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# DESIGN, DEVELOPMENT AND COMMISSIONING OF THE BOLDREWOOD TOWING TANK – A DECADE OF ENDEAVOUR

**B Malas,** University of Southampton, UK, **L Creasey**, Iconsys, UK, **D Buckland**, University of Southampton, UK and **S R Turnock***, University of Southampton, UK
* Corresponding author. (Email) srt@soton.ac.uk

## SUMMARY

The process of design, build and eventual commissioning of the towing tank on the Boldrewood Innovation Campus is described. The design brief required a facility that would have a capability to test models at a commercial scale but that would be effective as teaching environment for the next generation of Naval Architects  as well as providing a flexible space for future fundamental research. Each of these provided their own challenges but the eventual solution of a 138 m long, 3.5 m deep, 6 m wide facility has more than met the initial aspirations. Equipped with 12 independent 0.5 m wavemaking flaps at the West end, a passive beach at the East end, a deployable side beach along the South wall for post run wave absorption and a monocoque Aluminium alloy carriage, the Boldrewood towing tank has now been successfully operating for more than a year.  The carriage position and speed are controlled by a twin winch arrangement using a laser positioning system and low embodied energy composite cables. The carriage can reach a maximum speed of 10 m/s with controllable acceleration rates and can have up to four constant speed phases per run.  Initial commissioning results and comparisons with benchmark data for the KCS hull confirm the accuracy and repeatability of the facility. In particular, the position and speed of the carriage are known to a high level of precision. To date research and consultancy work has spanned the performance of high speed vessels, uncrewed underwater and surface vessels, wave energy and tidal current systems, floating platforms for wind turbines, performance sport work for sailing, kayaking, rowing and swimming, open water propeller tests as well as conventional displacement vessel testing for self-propulsion and resistance.  All ship science and maritime engineering students use the facility as part of their taught modules in every year of their programme as well as for individual, MSc and group projects as appropriate. It has also made a strong impact on the many thousands of visitors a year to the campus for science and engineering open days.

## KEYWORDS

Towing tank; wave tank, hydrodynamics, experimental, instrumentation, dynamometry, PIV

## NOMENCLATURE

| | |
|---|---|
| AMC | Australian Maritime College |
| CFD | Computational Fluid Dynamics |
| DIC | Digital Image Correlation |
| DSLR | Digital Single-Lens Reflex |
| ECN | Ecole Centrale de Nantes |
| FDS | Functional Design Specification |
| FNC | Fraser-Nash Consultancy |
| g | Standard Earth gravity (9.807 $m/s^2$) |
| H&S | Health and Safety |
| IMOCA | International Monohull Open Class Association |
| ITTC | International Towing Tank Conference (www.ittc.info) |
| KCS | Kriso Container Ship |
| MEng | Master of Engineering |
| MSc | Master of Science |
| NOC | National Oceanography Centre |
| NWTF | National Wind Tunnel Facility |
| PLC | Programmable Logic Controller |
| PIV | Particle Image Velocimetry |
| RANS | Reynolds-Averaged Navier–Stokes |
| SPAR | Single Point Anchor Reservoir |
| SYRF | Sailing Yacht Research Association |
| TU Delft | Technical University of Delft |
| WAB | Walk Around Box |
| WUMTIA | Wolfson Unit for Marine Technology and Industrial Aerodynamics |

## 1 INTRODUCTION

The UK has historically been at the forefront of experimental hydrodynamics, with many different towing tanks being built since 1870 and the first ever tank built by William Froude in Newquay, Cornwall (Brown, 2006). At times, there were more than ten towing tanks in operation in the country. In the 1990s and 2000s, several facilities were shut by the government or by commercial companies, mainly for financial reasons. Around the same time, CFD tools were becoming more reliable and used in the ship design process, and towing tanks were by some seen as less important.

The aim of this work is to document the process of design, build and commissioning of the first new large scale towing tank in the UK for nearly 50 years. The objectives are to capture the lessons learnt, the process used to design and experience of the construction process. Despite the advances in CFD, there is still the need to carry out both fundamental and applied physical experimentation. The results will help inform the development of better modelling approaches and for validation of simulations and crucially provide an educational experience of physical reality that will be evermore essential to the next generation engineers who will be using complex computer simulations as part of their day-to-day work.

It is also worth noting there is a trade-off between the energy cost for a computer based simulation for evaluation of ship resistance and that needed for a physical model towed down a tank. With computer power continuing to increase (Hawkes et al, 2018) there still will be an energy cost per computation made up of direct electrical power and the energy embodied in the continual cycle of investing/disposing in the processors used, whereas for a physical model test as it is at scale the energy needed per run will be small and independent of the unsteadiness of the flow during the run. For complex problems such as self-propelled and/or seakeeping experiments especially physical experimental will continue to have many benefits compared to the computational overhead needed.

## 2 BACKGROUND

### 2.1 MARITIME RESEARCH AT THE UNIVERSITY OF SOUTHAMPTON

In the 1960s, the University of Southampton had an active yacht research group but no real way to commercialise the extensive knowledge available. Thanks to a grant from the Wolfson foundation, WUMTIA was created in 1967 (Deakin, 2008) and has been offering consultancy services as a University Enterprise unit ever since. These services include towing tank and wind tunnel experiments, full-scale sea trials as well as marine software sales, dynamometry design or CFD calculations. WUMTIA has developed a significant amount of expertise in running scale experiments in various facilities, which has served students, industry and research for many decades and would also provide an invaluable resource when considering what design features would be required for a new tank.

### 2.2 THE NEED FOR A TOWING TANK

The aspiration for a University of Southampton towing tank goes back a long time. Ever since the creation of the Ship Science teaching programme in 1968, the practical labs had to be performed in the small Lamont tank (30 m long). Research and commercial experiments were also conducted in other facilities such as the GKN tank on the Isle of Wight – closed in 2008, the QinetiQ tank in Haslar, or the Solent University tank (Molland, 1996), (Molland et al., 2004), (Bahaj et al., 2007) and (Cartwright et al., 2008).

In an era of increasing competition in students recruitment; it was also noted that other institutions such as Strathclyde University, Newcastle University, Imperial College, University College London, Plymouth University, Edinburgh University or Solent University all had their own large hydrodynamic facilities. Major equipment is nowadays a real asset to attract students to join a particular course.

In the 1990s and 2000s, several possible sites were investigated, such as the University's oceanside campus shared with the National Oceanography Centre, Trafalgar Wharf in Portchester (where the Vosper Thornycroft cavitation tunnel used to be) and finally the Boldrewood Campus in Southampton. A Southampton site was most favoured by the University in order to reduce students and staff travel distances.

### 2.3 THE CHOICE OF THE BOLDREWOOD SITE

Built in 1975, the first Boldrewood Campus (SO16 7QF) was dedicated to Medical and Biological sciences. With age, the concrete used for the buildings deteriorated and by the early 2000s, the maintenance of the campus was very costly to the University. In April 2006, the University announced plans to develop a 'professional campus' on the Boldrewood site, to house the Lloyd's Register Global Technology Centre as well as several University engineering departments. In October 2010, the Boldrewood Campus was fully closed for redevelopment.

Although the discussions about the campus redevelopment always included the possibility of a towing tank, it was a sudden decrease in construction prices in 2012 that allowed to include the towing tank building in the existing construction budget, so it was decided to go ahead. The main characteristics were agreed later that year and construction started in 2013 with an expected completion time of 3 to 4 years.

Figure 1: Construction site in February 2014. View towards the West end where the tank had to be cut deepest into the ground

## 2.4 A BALANCED BUSINESS CASE

The business case for the build of the Boldrewood towing tank relied on three pillars: Education, Research and Commercial activities. The tank has also been designed with future flexibility in mind, so that a wide range of experiments in various domains can be performed in addition to conventional towing experiments, in particular for education and research. To date, the facility has been used for experiments in domains such as fundamental hydrodynamics, sailing, wave energy, offshore wind, sports engineering, shipping, autonomy and biomechanics.

### 2.4 (a) Education

Each academic year, a series of ten practical lab classes are offered to both MEng and MSc students across the Faculty of Engineering and Physical Sciences (Table 1). The facility is also available for practical individual and group design undergraduate and MSc projects. It is very important to the University to allow students to have exposure to physical experiments and their associated procedures and problems (preparation, calibration, scaling, analysis, etc). At a time when engineers spend most of their time working on computers, it is critical for students to acquire practical knowledge and to understand the importance of validation data for any numerical simulations they may undertake.

