Improving our understanding of ship side thruster forces on existing armoured berths through physical modelling of prop-wash

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Abstract

Ship movement without supporting tugboats and the emergence of powerful self-propelled vessels has led to potentially devastating effects on structures that were not designed for jet impacts. Port operators are now left facing a decision of whether to restrict bow and stern thruster operations or to update the structure protection.

The Water Research Laboratory (WRL) in the School of Civil and Environmental Engineering at UNSW Sydney has recently open a dedicated prop-wash facility for the physical modelling of the effects of ship side thruster forces on existing armoured berths and ports. WRL has now undertaken five major port studies at large scales ranging from 1:13.5 to 1:20. Froude scale testing at these scales is unique and ensures that turbulence and drag effects are well reproduced with a high Reynolds number. The scaling rules have ensured adequate turbulence based on coastal engineering scaling rules for armour mass and providing adequate resolution and accuracy for model measurements.

This paper presents several case studies, including different structures and armour types of rock, articulated concrete mattresses and rock-filled bags). Testing found that analytical methods and guidelines generally predicted larger (more conservative) velocities, while the physical modelling demonstrated complex jet dispersion. Armour was found in some cases to be more stable than predicted by empirical methods due to a combination of structure slope, jet dispersion and energy dissipation though the armour layers.

In summary, physical modelling of the effects of ship side thruster forces on existing armoured berths has demonstrated that when an appropriately scaled model is used, the port design and operational restrictions can be balanced and optimised. While existing guidelines provides generally conservative analytical methods, modelling allows for a greater understanding of each specific port.

Keywords: physical modelling, prop-wash, vessel, port, stability, coastal structures

1. Introduction

Ship movement without supporting tugboats and the emergence of powerful self-propelled vessels has led to potentially devastating effects on port structures that were not designed for direct jet impacts. Modern vessels are often equipped with powerful propulsion systems that can typically create multiple jets with velocities up to 10 m/s directed at port infrastructure or scouring seabed fronting quay walls.

Port operators may need to decide whether to restrict bow and stern thruster operations or to update the protection of the structure. While guidelines exist [1, 2] to help the design process allow for desktop assessment and empirical equations allowing for the estimation of jet velocities and rock stability of scour protections, these guidelines also have been shown to provide results with a wide range of variability [3]. As such physical modelling is a unique tool to help developing a solution.

An extensive range of type of structures (vertical quay wall, revetments) and type of armour (rock, piles, rock bags, articulated concrete mattress) had been tested in WRL's new specialist prop-wash facility.

The paper provides an overview of the importance of conducting physical modelling at large scales and WRL dedicated facility. This will be followed by an overview of the different type of structures and armour categories that have been tested and highlight the main failure mechanism that have been observed during testing.

The testing that WRL has undertaken have tested include up to 4 azipods and 4 bow thrusters with typical propeller diameter ranging from 4 to 7 m. Typical draft of the tested vessels are approximately 10 m and the water depth at the berthing area could be as low as 12m during low tides. The "Oasis of the Seas" is an example of such a vessel. The azipods and bow thrusters of the "Oasis of the Seas" is shown in Figure 1 and Figure 2.

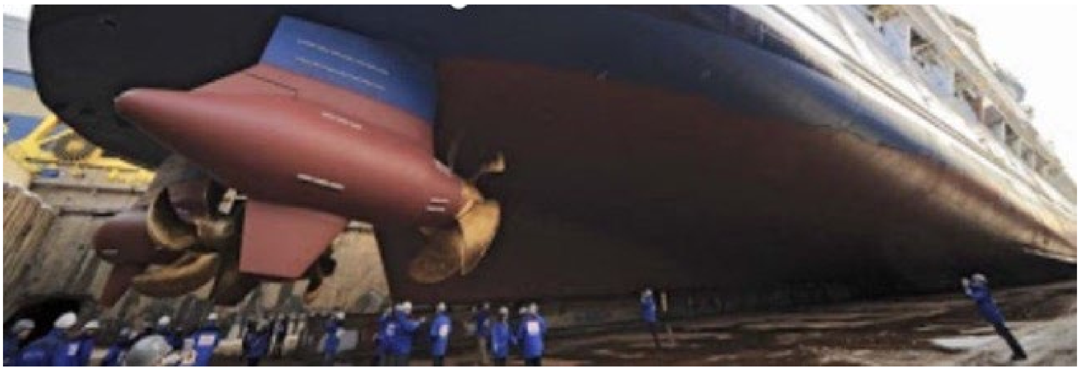


Figure 1 Oasis of the Seas Azipods

Figure 2 Oasis of the Seas Bow Thrusters (Cruise News Daily Newsfile)

