreme response (for example when only those waves will hit a structure well above water level) it is easy to isolate these events. However, in cases such was wave overtopping of a structure in shallow water, many effects (such as shoaling, breaking and partial reflection) affect the results, so it is not easy to identify which waves will cause the greatest response.

Hofland et al (2014) have adopted a practical approach to these, more complex, test cases. They have developed a procedure for running a single, long duration, test, and using this test to identify the most extreme events. Shortened time series which include the wave groups with the largest events are then run for repeat tests, or those with small changes to the structure. The results are sensitive to the length of time signal around an extreme event that is used to construct the short time series and this varies with the travel time of short waves from the paddle to the structure and the degree of reflection from the structure. Tests with a deterministic New Wave extreme wave group led to overtopping volumes of the same order of magnitude as the long time extreme events.

Focussed wave groups in shallow water

Extreme waves, such as the deterministic New Wave extreme wave group, have been generated in deep water wave flumes and basins for several years using different means of focussing wave groups. Where these techniques generally do not work well is in the presence of a varying bathymetry or a reflective structure.

Fernández et al (2014) have developed the Self Correcting Method (SCM) for the generation of focused waves or other deterministic wave sequences by means of a few iteration steps. The method has been developed, tested in a Numerical Wave Tank (NWT) and eventually validated in the Large Wave Flume or Großer Wellenkanal (GWK). In the SCM phase and amplitude correction steps are used to correct a second order wave profile, so that a focussed wave group can be reproduced at the desired location. The method was developed for flat seabeds then was extended to cases with variable water depths, wave reflection and the combination of both with very good results. The validity of the SCM to produce both non breaking and breaking focused waves over constant depth, variable water depth and with a reflecting structure was demonstrated in experiments in the GWK (Figure 2).


Figure 2 - Focussed wave generated using self-correcting method in shallow water in front of a truss structure (courtesy of LUH)

Assessment of structural response

Active transducers

Physical models of moored floating structures are used extensively when looking at complex wave-structure interactions such as vessel downtime & mooring analysis. In order to correctly represent the motion of a vessel at berth, the nonlinear characteristics of mooring lines and fenders need to be correctly recreated at scale. It is common practice to represent the mooring lines or fenders using either cantilevers or coil springs with integrated strain gauges. However, when faced with modelling a highly nonlinear mooring line or fender response the use of multiple coil springs and cantilevers becomes increasingly impractical. In response to these limitations Sutherland et al (2014) have created a novel active mooring line transducer (AMLT) that uses servomotors to replicate the stiffness characteristics of the mooring line.

The heart of the AMLT system is a servomotor and a programmable logic controller , with a 1ms time base and low latency. A stable torque, which varies with the position of the servomotor, is generated, so the AMLT can be programmed to produce a non-linear force – displacement curve. This reproduces the non-linear characteristic of a vessel's mooring lines. The same technology could be applied to reproduce the nonlinear characteristics of render recover winches, constant tension winches, fenders, or dynamic loading.


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Quadratic transfer functions

The second order interaction between waves leads to oscillating terms at double, sum and difference frequencies. In the presence of a moored floating body, the second order forces and moments may excite low frequency resonant motions when the difference frequencies become small and they can generate relatively high, low frequency mooring line forces. The magnitude of the low frequency force generated by two component waves is related to those waves by a Quadratic Transfer Function (QTF). A QTF matrix, covering plausible ranges of incident wave frequencies can be built up from measurements of a large number of bi-chromatic sea states, although this is time consuming. Within HyReS MARINTEK, DHI & IFREMER have been developing numerical algorithms to extract the low frequency Quadratic Transfer Functions from random sea tests in wave tanks (Figure 3). Time-domain and cross-bi-spectral analysis methods have been developed.