Table 1: Laboratories Boldrewood towing tank

| Lab | Year | Description |
|---|---|---|
| Induction week | 1 | Trials of boats designed and built by students |
| Resistance | 2 | Resistance tests of a semi-displacement model |
| Propeller | 2 | Open-water tests of a propeller |
| Planing Craft | 3 / MSc | Resistance of a planing model |
| Roll | 3 | Roll motions of a static model |
| Seakeeping | 3 | Seakeeping of a displacement model |
| Maritime Robotics | 4 / MSc | Trials of ASVs designed and built by students |
| Offshore | 4 / MSc | Forces and motions of anchored bodies |
| Wave Energy | 4 / MSc | Motions and performance of a wave energy device |
| Wave Resistance | 4 / MSc | Wave resistance of a displacment model |

### 2.4 (b) Research

The Boldrewood towing tank is classed as a ‘badged facility’ within the University, which means it can be costed on research grants and contracts. It is also a strategic national facility as part of the NWTF group, which means that any academic across the UK can easily obtain access to the facility, under some conditions at a reduced rate[1], which is of particular benefit for early career researchers.

### 2.4 (c) Commercial

The Boldrewood tank is available for support to the marine industry. This can be done by bare charter hire of the facility, where a company bring its own equipment and run its own experiments with the support of a technician to operate the carriage and wavemaker. Interested companies should contact the towing tank staff to discuss this possibility and their requirements[2].

The other option is to contract WUMTIA, who will run the project from start to end for the customer, including the design and manufacture of the model, the preparation and conduction of the tests and the delivery of a scientific report.

## 2.5 BUILDING 185: MORE THAN JUST A TOWING TANK

As part of the Boldrewood campus redevelopment, the School of Engineering staff were consulted to express their needs in terms of experimental facilities. There was a large interest in getting new equipment as well as replacing existing older facilities, which resulted in the following large facilities to be installed in Building 185 : the NWTF open jet anechoic wind tunnel[3], a boundary layer wind tunnel, a tilting water flume and an environmental water flume[4]. In addition to these, some smaller wind tunnels and flumes are also present in the building.

## 2.6 A NEW TOWING TANK IN THE 2020s – WHAT FOR?

Amongst the 10,000+ visitors that have seen the tank since 2015, lots of people ask why the University has

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[1] https://www.nwtf.ac.uk/about/access-for-researchers/

[2] https://www.southampton.ac.uk/research/facilities/towing-tank

[3] https://www.nwtf.ac.uk/facility/anechoic/

[4] https://www.southampton.ac.uk/research/facilities/flumes-wave-tanks

decided to build a tank in an age where CFD is seen by many mature enough to replace towing tank experiments. The question is widely discussed in various conferences and magazines in the marine industry. There have been several CFD workshops in the last few years (Larsson et al., 2014), (Claughton, 2015), (Ponkratov, 2017) and (Hino et al., 2020) where participants performed blind RANS calculations on a given hull geometry and benchmarked their results against the model tests and/or sea trials results. Looking at the most recent workshops results for calm water resistance, they show a large scatter in the results (typically between 10% and 15%), which is a concern, especially as these cases "only" consisted in relatively basic calm water resistance predictions. There are many more complex problems where numerical approaches need validation against high quality spatial and temporal experimental data, such as propulsion, manoeuvring, seakeeping, and novel hull forms. Although CFD is a great tool in the early design stage of ships, especially when it comes to hull form optimisation and relative comparisons, these workshops results show that scale model experiments still have and will continue to have a major role to play in the marine industry, albeit with an evolving role compared to the pre-CFD era.

## 3 DEVELOPMENT PROCESS AND HISTORY

### 3.1 SPECIFICATION DEVELOPMENT

Once the decision to build a tank was made, the specification of the facility had to be developed quickly in order to proceed within the campus redevelopment schedule. It was therefore decided to proceed iteratively. The main dimensions of the towing tank (and thus the building) were quickly agreed in 2012. In order to match the business case (2.4), it was decided to go for the longest possible tank on the campus, i.e. 138 m long, 6 m wide and 3.5 m deep. A gas main and a protected tree constrained the length and the cost of additional excavation limited the depth. This makes the Boldrewood towing tank by far the largest University towing tank in the UK and the second longest existing towing tank in the UK. It was also decided to aim for a maximum carriage speed of 12 m/s, in order to accommodate a wide range of experiments. The shape, cross-section and the final building design were very much driven by the towing tank dimensions, with the other spaces being designed around the facility. The building is supported by 340 steel piles of 400 mm diameter, reaching a depth of 21 m in sandy clay. The requirement to specify the level of the tank base, how parallel and flat the walls was constrained by the capability of the University's building contractor. A typical tolerance of 10 mm was agreed over the length of the tank.

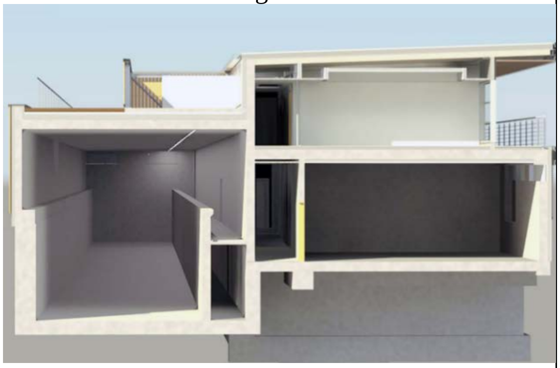
### 3.2 PROCUREMENT

Engineering design consultancy FNC was appointed to support the academic staff and WUMTIA engineers in creating the design brief and technical staff. The rapid pace of development of the building constrained the effort that could be spent on the dimensions and shape of the carriage walls. However, the use of the consultants did allow an initial safety case to be developed that was used to inform the whole process and allowed safe operation to be at the heart of design alongside ensuring access would be possible for all.

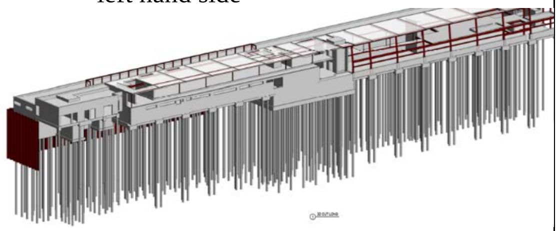
It was identified early on that a non-standard carriage drive system would be required to achieve the high speed due to site length constraints. It was decided that a solution evolved from the Isle of Wight GKN tank using cable drive rather than carriage mounted motors would be suitable. This has the beneficial effect of reducing carriage mass as well as allowing accelerations much greater than the 0.1g of conventional friction contact of steel wheel on rail.

(a) Final Plan building with towing tank in blue on North side

(b) Architect's render of entrance and South face of building



(c) Cross-section with tank and walkway on left hand side



(d) Concrete layout showing steel piles

Figure 2: Various views of Building 185

Procurement regulations required a tender process for the carriage, its drive system, and the side beaches whereas the rail installation, wave maker installation were within the remit of the main building contractor Wates. A competitive tender process in 2014 resulted in the award of the construction to Penman Ltd. of the carriage and side beaches to the design specification of FNC.

### 3.3 BUILD DELAYS

Delays often associated with the concrete construction and poor weather resulted in a six month delay to the handover of the building to spring 2015. One short section of the South wall had to be re-engineered to achieve necessary tolerance of verticality. Overall the smoothness of the concrete walls and section profile was achieved. The exposure of the tank to the environment before the roof was completed meant that a layer of dirt was deposited within the tank which caused water quality problems later on.

### 3.4 FIT OUT

In parallel of the build, the remaining equipment was specified and selected internally with the support of FNC. This included discussions about the carriage concept design, the choice of wavemaker and the side beaches and end beach designs.
The carriage was delivered in June 2015, at the same time the tank was filled with water (4.2).

When the time came to procure the carriage drive system in 2015, Penman was selected as the main contractor, with another Scottish company ACE Winches supplying the winches.

### 3.6 SUPPLIER BANKRUPTCY

In the Autumn 2016, Penman was declared bankrupt and went into liquidation. At that time, the work on the drive system was well underway for a planned delivery in the summer 2017. The winches had already been manufactured by ACE Winches.

A first iteration of the side beach had also been installed in the tank back in 2015, but the wall building tolerances, the size of the wall recess and the choice of too heavy materials were causing major issues. A major redesign of the beaches had already been started by Penman.

### 3.7 RECOVERY AND COMPLETION

Soon after Penman's bankruptcy, discussions started with ACE Winches with the intention of appointing them as the new prime contractor for the carriage drive system, with English company Iconsys in charge of the control system.