Figure 3 WRL’s Prop-Wash Basin

2. Scaling Considerations

All prop-wash models tested at WRL were carried out at a relatively large scale of 1:13.5 to 1:20. Testing at such large scale was critical to ensure:

- representation of propeller wash jet characteristics.
- adequate turbulence for stability testing.
- adequate resolution and accuracy for model measurements
- Sufficient armour (rock or concrete) size to ensure good geometric characterisation (shape) and roughness,

Modelling is completed using Froude scaling as gravitational processes dominate. The limitation on the scale is to ensure that adequate turbulence is included by ensuring the Reynolds number is high enough (generally > $3x10^4$) for fully turbulent flow conditions. An illustration of the importance of conducting physical modelling at large scales is provided in Table 1 with Reynolds numbers calculated for 3 different example configurations:

- A 6.0 m propeller jet with a velocity of 8.0 m/s.
- A 5.0 m/s jet impacting a 3T rock revetment.
- A 5.0 m/s jet on a 0.5m unit size ACM.

Table 1 Reynolds Numbers Example configurations

Config.	Jet	Rocks	ACM
Velocity (m/s)	8	5	5
Length (m)	6 prop. dia.	1 D50	0.5 unit
Scale	**Reynolds Number**		
(prototype)	$4.8x10^7$	$5.2X10^6$	$2.5X10^6$
15	$8.2x10^5$	$8.9X10^4$	$4.6X10^4$
20	$5.3X10^5$	$5.8X10^4$	$2.8X10^4$
30	$2.9X10^5$	$3.2X10^4$	$1.5X10^4$
40	$1.9X10^5$	$2.1X10^4$	$9.8X10^3$

These examples shows that a scale of at least 1:30 is necessary for a 3 T rock revetment and a scale of at least 1:20 is recommended for the ACM example.

By their nature, models are simplifications of the reality under investigation. Physical modelling and testing should aim to answer specific questions. The kind of models tested in WRL prop wash basin focus predominantly on modelling the impact of water turbulent jets generated by vessel propellers, the jets' dissipation and the stability of the tested structure. The propellers are scaled to match the diameter and efflux velocity but not always match the exact pitch and number of blades. Differences in pitch and number of blades are not expected to have significant effect on results, however there may be slight differences in the characterisation of turbulence and to a lesser degree the jet dispersion.

3. Large scale calls for large facility

The Water Research Laboratory (WRL) in the School of Civil and Environmental Engineering at UNSW Sydney has recently open a dedicated prop-wash facility for the physical modelling of the effects of ship side thruster forces and vessel propeller wash on port and coastal infrastructure (Figure 3).

This new facility consists of a 4m x 7m x 1.4m deep basin in which project specific bathymetry, mobile sediments and breakwater armour can be installed. The basin is equipped with four submersible frequency-controlled power motor units (Figure 4) and various sized propellers which can simulate a wide range of thrusters or azipods and vessel types. The combined advantages of testing with large water depths (up to 1.2 m) and high velocity jets (2 m/s) allow WRL to test at unprecedented large scales ranging from larger than 1:20.

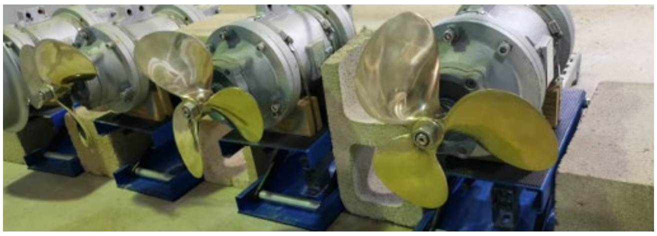


Figure 4 Four independently controlled propellers

As the water depth of a port is typically 12 to 15m, the basin needs to be more than 1m deep.

Independent control of each motor allows for modelling of Azipods or Bow Thrusters. WRL has further found that the jet from a propellor behaves differently from a water based jet, making a model scaled propellor more appropriate.

