Comparison of water jets and conventional propeller jets

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Conventional ship propulsion systems and hydro jets differ in many ways. However, they are both responsible for sailing and manoeuvring of ships in a forward or reverse direction. The hydrodynamic jet is what they have in common, but the characteristics of the jets differ. For example, the outflow velocity of hydro jets is much higher than the one of conventional jets. Another very relevant difference is the jet direction towards the river or canal bed when the jet is in the reverse mode. Formulas are presented to estimate the flow velocities for two types of hydro jets and compared with formulas for a propeller jet and a free jet. The high flow velocities at the bed in reverse mode can result in scour, therefore, also formulas are presented to estimate the scour depth.

Keywords*:* hydro jets, ship propellers, propulsion systems, scour.

1. Introduction

Ships manoeuvre in turning basins and during mooring and unmooring. Therefore, the vessels are equipped with a main propulsion system and sometimes also bow thrusters. These devices generate flow fields that may cause scour. One should take the flow fields into account when designing a quay wall, a ferry ramp or revetments. In particular container vessels, ro/ro vessels and ferries are known to be major contributors to erosion near berths.
Until a few years ago bow thrusters were responsible for the heaviest attack on bed material, but nowadays also other propulsion systems are responsible (Figure 1):

- Main propellers at the ship's stern: conventional propellers, azimuthal systems
- Thrusters
- Water jets

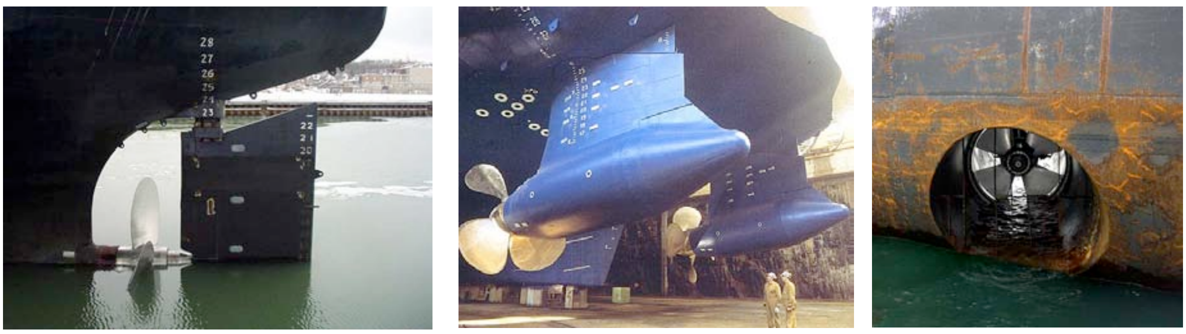

Figure 1. Examples of main propulsion systems: conventional propulsion system (left), azimuthal system (middle), bow thruster (right)

Azimuthal systems distinguish themselves from regular propellers in a way that there is no rudder. There advantage is the capability to rotate the pods, providing 360º for manoeuvring purposes. The total power can reach 25 MW.
Conventional propellers, azimuthal systems and thrusters have been subject to numerous studies in the last decades. The flow field and the consequences for bed material can be predicted reasonably well. Refer can be made to Blaauw et al (1978), Verheij (1983), PIANC (1997).
In the next sections the characteristics of water jets will be discussed in more detail.

2. Water jet propulsion

Water jets are often applied in fast ferries and small boats (Figure 2). There are different manufacturers, for example Kamewa, Lips and Hamilton, and a wide range of jets is available. However, they have in common the high outflow velocities. The installed power of these systems range between 500 kW up to 25 MW.
In inland navigation a comparable system exists, viz. pump jets with a power up to about 500 kW.

Figure 2. Small boat (left) and fast ferry (right) equipped with hydro jets.

The principle of the hydro jet is shown in Figure 3. Sea water passes through a nozzle where an axial pump is located. A considerable jet of water is impelled backwards through the aft pipe system. In the forward mode the water jet allows a vessel to sail with speeds up to 75 kn. In the reverse mode "a reverse bucket" directs the flow to the bed. The downward angle is about 30 to 35^0.