Delays in the tendering and legal processes meant that the contract was only awarded to ACE in May 2018, with a change in winches position from being mounted on the vertical tank East and West walls to being located on the roof. ACE proposed this improved technical solution for the winches position and also suggested to add motors so the winches could move transversally whilst pulling the carriage, allowing the cable to stay in line with the tank longitudinal axis and therefore increasing the tank usable length. After internal discussions with regard to potential planning permission challenges, the roof solution was discounted by the University in the Autumn 2018. A revised solution was proposed by ACE: two winch houses would be built at each end of the building. A planning application submitted in December 2018 was refused in April 2019. After consultations, a permitted development route was however granted in August.  The winch house erection started in the Autumn 2019, at the same time as the six kilometres of electric and data cables and the drive cabinets were installed. The winches were delivered in January 2020 and the roofs installed shortly thereafter (Figure 3).

Figure 3: East winch delivery

Soon after the first carriage movement on 18th March 2020 the UK went into COVID-19 lockdown and the project was halted. Due to key contractor staff availability, it was only in September 2020 that the project team was able to return to site. The project was again halted in January 2021 during the second lockdown and then resumed in the summer of 2021. Work on the tuning of the control system then proved more difficult than anticipated. There were also some delays due to technical issues with the crash-stop brakes and the design of the cable link with the carriage. Once these were resolved, the drive system was finally handed over to the University on 1st February 2022. This was almost 10 years since the team at Southampton started with a blank sheet of paper for B185. Cumulative delays with construction, procurement, bankruptcy, a global pandemic and tuning amounted to 55 months and with a further technical delay of 5 months out of that 10 years.

A Dorset based company Scale Engineering was in parallel contracted to take over the side beach redesign and completion, as they had already worked in the preliminary specification phase of the system pre-bidding. Using the Penman work on the system redesign as a basis, Scale was able to prove that concept by installing a prototype on a perfect dummy wall section and then a near-final batch of beaches in the tank. They were then contracted to supply the rest of the system in 2019 and the whole installation was completed in February 2020.

## 4 FINAL DESIGN AND CAPABILITIES

### 4.1 RAILS

When the GKN towing tank on the Isle of Wight closed in 2008, the University was able to salvage the carriage bogeys, the rails and the soleplates. Although the bogeys could not be re-used and the rails had been cut in random places, 440 soleplates were refurbished and fitted in the Boldrewood tank. They allow for horizontal, vertical and roll adjustment of the rails. The new rails were delivered in sections and welded in situ (Figure 4) in January 2015.

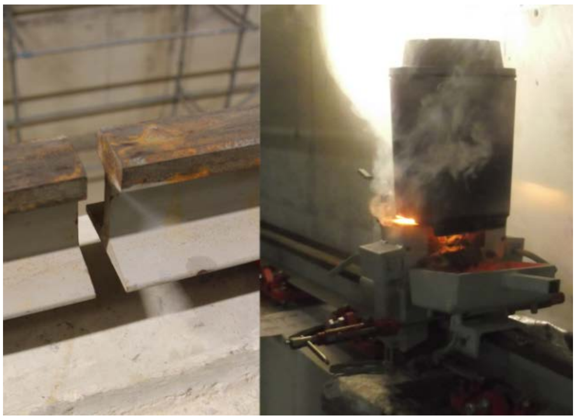


Figure 4: Rail welding

The rail alignment in a towing tank is a very important process and must be carefully thought through. Misaligned rails can lead to a bumpy ride and noisy measurements.

A review of existing literature (Du Cane, 1964) and the excellent work at AMC (Sprent and MacFarlane, 2007) showed the following:

- The concrete should be allowed to settle in once the tank is filled with water. The AMC tank staff measured deflections of up to 1.2 mm in the rail alignment within 12 months of filling the tank;
- The use of a laser or telescope is not recommended due to the temperature and humidity gradients in the air;
- The rails must be aligned vertically to follow the curvature of the earth (in Southampton, the Sagitta for an east to west orientated tank of 138 m is about 0.6 mm), horizontally and in roll;
- The top faces of the rails must be level to within ±0.1mm over their length.

The rail alignment process was started in January 2016, or eight months after the first tank filling. This was assumed to give enough time for the concrete to settle.

The following methods were used, as recommended by the literature review and refined in house (Figure 5):

- For top surface roll adjustment, a master spirit level with a precision of 0.02 mm/m was used;
- For the longitudinal alignment, a 150 m long and 0.3 mm diameter Dyneema® fishing line was attached to one bespoke winch at each rail end. This line has a breaking point of about 25 kg and very little stretching: it could then be pulled very tight and reduce the catenary effectively. A microscope was mounted on the rail to look down at the line and perform the adjustment with high precision (A and B on Figure 5);
- For the vertical alignment, the tank walls had been designed with a continuous small trough along the tank walls in the concrete. This trough was filled with water (a surprising 600 L). Two steel pins were precisely machined and fitted on a sliding bracket on top of the rail. A datum was taken at one end of the tank to adjust the vertical drop of the pins so their pointy end just broke the surface tension of the water (C and D on Figure 5). The bracket was then moved along the tank to the desired alignment location. Each pin was checked and readjusted to the datum on a regular basis due to the water level changing slightly with evaporation.

These methods, relying on the human vision, allowed the rail alignment to be performed by one single person. The towing tank technician David Turner took about three weeks per rail to finish the alignment process. The Boldrewood towing tank only has a walkway on its south side, so a floating pontoon had to be used for the north rail alignment, which made it even more challenging.

Figure 5: Rail alignment techniques

The vertical alignment of the south rail was checked in 20 spots along the tank length in June 2016. This showed that the concrete did not move during that period. Periodic spot checks were performed every year on the south rail before 2023 and showed no measurable movement.

After the carriage was commissioned in 2022, it was always the intention to perform an accurate vertical alignment check using two ultrasonic wave probes (one on each side of the carriage). Due to the long experiments waiting list, this was only performed in April 2023 (Malas, 2023).

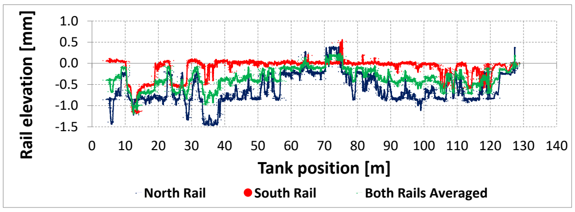


Figure 6: 2023 rail alignment check results

Results (Figure 6) show that:

- The south rail is almost perfectly aligned in the central section of the tank. Both the east and west ends show some more variations which are believed to be the consequence of the presence of surface rust, which is itself caused by the proximity of the ventilation louvers and the less efficient action of the carriage rail brushes at each end of the tank;
- The north rail’s vertical alignment is less satisfactory, with more variations in relative height (from -1.0 mm to 0.5 mm in the central section). It is believed that this is the direct consequence of having had to perform the alignment from a floating pontoon
- On average, the rails’ vertical alignment is good, especially in the central section where the steady state measurements are performed (±0.5 mm)..

Potential actions will be discussed in the near future and could include:

- Implement an automatic correction for the sinkage measurements as a function of carriage position (as done in the SSPA towing tank in Sweden);
- Perform a new alignment of the North rail using a bespoke platform mounted on the rolling bridge (and therefore not floating);
- Repeat these measurements to monitor potential concrete movement and seasonal effect on the rails’ vertical alignment.

## 4.2 WATER AND FILTRATION

The tank room has been designed without any windows to avoid direct sunlight on the water. This has been known to cause issues in some tanks due to re-circulating currents, thermocline or algae growth that can affect the quality and repeatability of the results over the seasons. The towing tank was filled in June 2015 with about 2900 m$^3$ of freshwater. As the Boldrewood campus is located close to the highest point in Southampton, there was a concern about a possible drop in the water pressure in the mains, so the water was delivered by 120 tankers over the course of about three weeks.

The installed filtration system had been incorrectly specified and could not cope with such a large volume of water. Towards the Autumn 2015, a layer of white slime had developed on the surface of the water. A water analysis revealed that this consisted in high levels of unidentified bacteria, but not of a dangerous type for humans (results came back negative for E. coli, coliforms and Pseudomona aeruginosa).