Measuring high 3D velocities in a model requires specialist equipment such as multiple ADVs (Figure 5).

Performance and damage are assessed during testing sequence (transient) using underwater videos (such as uplift of flapping of ACMs) and after testing using 3D laser scanning to assess damages by comparing it to pre-test scans (Figure 9).

Finally, we have found it important to be able to test with both rigid and mobile bed configuration. Scour of sand is not scalable (i.e., does not give a precise prediction of temporal evolution of scour holes) but allows the model to indicate performance of scour protection/structure when scour hole progress and impedes onto structure.

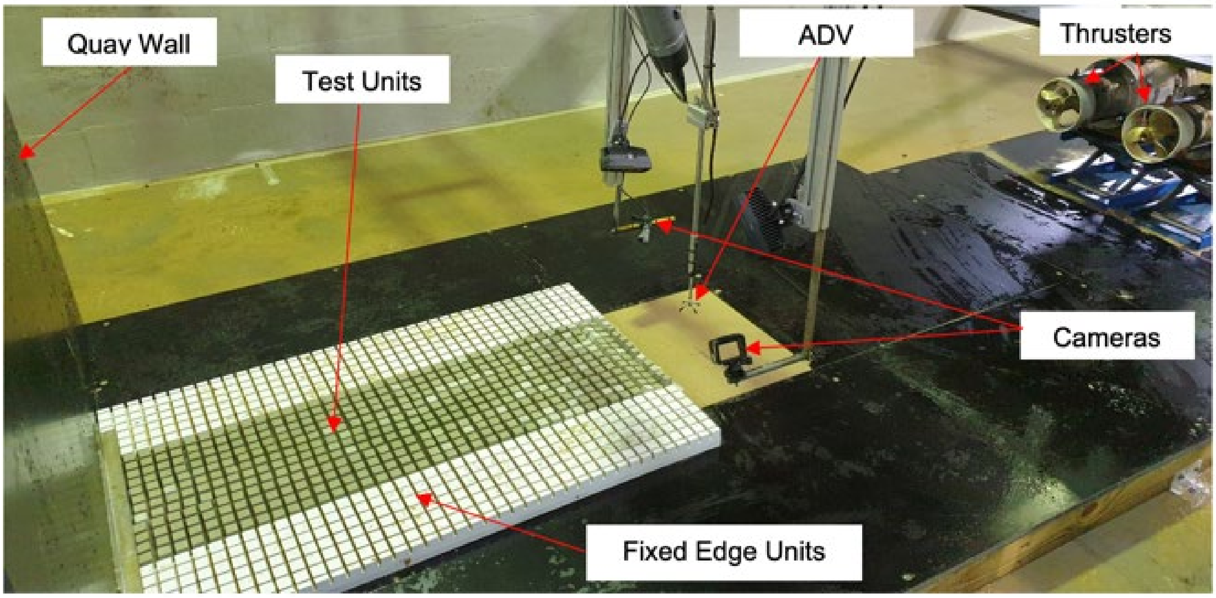


Figure 5 Photos of a model setup with ADV and underwater cameras

A typical model setup using 4 submersible motors in front of a quay wall and a bed protected with concrete mattresses is shown in Figure 6. The propellers are installed within scaled pipes to model the jets from 4 bow thrusters.