Tactile Sensors

Pressure distributions on structures during wave impacts are often measured using an array of pressure transducers. However the number of

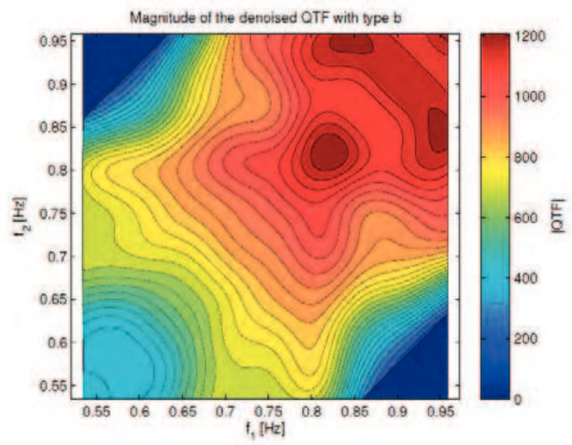

Figure 3 - Quadratic Transfer Function matrix (courtesy of MARINTEK)

sensors is often limited. Within HyReS a number of institutions have been applying tactile (flexible, electronic, grid-based) sensors to a range of scenarios as an alternative to pressure gauges (Ramachandran et al, 2013, Marzeddu et al, 2014, Evers and Lu, 2014).

Tactile sensors are made from two flexible polyester sheets (about 0.1 mm thick) with silver conductive electrodes printed in columns on one sheet and in rows on the other. The intersection between a row and a column creates a sensor or 'sensel'. These matrix based sensors are able to record real-time static and dynamic loads with very high spatial resolution at a reasonable sampling rate. However, each application requires an optimal match between the measurement area, spatial resolution and the pressure range provided by the manufacturer. This optimisation is required as the resolution is low (8-bit) and the total number of samples per second (given by the number of sensels times the sampling frequency) has an upper limit, so high frequencies (in the kilohertz ranges used for wave impacts) can only be obtained by reducing the number of sensels.

Ramachandran et al (2013) explored the application of a tactile sensor to measure wave impact pressures with high spatial and temporal resolution in large scale model tests. They also developed and analysed a dynamic calibration technique. This was tested on the surface of a sloping revetment in the GWK (Figure 4). The sensors were again successfully applied in a HYDRALAB Transnational Access project to measure the wave impact pressures on parapets mounted on a vertical wall.

Marzeddu et al (2014) tested a scaled model of a vertical breakwater in a small flume. The vertical wall of the breakwater was equipped with six pressure sensors, two load cells and a tactile sensor, in order to record the pressure and the total force at the same time. About 290 tests were conducted. Various tests were made under the same wave conditions recording at different sample frequencies (from 50 Hz to 19200 Hz). The total force on the vertical wall was computed for each test using the load cells and the pressure sensors (using interpolation and extrapolation techniques) while the tactile sensor was used to give information on the coherence of impact pressures.

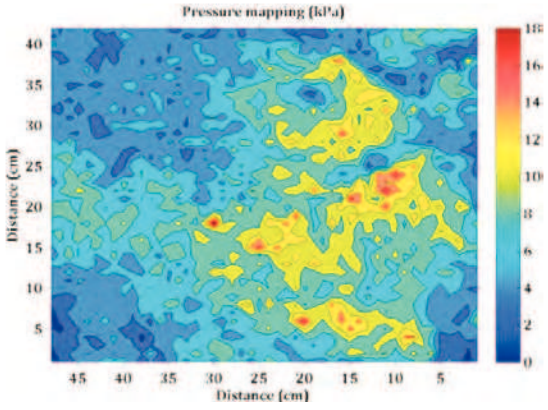

Figure 4 - Spatial distribution of pressure on surface of sloping revetment caused by a breaking wave (courtesy of LUH)

It is common practise in ice model testing to measure the global ice load acting on the entire structure, while in practice most of the load is transmitted through local high pressure zones. The application of tactile sensors to ice loading (Evers and Lu, 2014) is therefore an interesting development as it provides the spatial resolution hitherto unattained in physical models.

Conclusions

The work conducted in the Joint Research Activity 'Hydraulic Response of Structures' as part of HYDRALAB-IV has made noticeable advances in developing techniques for conducting hydraulic model experiments, which have included:

- improved methods for generating water waves,
- improved the efficiency of tests for measuring the structural response to waves,
- developed a technique for focussing wave signals in shallow water or with a structure,
- developed an active mooring line transducer,
- developed code for calculating QTFs from random wave series, and
- investigated how tactile sensors compare to the use of pressure sensors and load cell.

These advances are in the spirit of HYDRALAB as they seek to keep physical modelling as an indispensable tool in hydraulic modelling.

Acknowledgement

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