A visit in the ECN tank in France – which is very close in size – showed that the installed pump and filters were too small. It was therefore decided to perform a manual shock treatment with Sodium Hypochlorite (or chlorine) to stop the growth and kill the bacteria, to overhaul the filtration system including the addition of a chlorine injection system in order to prevent this growth happening again

By the end of 2016, the new filtration system was operational. A new bigger pump (designed to run at a flow rate of about 35 m$^3$/h), two large sand filters, a large UV lamp and the chlorine injection pump were installed. The pipes diameter was increased from 50 mm to 100 mm. The new system runs every night from 6pm to 5am in order to avoid recirculation currents in the tank during experiments. It treats the whole volume of water in approximately a week. Chlorine levels are monitored weekly and are kept around 1 ppm. In addition, the tank bottom is cleaned a couple of times a year using a swimming pool robot. Since the new filtration system was installed, there has been no issue with the tank water quality.

## 4.3 CARRIAGE

### 4.3 (a) Carriage design

Several options were considered for the carriage design: a conventional carriage with either on-board or out-board propulsion or a dual carriage (main manned carriage for lower speeds and unmanned high speed secondary carriage). In order to reduce complexity and to achieve the target speed in the relative short length of the tank, the conventional carriage with a dual cable out-board propulsion system was chosen.

The carriage design was refined in collaboration with FNC and consisted in an innovative lightweight aluminium ring design, which had to be delivered in four sections due to the building configuration (Figures 7 and 8). The ring structure brings structural stiffness without having to have additional beams like in many other tanks.

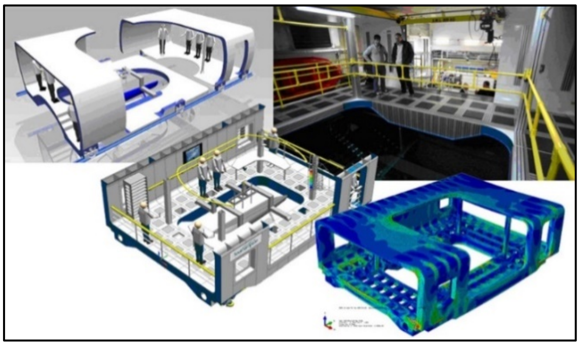


Figure 7: Development of the carriage design

Figure 8. Delivery of a carriage section

The sections were then assembled together using eight large threaded rods (Figure 9). This was performed in June 2015.

The carriage was designed with ease of work in mind. It provides a very open layout, so installing and securing equipment around and under the moonpool is easily done. As the tank is too short to be fitted with a dock, a lifting moonpool platform allows good access to the model. There is a large 2 t overhead crane at the East end of the tank allowing the transfer of models from the workshop to the water or equipment on the carriage and a smaller 500 kg hoist on-board.

Underneath the carriage are permanently installed two video cameras, two DSLR cameras and two spotlights. These provide the driver with a live video feed from under the carriage and users with the possibility of taking high definition photos or videos of the experiments.

The carriage is fitted with four two-wheels bogeys, each of them being equipped with four plastic horizontal wheels to prevent any lateral movement. Each corner of the carriage is fitted with a rail brush and the south bogeys (on the walkway side) are also fitted with guards.

Figure 9: Completed carriage

### 4.3 (b) Drive system and winches

The drive system consists in a dual cable tow system. The two cables wound/unwound from a winch drum at each end of the tank allows a differential tension to be applied that can give greater control of speed. Although continuous cable driven carriages have been operated in the past, it is believed that the Boldrewood carriage is the first one with a dual cable propulsion system.

The carriage can be controlled from either on-board the carriage or remotely from the East end dock. This allows remote or autonomous operations if deemed necessary. In addition, it is also possible to control the carriage from inside the winch houses (using the WAB) during maintenance operations.

The two winches are electric and can pull up to 3.6 t thanks to the two 315 kW main motors. As described in 3.7, they are fitted with traverse motors and slide sideways so they always pull parallel to the tank longitudinal axis. The winches are fitted with disc brakes operated by an air compressor in each winch house. Each winch sits lower than the carriage link which is located at the top of the structure. As a consequence, the winches are pulling vertically as the cable is going through a 90° sheave. This allows a load pin to be fitted on each sheave to monitor rope tensions.

The cables consist in two 150 m long and 14 mm diameter Dyneema© synthetic ropes. Dyneema© was chosen as it is stronger, lighter and stretches less than steel for a same diameter. These ropes can sustain 18 tonnes tension before breaking, which provides a safety factor of 4.5.

The cables are connected to the carriage via two weak links or breakaway connectors. These consist in one male part and one female part held together by a brass pin designed to break at 4 t tension and free the link, to avoid damaging the carriage in case of overload.

The carriage position is measured at all times by two on-board high-speed lasers and another one located at the west end of the tank room. The carriage speed and position signals are provided to the carriage acquisition system.

The drive system is designed to allow the carriage to be operated both ways, towards and away from the wavemaker. This allows following seas experiments in addition to the typical head seas tests. In order to be as flexible and efficient as possible, up to four incrementing speeds can be programmed for a given run.

The input parameters of each run are saved in a database and can be consulted or recalled at any time.

### 4.3 (c) Control

The carriage drive system is controlled by the bespoke control and safety softwares through a suite of high-end Siemens© drives (Siemens© Sinamics S120 chassis modules).

Typical high-performance drive systems rely on a stiff mechanical system between the motor and the load. This ensures that accurate dynamic positioning of the motor shaft results in equivalent accurate positioning of the load. Traditionally, the design of the mechanical system between the motor and the load results in sufficiently high torsional stiffness and sufficiently low backlash or other ‘lost motion’ that the ‘motor shaft to load’ position error under dynamic conditions (acceleration and deceleration) is negligible.

To achieve this scenario with the Boldrewood tank and carriage would require that the transmission system, motor and drive system are mounted on the carriage. This increases the space required (which is not available) and the mass to be transported by the carriage. This creates a self-inflicted problem. The carriage mass increases, so a bigger drive system is required, so the mass increases, so a bigger drive system is required, etc. This is particularly the case where reasonably high accelerations are required to achieve the high target speed in a limited length, as increasing acceleration requires increasing torque which requires larger hardware.

Moving the drive system away from the carriage removes this problem but creates a new one. Using two winches, one at either end of the tank in an ‘unwind/rewind’ configuration, allows the carriage to be pulled in either direction, with the other winch ‘holding back’ the carriage during deceleration.

This creates a transmission system that differs significantly from a traditional mechanical system:

- The rope stretches based on the tension applied to it. This changes during acceleration and deceleration;
- The working length (paid off the drum) of both ropes changes as the carriage travels from one end of the tank to the other.

These two factors create a non-linear relationship between the motor and the load, that must be solved continuously in the control software. The solution implemented in the control software achieves performance similar to a mechanically stiff system, using software techniques to overcome the drawbacks associated with the winch and rope solution, whilst still achieving the weight and space saving of an off-carriage drive system.

The control system runs with a fixed 1 ms cycle time, synchronised across all hardware in the loop (the drive system itself, as well as the encoders and analogue inputs located in each of the winch houses). The current controller in each drive runs at 250 µs. Every millisecond, the carriage position and speed are read from the laser located at the West end of the tank, along with the position and speed of each winch drum and the tension in each rope. The control system directly controls the position of the two drums, with individual instructions of the order of tenth of millimetres, to adjust for the expected rope stretch based on the known characteristics of the system, as well as the actual rope stretch, as observed by the load pins.

The system is highly tuned, to the extent that it accounts for the manufacturing tolerances of the winch drums. The two circumferences (3213 mm and 3201 mm) differ by 0.37%, which is enough to create a disturbance that must be accounted for within the software.

### 4.3 (d) Carriage stopping

There are three stopping processes implemented in the tank drive system:

- The normal stop is performed by the forward winch stopping the pull and the aft winch slowing down the carriage by reducing its rotation speed and therefore increasing the tension in the aft cable. This braking is designed to stay within the same mode of operation as the run being performed. This is performed automatically by the drive system at the end of the run, with the stopping point being calculated to maximise the usable length in the tank. It can also be triggered by the driver or the emergency stops present in various places around the facility (4.8);
- Should the normal stop fail to be activated within the pre-calculated limits in the tank, a back-up stop process is automatically triggered by the

system. The back-up stop does not use the carriage motion controller, but rather is controlled through safety-rated software and hardware. This stop has therefore higher integrity and robustness. The downside is that the ramp down stop is just a simple ramp. There is no tension control of the other rope, so it is likely that more of a reset is required to get back up running afterwards. In terms of deceleration, it is set to stay within the same mode as the performed run;

- The last stop is called the crash-stop. As suggested by the name, this is what prevents the carriage crashing into the end wall and/or the wavemaker should the first two stop not happen or one of the rope snaps. This process is completely independent from the winches and consists in eight brake pads located next to the East carriage bogeys. The pads are activated by a pneumatic/spring device, with a dedicated compressor on-board the carriage. When the crash-stop is activated, the winches are left free-coasting for a few seconds before they are stopped by the disc brakes, dumping the ropes in the water and avoiding any high tensions in the system.