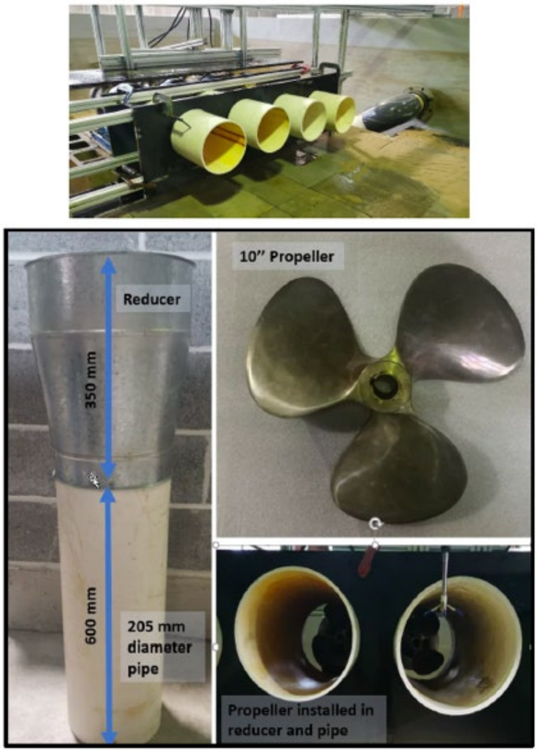


Figure 6 Example of a model setup with 4 propellers in front of a quay wall

4. Analytical Methods vs Physical Modelling

Velocity measurements at high velocities in front of a 12'' and 14'' propellers central axis were collected and compared to analytical methods recommended by PIANC (2015). The two methods considered are:

- The Dutch Method:

  $$V_x = (2.0\ to\ 2.8) * \ V_0 * (\frac{D_p}{x})$$

  V_0 is the velocity half a diameter from the propeller, D_p is the propeller diameter and x is the distance from the propeller

- The German Method: This method is similar to the Dutch Method with a constant value of 2.6 (instead of a range of values varying from 2.0 to 2.8):

  $V_x = 2.6 * \ V_0 * (\frac{D_p}{x})$ for x > 2.6 * D_p

  $$and$$

  $$V_x = V_0\ for\ x < 2.6 * \ D_p$$

Measured velocities compared to the analytical solutions are shown in Figure 7 and Figure 8. A constant value of 2.0 was selected for the Dutch method to obtain the best agreement with the measured data. V_0 correspond to the measured velocity 0.5 * D_p from the propeller.

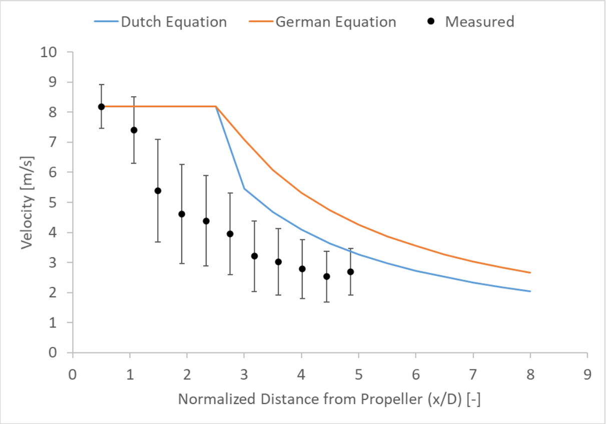


Figure 7 Measured velocity (model scale of 1:13.5 – velocities are converted to prototype unit) in front of a 14'' propeller diameter compared to the Dutch and German methods.

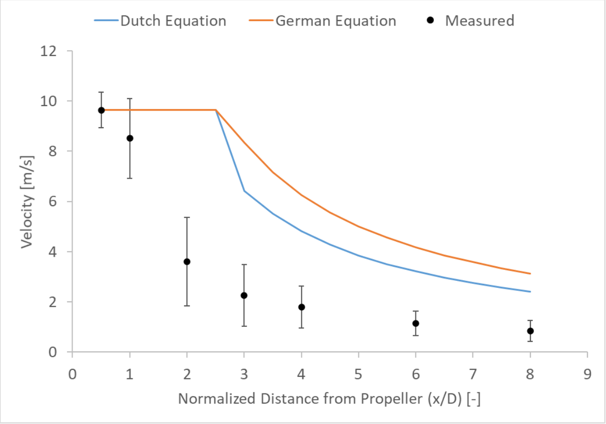


Figure 8 Measured velocity (model scale of 1:20 – velocities are converted to prototype unit) in front of a 12'' propeller diameter compared to the Dutch and German methods.

A constant efflux velocity in front of the propeller was not observed in the model. Instead, the measured velocity was observed to start decreasing at the propeller. As a result, the velocity appears to be overpredicted by both analytical methods.

5. Example of Designs Tested and Observed Failure Mechanisms

A wide range of armour and configurations involving rocks, concrete units, rock bags, sand and piles had been tested at WRL. Most designs tested at WRL were initially developed based on the PIANC (German methodology) or CIRIA (e.g., Dutch/Pilarczyk method) guidelines. These methods generally yield different results to each other and include approximations that are not specific to the conditions being investigated. Therefore, physical model testing was used to refine the stability of a design solution. The main failure mechanisms observed for a wide range of configurations are discussed hereafter.