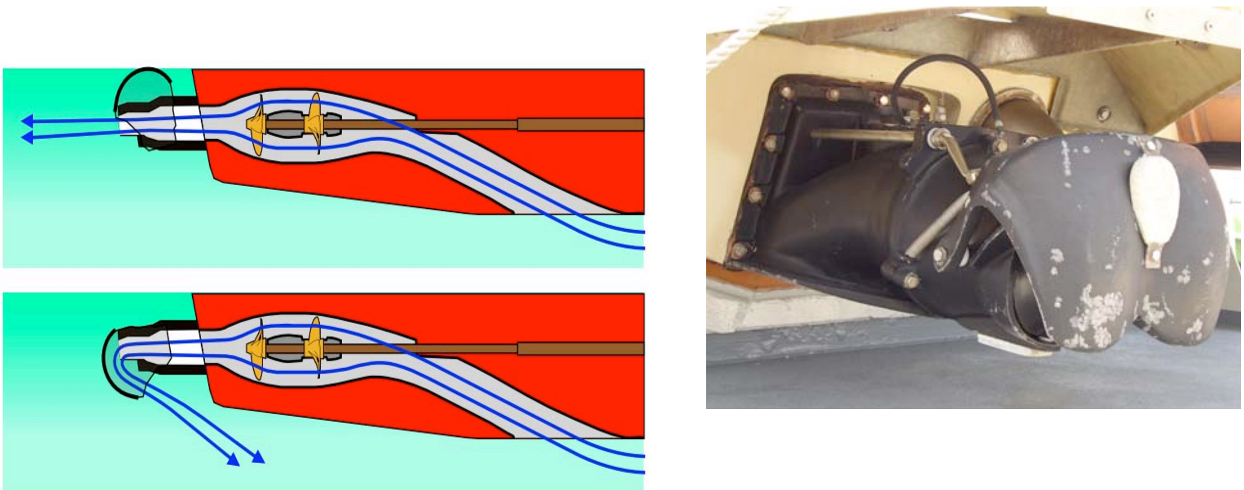

Figure 3. Principle of the water jet: in forward direction (left above) and in reverse option (left below) and water jet device (right).

Water jets are usually installed in pairs. Manoeuvring is very easy when one jet is pushing forward and the other pulling backward.

3. Comparison water jets and conventional jets

3.1 Flow fields induced by hydro jets

For conventional propellers and thrusters formulas have been derived for estimating the flow field. Verheij et al (2007) presented formulas for the water jets of the high-powered ferry Stena Discovery equipped with Kamewa water jets type 180SII (Figure 4):

$$u_{x,r} = u_{\max} \exp\left[-92.75 \cdot r^2 / x^2\right] \quad (1)$$

$$u_{\max} = 12.4\, u_0\, x^{-1.17} \quad (2)$$

$$u_0 = 0.92\left[P_d / \left(\rho_w A_0\right)\right]^{0.33} \quad (3)$$

in which: u_0 = outflow velocity related to the applied engine power (m/s), P_d = applied engine power (kW), A_0 = outflow opening (m^2), ρ_w = density of water (kg/m^3), x = distance to the outflow opening measured along the jet axis (m), r = radial distance to the jet axis (m), and u_{max} = flow velocity in the jet axis at a distance x from the outflow opening (m/s).

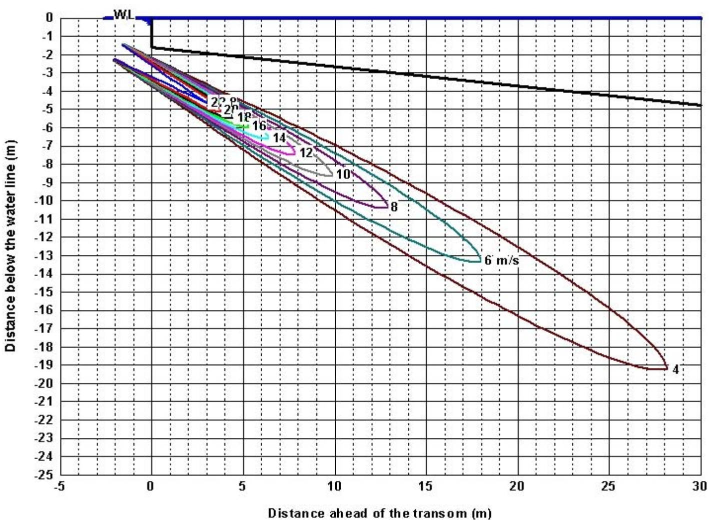

Figure 4. Velocity field in the direction of the river bed for a Kamewa hydro jet in reverse option (left) and water jets mounted at the stern of the ferry (right).

As can be seen it results in very high flow velocities if the maximum installed power is applied. PIANC (2010) recommends to apply 10% of the installed power. It can be estimated with Equation (3) that applying 10% of the installed power results in about 40 to 50% of the maximum outflow velocity. But even then the flow velocities in the jets are very high.
For yachts Kamewa produces the water jet type 90SII which is able to generate an outflow velocity of 17 m/s.