## 4.4 WAVEMAKER AND END BEACH

The HR Wallingford deep water hinged paddle wavemaker was installed at the west end of the tank in the Spring 2015 (Figure 10). It consists of 12 independent paddles and can also generate oblique waves, which is not a conventional feature for a towing tank wavemaker but allows static experiments to be performed at varying wave angles using the underwater platform (4.7).

Figure 10: View of the wavemaker after installation

A parabolic end beach (Figure 11) was also designed in house and installed in the Spring 2015 at the east end of the tank to dissipate the energy of the waves and cancel reflections. This beach works well for low amplitude wave <0.1 m but less effective beyond that although combined with the side beach the wave energy can typically be dissipated in less than 10 minutes.

Figure 11: View of the East end static beach during tank filling

## 4.5 SIDE BEACH

In addition to the end beach, and in order to increase the facility productivity, the tank is fitted with an automatic side beach system on the South wall. This is in essence a replica of the GKN tank system, which was considered to be the most efficient solution. The wall is fitted with twelve batches of five 2 m wide beaches each (Figure 12). Each batch has a dedicated control box and linear actuator and the whole system is synchronised. The side beach panels deploy 100° from the vertical and about 20% of the panels (about 90 mm) is immersed.

Unlike floating swimming lanes that can take a long time to be deployed or removed and cannot be deployed between runs, the side beach deployment is activated by pressing a button on the carriage drive station or in the walkway. They are left deployed during calm water runs and can be deployed between seakeeping runs to reduce the waiting time and increase the facility productivity.

It should be noted that there is a gap between the bottom of the beach panels and the side walls. This gap being above the calm water level, causes small short transverse waves to be created in the tank when the wavemaker generated waves get large enough to reach it. Although this issue is more visual than anything else, a folding rubber flap that covers the gap has been designed in-house and is currently being installed.

## 4.6 DYNAMOMETRY AND ACQUISITION

### 4.6 (a) Carriage dynamometry and acquisition

The carriage dynamometer was specified and designed in-house by WUMTIA. It consists in a one to three post flexible cage system that can be fitted with three different sets of flexure plates:

- Drag and side force range: 0 - 150, 500, 1000 N;
- Vertical force: not measured;
- Roll moment range: 0 – 30 Nm;
- Yaw moment range: 0 – 40 Nm;

- Pitch moment: not measured;
- Pitch range: ±18 degrees;
- Roll range: ±45 degrees;
- Pitch: free;
- Roll: free or adjustable fixed;
- Yaw: adjustable fixed;
- Heave: free;
- Surge and Sway: fixed.

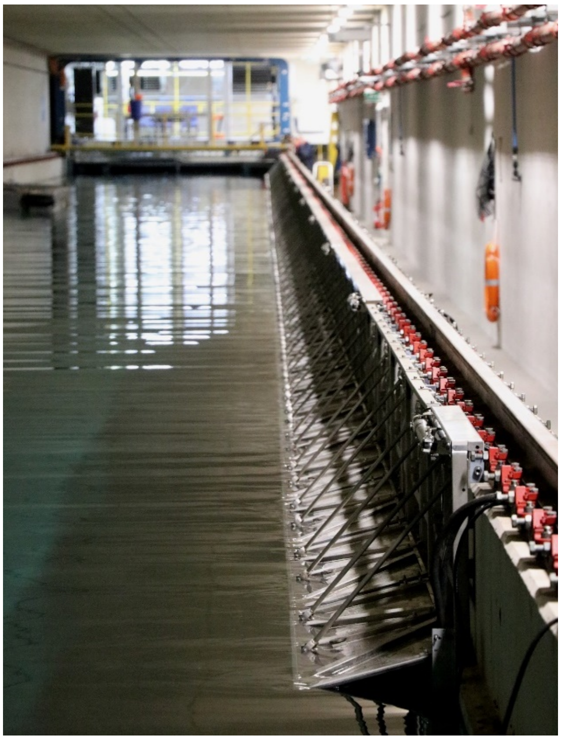


Figure 12: View of the deployed side beaches

An acquisition software was also specified internally, based on past experience and WUMTIA existing programme LASSO. The software was then developed in LabVIEW by SSDC, a local Hampshire based company. It includes an automated backup feature on a University server, allowing users to download their experiments data remotely.

### 4.6 (b) Motion capture

The University purchased two Qualisys motion capture systems for the towing tank in 2016: one for above water measurements and one for under water measurements. The two systems can also be coupled for hybrid measurements. Using reflective markers, the measurements can precisely track single point trajectories in space or six degrees of freedom for rigid bodies. This technology is versatile and has allowed the university to develop new experimental methods and setups used for various education, research and commercial projects in the facility (Malas et al., 2019) and also in swimming pools.

### 4.6 (c) Wave probes

A set of four General Acoustics ultrasonic wave probes and their dedicated acquisition box were purchased in 2015. The probes can be individually connected to up to four channels, or be combined in groups of two or three per channel in case of steep waves or high speed, which can sometimes be a challenge for single ultrasonic probes. Each channel can then be connected to the carriage acquisition software.

### 4.6 (d) PIV

A LaVision stereo underwater PIV system was purchased in 2015. This system consists in two cameras housed in a torpedo pointing at a middle laser sheet. In order to seed the tank with the necessary plastic particles, a dedicated system was designed and built, based on TU Delft’s past experience:

- Particles are pre-mixed with water pumped from the tank in a container;
- That premix is then “jet mixed” with more tank water just before reaching a manifold;
- A lifting rake is used to seed the tank when returning to the Home position.

The PIV and seeding systems were proof-tested at low speeds by manually pushing the carriage due to the tank delays (Lidtke and Banks, 2018).

The system can also be used for underwater DIC measurements (Araujo Bento de Faria, 2019).

### 4.6 (e) Environmental monitoring

The following sensors were installed in the tank:

- 6 water temperature probes distributed along the tank length (20 m, 70 m and 120 m from the wavemaker) and at two different depths (0.5 m and 3.0 m);
- 2 air temperature and air humidity probes;
- 1 air pressure probe in the middle of the tank;
- 1 water depth probe by the wavemaker.

Using a dedicated LabVIEW software developed by SSDC, these sensors record constantly, and since 2019, the data is stored in an online database accessible through an internal webpage.

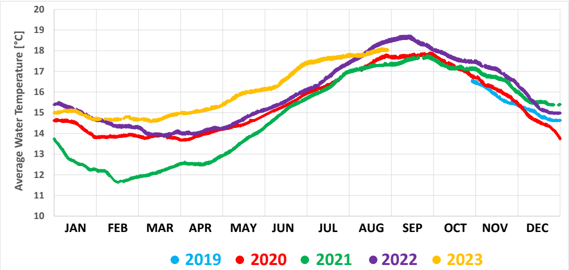


Figure 13: Average water temperature history

Over the course of a year, and thanks to the thick windowless concrete walls, the largest observed amplitude of the average water temperature in the tank is about 6°C (in 2021, Figure 13), which is minimal. For a two weeks experiment, the temperature variation is always less than 0.5 °C when other facilities are known to see variations of several degrees over the course of a single day. The measurements also show that the tank water temperature is pretty much homogeneous, with the water temperature being on average 0.2% higher at 3.0 m depth than at 0.5 m depth and the average instant measurement amplitude between all sensors being 0.2°C.

### 4.7 ROLLING BRIDGE AND UNDERWATER PLATFORM

A small secondary carriage (Figure 14) was designed and manufactured in-house in 2016. This rolling bridge is 6 m long and 2 m wide with a 500 kg central electric lifting platform that provides good access to the water surface. The bridge is moved along the tank manually and is used to launch models or mount equipment, mostly for static experiments.

In addition, an underwater 500 kg hydraulic platform was purchased from Blackfish Engineering and installed in June 2018. This lifts all the way above the water surface and is used for mooring experiments. 56 prepositioned M10 threaded holes are available on the platform top table to setup the mooring lines. The platform is located 10 m away from the wavemaker (Figure 14), allowing for high quality wave, an optimised experimental time and reduced reflections.