5.1 Rocks

Sizing rock typically relies on coastal structures guidelines such as CIRIA. However, testing showed that initial design considerations typically result in conservative rock sizing on the slope of submerged rock revetments. This is due to the propeller wash jets velocities push rocks or other armour units (e.g., rock bags) into the slope.

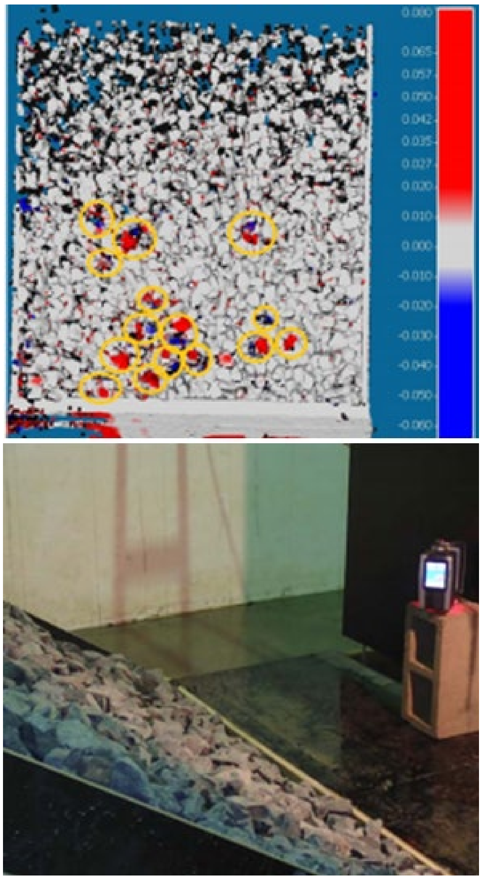
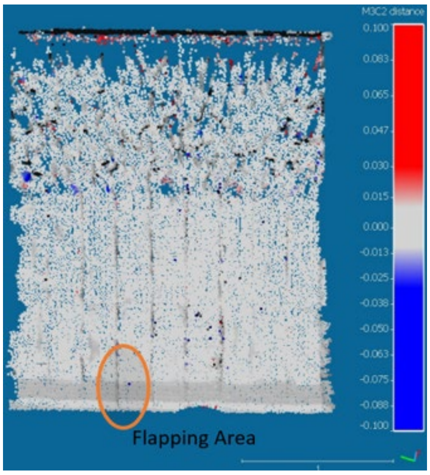


Figure 9 Example of a Faro scan to assess rock movement

(a) Underwater video footage showing flapping of leading edge of ACMs



(b) 3D FARO scan post test

Figure 10 ACMs moving during testing

This is different from wave damage on coastal structures where rocks can be damaged during down rush of waves (i.e. pulled from structure). Movements of rock on a slope from propeller wash jets were generally observed in the region directly in front of the jet. A 3D laser scan was performed before and after each test to accurately evaluate the damage (Figure 9).

5.2 Rock Bags

Rock bags were usually stable for the conditions tested (Figure 11). As per rocks, the jet pushed the bags up and into the slope resulting in greater stability than originally expected. The bags were susceptible to jets at angles. Also being a single layer, if a bag was moved then large sections of the slope could become unstable. The long-term integrity of the bag fabric was not assessed.

Figure 11 Rock bags on revetment slope in front of bow thruster setup

5.3 Grout Mattresses

Grout mattresses were found to be potentially unstable when propellers were placed above them due to uplift forces. Damages are generally expected to result from jet impact. However, the failure mechanism observed for grout mattresses was due to the uplift of units when located directly under the propeller (Figure 12).