Recently, scour occurred at the Harlingen terminal of the ferry to the Wadden island (Figure 8). The flow field in the reverse mode generated by the ferry ms. Tiger (length x width x draught = 52m x 11.8m x 1.4m; max speed 32 kn) and equipped with 750 kW Lips LJ90DT water jets can be approximated with (Figure 5):

$$u_{max} = 2.8\, u_0 D_0\, x^{-0.85} \qquad (4)$$

$$u_{x,r} = u_{max} \exp\left[-25 \cdot r^2 / x^2\right] \qquad (5)$$

The value of the coefficient 25 is not an exact value, but should be in the range from 20 to 30, and is close to the value of 22.2 used in the German formulas for propellers (PIANC, 2010).

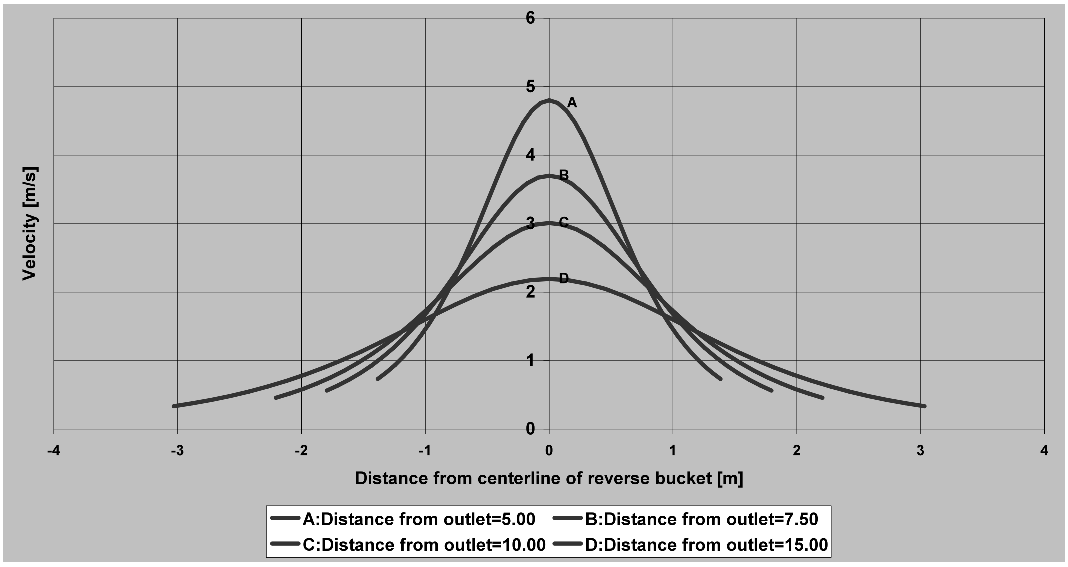

Figure 5. Velocity field in the direction of the river bed for a Lips hydro jet in reverse option

The flow velocities as presented in Figure 5 resemble very well results of CFD simulations, as can be seen in Figure 6.