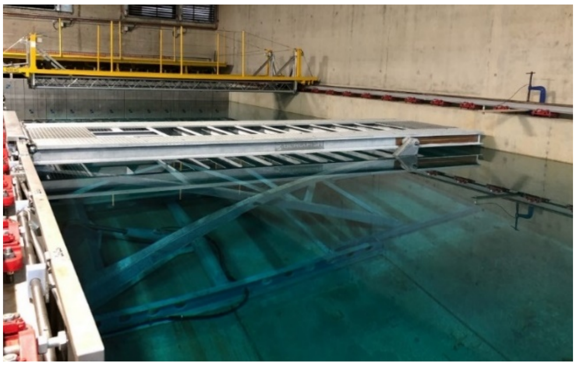


Figure 14: View of the rolling bridge (in yellow) and underwater platform (in gray)

### 4.8 SAFE OPERATIONS

The philosophy of the carriage operations was based on staff experience and past research about the effects of acceleration or deceleration on people in transport (Abernethy et al., 1977), (Martin and Litwhiler, 2008) and (Powell and Palacin, 2015). Based on these, the maximum acceleration and deceleration in normal operations were set to 0.25.g at the targeted maximum carriage speed of 12 m/s. This gives a maximum acceleration factor of 2.08% and therefore a maximum acceleration A for each target speed V:

$$A = 2.08\% \times V \times g \quad (1)$$

This factor can be reduced by the carriage driver as deemed necessary, for example when testing heavy and slow models and to avoid unwanted inertia effects in the dynamometry (especially in the transition between the acceleration phase and the constant speed plateau phase).

In addition, three modes of operation were introduced (Table 2).

Table 1: Modes of operation

| **Speed** *m/s* | **Mode** - | **Acc.** *$m/s^2$* | **Acc.** *.g* | **Max. no passengers** | **Restrictions** |
|---|---|---|---|---|---|
| 1 | I | 0.20 | 0.02 | 10 | Passengers can stand up. It is recommended to hold a safety rail. |
| 2 | | 0.41 | 0.04 | | |
| 3 | | 0.61 | 0.06 | | |
| 4 | | 0.82 | 0.08 | | |
| 5 | | 1.02 | 0.10 | | |
| 6 | II | 1.23 | 0.13 | 4 | Passengers to be seated (in a seat or on the floor). |
| 7 | | 1.43 | 0.15 | | |
| 8 | | 1.63 | 0.17 | | |
| 9 | | 1.84 | 0.19 | | |
| >9 | III | 2.04 | 0.21 | | Passengers seated and belted. |

From past experience and accounts of people being hurt during carriage braking in other facilities, it was decided that an emergency stop in the Boldrewood towing tank would consist of a controlled stop only, i.e. a deceleration within the same range of operation as the performed run. Giving the possibility to passengers to crash-stop the carriage was deemed too dangerous. The crash-stop can only be triggered automatically by the drive system in the following cases:

- The carriage reaches a distance too close to the end walls (in the unlikely event that both the normal stop and back-up stop failed);
- Rope snap;
- The carriage position data is lost (for this reason, the carriage lasers and reflection plate were covered with guards and warning signs preventing people from obstructing the laser beams).

The facility is also fitted with some emergency stop buttons for the drive system:

- 3 on the carriage;
- 1 on the remote PLC;
- 1 on the WAB;
- 2 pull cords covering the whole length of the walkway.

The emergency stops and crash-stop are all tested every six months. The crash-stop testing is done by using a voluntary triggering function implemented in the drive system (protected by password).

There are also a number of interlocks in the facility to prevent a run to be started if:

- The rolling bridge is not parked at the west end;
- The underwater platform is not at the bottom of the tank;
- The carriage crane is not locked;
- The gates to the walkway are not closed.

Due to the tank room configuration, access to the walkway during carriage operations has to be managed carefully – once in the walkway, there is no easy escape route. Access is therefore limited to a small number of experienced staff, who can escort visitors.

## 5 COMMISSIONING AND VALIDATION

### 5.1 WAVEMAKER AND END BEACH

The wavemaker was commissioned by HR Wallingford in the Summer 2015, using the first side beach design iteration to provide a straight wall (3.6). It is capable of generating regular and irregular waves with a maximum height of 0.70 m and a significant wave height of 0.37 m respectively (Figure 15).

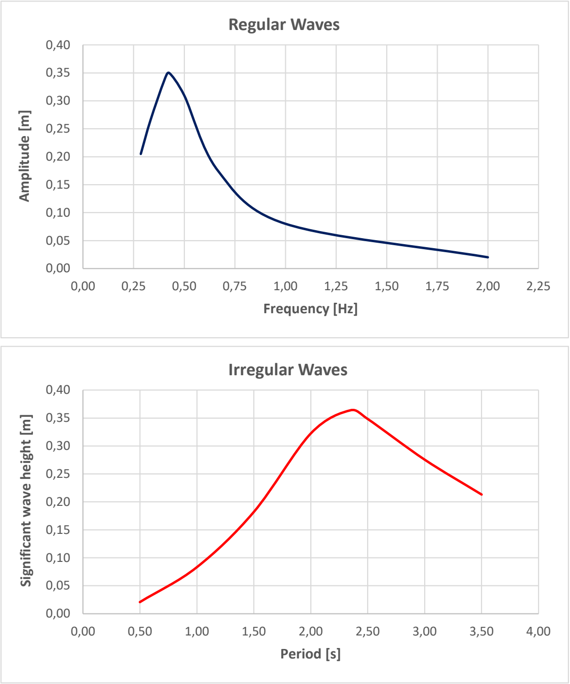


Figure 15: Wavemaker capability plots

The limits are defined by three parameters: the steepness of the waves (to ensure they do not break), the stroke limit of the paddles and the tank freeboard.

### 5.2 CARRIAGE PERFORMANCE

#### 5.2 (a) Crash-stop

Unlike the normal and back-up stops which performances are easily and accurately predicted, the crash-stop process was extensively tested during the commissioning phase, in order to fully understand the behaviour of the brake pads and the pneumatic system.

The compressor operates in fail-safe mode, meaning that it is holding the pads away from the rails permanently by maintaining a constant air pressure in the system. Should the pressure drop for any reason, the brake is activated and prevents the carriage from moving until the problem is resolved. The brake pads have to be bedded in with one voluntary induced crash-stop in each direction at about 2 m/s before they achieve their expected performance (Figure 16).

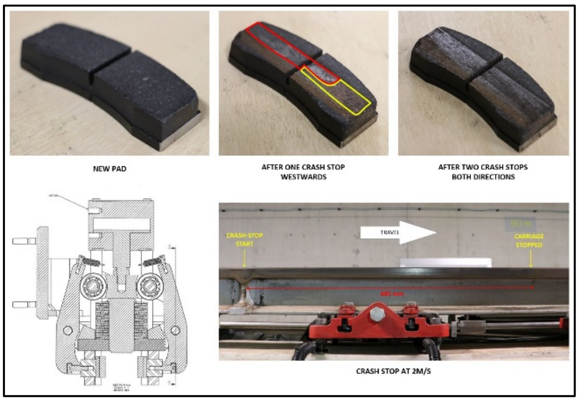


Figure 16: Crash-stop braking

As an example of the crash-stop effectiveness, when accounting for the reaction times of the system (about 200 ms), it takes about 1.1 m to stop the carriage at 2 m/s. The obtained deceleration was measured at about 0.35.g at the top speed.

The life of the brake pads is limited: at low speeds, they can cope with four or five crash-stops, and at the top speeds, they have to be changed after a single one. In all cases, they are inspected after each crash-stop.

#### 5.2 (b) Maximum speed

Towards the end of commissioning, and due to the delays and budget limits, the maximum achievable carriage speed was reduced from 12 m/s to 10 m/s westbound. The number of experiments expected above 10 m/s was always minimal. Due to small physical differences and again a lack of available time, the eastbound maximum speed had to be reduced to 8 m/s. These reductions have very little consequences with regard to the tank’s capabilities.

#### 5.2 (c) Weak link

The weak links are made of two heavy stainless steel parts. In the event of the pin breaking, the male part, connected to the rope, flies around the tank room. At first, this part was secured to the carriage using a secondary steel cable, but this caused a rope snap and sheave breakage during commissioning, so this solution was abandoned. In order to understand the behaviour of the male part, progressive breaking tests of the safety pin were performed with a static carriage. A high speed camera was used to film the link (Figure 17) and the distance travelled by the part along the tank X and Y axes was measured. The male part was covered with a yacht fender cut in half in order to prevent damage to other equipment.
The tests concluded that the part can travel up to about 30 m along the tank, but stays roughly in the middle.