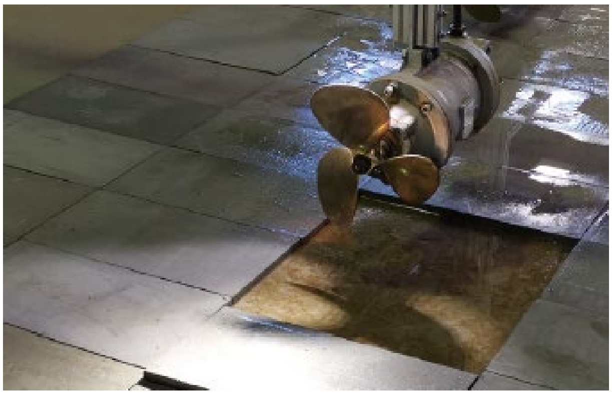
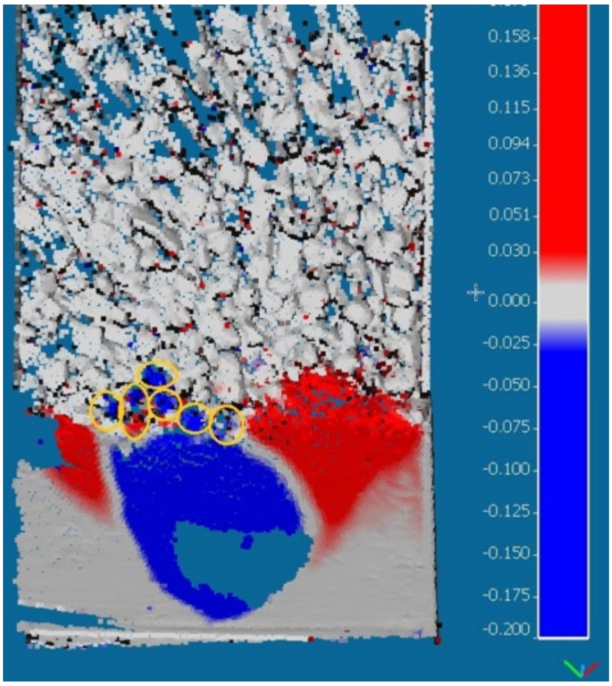


Figure 12 Concrete mattresses located directly under the propeller moved

5.4 Erodible Bed

Testing with an erodible bed showed the formation of a scour hole (Figure 13). The rocks or armour units were observed to fall into the scour hole. The toe of the structure is critical for the stability of a design solution. Whether the armour be ACMs, rocks or rock bags, the structure needed to be flexible enough to slump into this scour hole and avoid undermining. Alternatively, a toe trench needed to be constructed in advance.

(a) Photo post test



(b) 3D FARO scan post test

Figure 13 Rocks and Scour Hole

5.5 Further Considerations

Coastal damage process and design typically consider rare events (e.g., 100-year ARI) with low frequency and possibility to repair post event. Port infrastructures are typically subject to frequent events with very limited time windows for repairs (or at very large cost). Therefore, the threshold for tolerable damage to port infrastructure must be far stricter or even zero movement design. This is required larger protection, compared to coastal breakwaters which are generally designed for up to 5% damage.

It is also important to note that most designs tested at WRL have showed that under keel clearance in ports is very limited due to larger vessels (<1.5 m of under keel clearance). Design should consider risk of navigation hazard due to damaged structure and loose armour.

WRL has further found that the proximity of the prop-wash to the bed is a major factor in stability. All our testing has focused on vessel at lowest astronomical tide (LAT). In some cases, it may be practical to limit vessel movement to tides much higher than LAT.

6. Conclusions

The complexity of the interaction between prop-wash and armour units and the simplification in various analytical methods means that physical modelling is often required. A large model scale is required to model the stability of a structure under propeller wash. A range of possible failure mechanisms have been observed and presented.

It is also recommended that testing is conducted as early as possible and be used for concept design and optimisation more than validation. Testing must consider vessel configurations, including the approach of the ship, the angle of the jets, the power levels and the combined use of multiple azipods or bow thrusters.

Testing is often conducted for water levels at LAT and rightfully as more conservative. If this creates unsurmountable constraint, port should also consider vessel restrictions guidelines such as no vessel movement below certain tides.

7. References

[1] CIRIA, CUR, CETMEF (2007). "The Rock Manual. The use of rock in hydraulic engineering". 2nd Edition.

[2] PIANC (2015). Report No 180, Guidelines for Protecting Berthing Structures from Scour Caused by Ships, PIANC, Brussels.

[3] Berard, N., Prasad, S., Miller, B., Deiber, M., & Fuller, N. (2018). Physical Modelling of Propeller Scour on an Armoured Slope. Coastal Engineering Proceedings, (36), 11-11.