For this reason, the safety procedures were modified and now prevent people from standing behind the carriage during operations (the area forward of the carriage was always forbidden). The walkway access procedure remained unaffected.

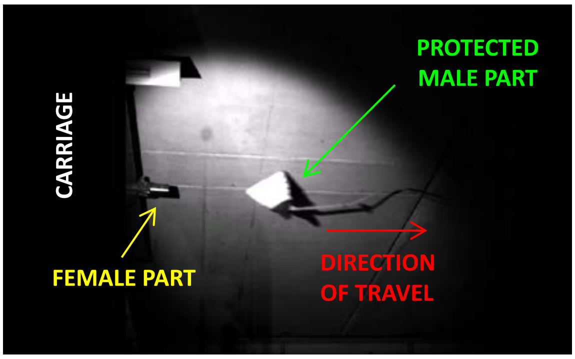


Figure 17: Weak link release

5.3 (c) Carriage performance

Speed tests in both directions were performed in 2022 with the carriage manned by one person and no model in the water. The detailed results are provided in a dedicated report (Malas, 2022) and can be summarised as follows:

- Speed finding: The average measured speed is constantly below the target speed. The difference decreases almost linearly to reach a maximum between 10 and 15 mm/s at 8 m/s. For the westbound travel, the difference then decreases to 7 mm/s at 10 m/s. There is a discrepancy between both directions, with the eastbound speed finding being less precise than the westbound one. It was suggested during commissioning that the source of the speed finding error and discrepancy could be some inaccuracies in the physical measurements of the winches circumferences. As a result and as recommended by ITTC, the speed used should always be that actually measured (ITTC, 2021);
- Speed keeping: The amplitude of the noise is consistent between both directions of travel. It slowly increases from about 25 mm/s at low speeds to about 50 mm/s at 8m/s. For the westbound travel, it then increases sharply to about 150 mm/s at 10 m/s;
- Overshoot: The overshoot time remains fairly constant at about 2 s for the whole speed range;
- Usable time: The usable time is consistent between both directions of travel. It is about 10 s at 6 m/s and goes down to just under 2 s at 10 m/s westbound.

Discussions suggest that the speed finding can be improved by either checking and correcting the actual winches circumferences or by implementing a gain correction curve in the software. The noise of the speed keeping and the overshoot time could also potentially be reduced by further fine tuning of the system.

Overall, the speed measured due to the accuracy of the laser position system comfortably meets the ITTC requirements across the whole range that '*the speed of the model should be measured to within 0.1% of the maximum speed or to within 3 mm/s, whichever is the larger*', ITTC(2017b).

## 5.3 DYNAMOMETRY

A set of validation experiments for calm water resistance was performed on a 4 m long KCS model in March 2022, shortly after the drive system was handed over (Figure 18).

The runs showed good repeatability, within ±1.0% for the measured resistance. The results were compared against the benchmark model test data adopted at the Tokyo 2015 CFD workshop (Hino et al., 2021). As the scale was different (31.5994 for the Tokyo model and 60.9547 for the Boldrewood one), the Tokyo results were rescaled using the ITTC 1957 method. Testing the same model would have been preferable, but the Tokyo model is too large for the Boldrewood tank.

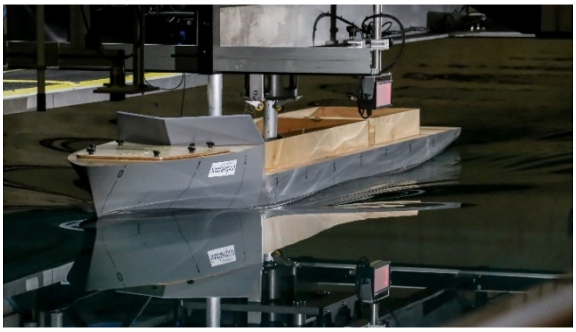


Figure 18: KCS validation experiments

Table 3: Results comparison of Boldrewood KCS with scaled data for Tokyo 2015 workshop

| | | TOKYO 2015 rescaled | Boldrewood 2022 | |
|---|---|---|---|---|
| $V_S$ knots | $V_M$ m/s | $R_{TM15}$ N | $R_{TM15}$ N | Difference - |
| 10.0 | 0.659 | 2.492 | 2.491 | 0.0% |
| 14.0 | 0.922 | 4.648 | 4.729 | 1.7% |
| 18.0 | 1.186 | 7.310 | 7.441 | 1.8% |
| 21.0 | 1.384 | 9.877 | 10.029 | 1.5% |
| 24.0 | 1.581 | 13.615 | 13.625 | 0.1% |
| 26.0 | 1.713 | 18.909 | 18.738 | -0.9% |

When using the rescaled Tokyo results as reference, the difference varies from -0.9% or -0.17 N to 1.8% or 0.15 N (Table 3) These differences are very small and well acceptable. They can be explained by uncertainty induced by the rescaling process, small differences in model making processes and therefore model shape and finish or different dynamometry arrangement and sensors.

## 5.4 CASE STUDIES

This section briefly presents some of the many projects that have been run in the Boldrewood towing tank since 2015.

5.4 (a) Freerunning full size kayak

As part of the involvement of the University in the sports engineering domain, an MSc project focused on the performance of kayaks. A full size kayak (Figure 19) was taken into the tank, with both the hull and the paddle fitted with motion capture markers and acquired as independent rigid bodies. This allowed to investigate of the relationship between the paddle position and kayak speed in waves (Suva, 2017).

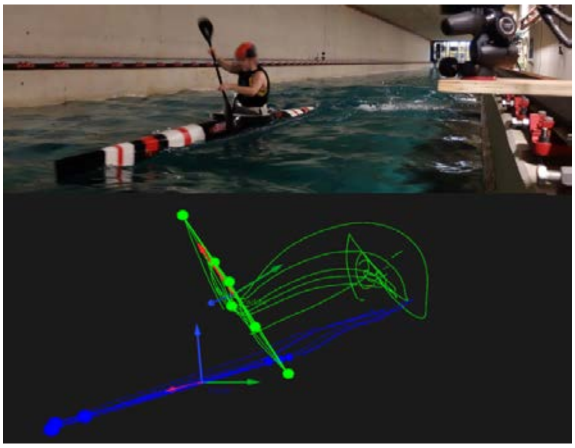


Figure 19: Free running kayak showing image of kayak and Qualisys motion capture tracks of kayak and paddle

5.4 (b) Freerunning IMOCA

The above water motion capture system was used to track the behaviour and speed of a freerunning scale model of an IMOCA yacht (Figure 20) whilst surfing large waves (Gauvain, 2019). The motion capture system was also used to measure the wave height with purpose made floaters fitted with markers.

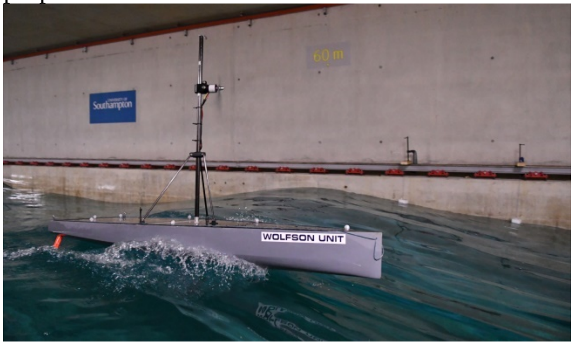


Figure 20: Freerunning IMOCA model surfing

5.4 (c) Floating wind turbine

A model of a SPAR floating wind turbine was moored in the tank using the underwater platform (Figure 21). The dynamic responses and mooring line characteristics of the turbine in rogue waves were then measured (Hayes, 2019).

Figure 21: Effect of a rogue wave on a moored floating wind turbine model. A propeller is used to represent the wind turbine thrust.

5.4 (d) Tidal energy

To investigate the effect of various winglets on the performance of a tidal turbine, a large model (Figure 22) was towed at low speeds in the tank whilst measuring its performance (Olvera-Trejo et al.).

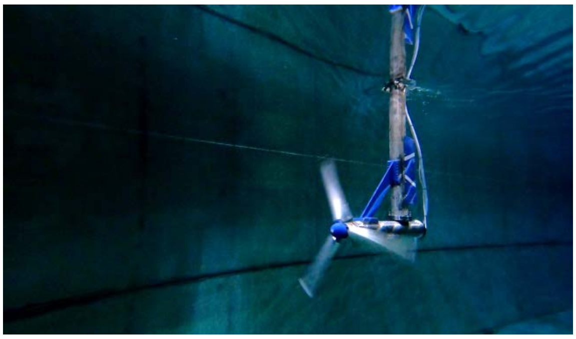


Figure 22: Tidal turbine experiments

5.4 (e) PIV benchmark case

As part of the tank validation, a standard PIV benchmark case (Muthanna et al., 2010) and (ITTC, 2017) was repeated in the facility in the spring 2023, using a flat plate and mounting system designed and manufactured in-house.

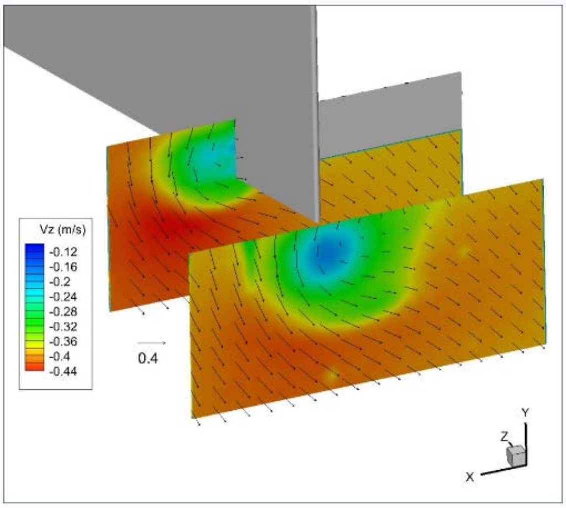


Figure 23: PIV benchmark case results

Preliminary results (Figure 23) and (Gregory et al., 2023) show a good correlation with other facilities and will be the subject of a future publication.

## 6 CONCLUSION

After ten years of efforts, the Boldrewood towing tank is now fully functional. It is an impressive world class facility that is loved by visitors and helps inspire the next generations as well as giving current and future students the physical insights their careers will need. It also provides researchers and industry an excellent tool to face the challenges of the coming decades.

## 7 ACKNOWLEDGEMENTS

The whole process of creating a fully functioning tank has required the support and dedication of a large number of external organisations and staff within the University of Southampton. Particular mention should be made of the dedicated staff of ACE Winches (Michel Horn), Iconsys, Fraser Nash Consultants, Scale Engineering (Clive Evans), SSDC (Steve Watts), HR Wallingford (Ashley Cooper), Blackfish Engineering, project managers Tom Prow and Graham Allerton, University staff Andy Claughton, Simon Cox, Barry Deakin, Barbara Halliday, Simon Mason, Rachel Mills, William Powrie, Martyn Prince, David Richards, James Sturgess, Sandy Wright, amongst many others and last but certainly not least David Turner who as tank technician has ensured the whole system has been refined and fully functions.

Funding from the EPSRC NWTF purchased the PIV and contributed to the carriage development costs. Internal University funds provided the Qualisys system. The remainder of the ~£6M fit out was funded by the School of Engineering. The whole Building 185 construction cost was estimated to be £16M.

## REFERENCES

1. ABERNETHY, C. N., PLANK, G. R. & SUSSMAN, E. O. (1977). *Effects of deceleration and rate of deceleration on live seated human subjects*. U.S. Department of Transport report no. UMTA-MA-06-0048-77-3.
2. ARAUJO BENTO DE FARIA, H. (2019). *Measurement of underwater deformation on simplified propeller blades using digital image correlation*. MEng Individual Project Thesis, University of Southampton.
3. BAHAJ, A. S., MOLLAND, A. F., CHAPLIN, J. R. & BATTEN, W. M. J. (2007). *Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank*. Renewable Energy, Issue 32(3), pp. 407-426.
4. BROWN, D.K. (2006). *The way of a ship in the midst of the sea: the life and work of William Froude*, Periscope Publishing Ltd. ISBN 978-1904381402.
5. CARTWRIGHT, R. A., WILSON, P. A., MOLLAND, A. F. & TAUNTON, D. J. (2008). *A low wash design for a river patrol craft with minimal environmental impact*. Transactions of The Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering, Issue 150(A2), pp. 37-56.
6. CLAUGHTON, A. (2015). *Wide-light project - final report*. Sailing Yacht Research Foundation.
7. DEAKIN, B. (2008). *Decades of development - 40 years history of the Wolfson Unit*. Ship & Boat International, RINA.
8. DU CANE, P. (1964). *High speed small craft*. 3rd Edition. Temple Press Books, London.
9. GAUVAIN, E. (2019). *The un-restrained sailing yacht model tests - A new approach and technology appropriate to modern sailing yacht seakeeping*. The 23rd Chesapeake sailing yacht symposium, Annapolis.
10. GREGORY, M., BOWKER, J., KURT, M., BANKS, J. & TURNOCK, S.R. (2023), *Underwater PIV benchmark at the University of Southampton Boldrewood Towing Tank*, NWTF.
11. HAYES, J. (2019). *An experimental study of the global dynamic responses and mooring line characteristics of a spar-type floating wind turbine in rogue waves*. MSc Thesis, University of Southampton.
12. HAWKES, J., VAZ G., PHILLIPS, A.B., COX, S.J. & TURNOCK, S.R. (2018). *On the strong scalability of maritime CFD*, Journal of Marine Science and Technology, Vol. 23, pp. 81-93.
13. HINO, T., STERN, F., LARSSON, L., VISONNEAU, M., HIRATA, N. & KIM, J. (2020). *Numerical Ship Hydrodynamics – An assessment of the Tokyo 2015 workshop*. Springer. ISBN 978-3-030-47571-0.
14. ITTC (2017). *Benchmark for PIV(2C) and SPIV(3C) setups*, ITTC Guideline 7.5–01-03-04.
15. ITTC (2017b), High speed marine vehicles resistance test, ITTC Procedure 7.5-02-05-01
16. ITTC (2021). *Resistance Test*, ITTC Guideline 7.5–02-02-01.
17. LARSSON, L., STERN, F. & VISONNEAU, M. (2014). *Numerical Ship Hydrodynamics - An assessment of the Gothenburg 2010 workshop.* Springer. ISBN 978-94-007-7188-8.
18. LIDTKE, A. & BANKS, J. (2018). *Underwater Particle Image Velocimetry (PIV) and dynamometry set up at the Boldrewood towing tank using BRIDGES thruster*. University of Southampton.
19. MALAS, B., BANKS, J., CAPPELLETTO, J. & THORNTON, B. (2019). *Applications of motion capture technology in a towing tank*. Advanced

Model Measurement Technology for The Maritime Industry Conference, Rome.

20. MALAS, B. (2022). *Boldrewood towing tank carriage performance analysis*. University of Southampton.
21. MALAS, B. (2023), *Boldrewood towing tank rail alignment check.* University of Southampton.
22. MARTIN, D. & LITWHILER, D. (2008). *An investigation of acceleration and jerk profiles of public transportation vehicles*. American Society for Engineering Education.
23. MOLLAND, A. F. (1996). *Resistance experiments on a systematic series of high speed catamaran forms : variation of length-displacement ratio and breadth-draught ratio*. Transactions of The Royal Institution of Naval Architects, Issue 138, pp. 59-71.
24. MOLLAND, A. F., WILSON, P.A., TAUNTON, D.J., CHANDRAPRABHA, S. & GHANI, P.A (2004). *Resistance and wash measurements on a series of high speed displacement monohull and catamaran forms in shallow water*. Transactions of The Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering, Issue 146(2), pp. 19-38.
25. MUTHANNA, C., DI FELICE, F., VERHULST, M., DELFOS, R. & BORLETEAU, J-P. (2010). *PIV operation in hydrodynamic facilities, a flat plate benchmark test comparing PIV systems at different facilities.* 15th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon.
26. OLVERA-TREJO, R., MYERS, L. E., BLUNDEN, L. & BAHAL, A. S. *An experimental study of the thrust and power produced by a 1/20th scale turbine utilising blade winglets*. Manuscript submitted for publication.
27. PONKRATOV, D. (2017). *2016 Workshop on ship scale hydrodynamic computer simulation*. Technical Investigation Department, Lloyd's Register.
28. POWELL, J. P. & PALACIN, R. (2015). *Passenger stability within moving railway vehicles: limits on maximum longitudinal acceleration*. Urban Rail Transit 1, pp. 95–103.
29. SPRENT, A. & MACFARLANE, G. J (2007). *The alignment of the Australian Maritime College towing tank*. Spatial Science Institute Biennial International Conference SSC2007, Hobart, Tasmania.
30. SUVA, F. (2017). *Measuring coupled kayak and paddler motions within a towing tank*. MSc Thesis, University of Southampton.