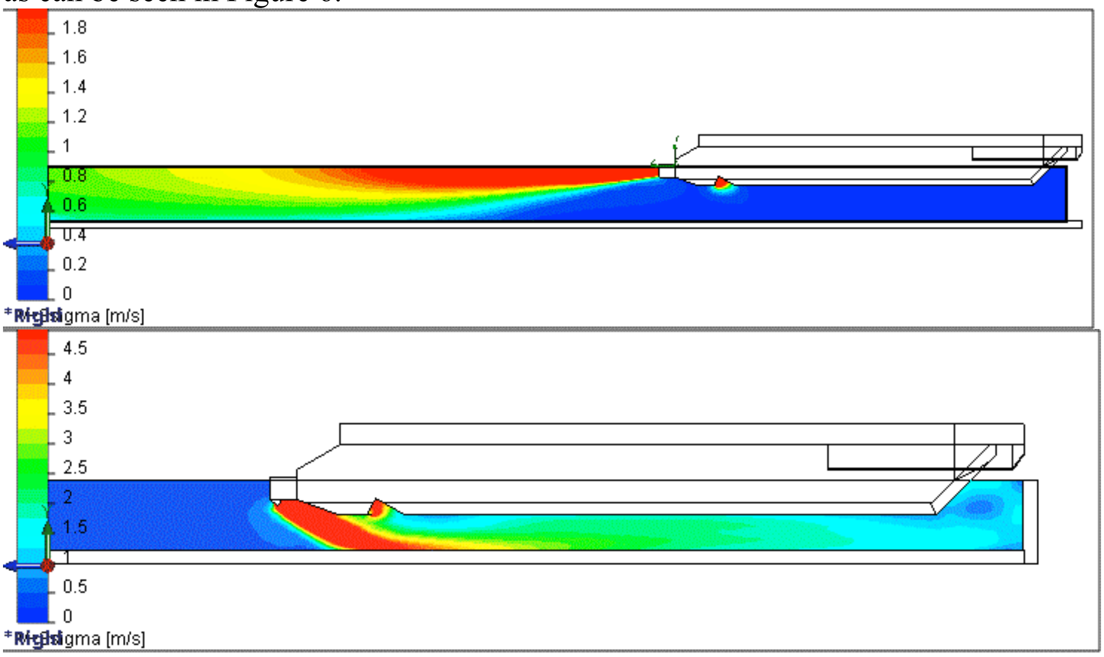

Figure 6. Velocity fields computes with a CFD model for the Harlingen ferry sailing forwards in a water depth of 7m (above) and in reverse mode in a water depth of 5m (below).

3.2 Comparison

The characteristics of the flow fields due to hydro jets can be compared with conventional propeller jets and free jets. For conventional propellers the following formulas, for instance, can be used (Blaauw and Van de Kaa, 1978):

$$u_{x,r} = u_{\max} \exp\left[-15.4 \cdot r^2 / x^2\right] \tag{6}$$

$$u_{\max} = 2.8\, u_0 D_0\, x^{-1.0} \tag{7}$$

$$u_0 = 1.15\left[P_d / \left(\rho_w D_0^2\right)\right]^{0.33} \tag{8}$$

For a circular free jet the equations read (Rajaratnam, 1976):

$$u_{\max} = 6.2\, u_0 D_0\, x^{-1.0} \tag{9}$$

$$u_{x,r} = u_{\max} \exp\left[-69 \cdot r^2 / x^2\right] \tag{10}$$

The coefficient 69 in Equation (10) varies in literature. Albertson et al (1948), for example, presents a value of 150. An average value can be 100.

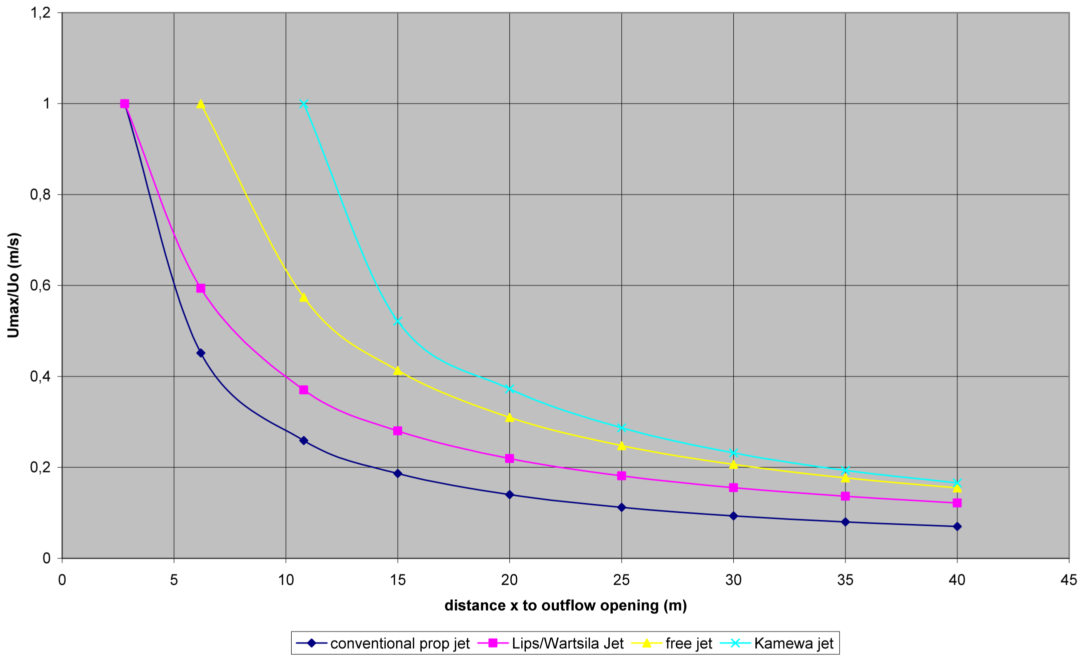

Figure 7. Comparison of the flow velocities in the jet axis for different types of jets

Two aspects are relevant when comparing hydro jets with conventional propeller jets and free jets:

- Decrease of flow velocity in the centreline of the jet, and
- Diffusion of the jet in radial direction.

Figure 7 shows the relative flow velocity in the jet axis as function of the distance to the outflow opening. It is assumed in the relevant Equations (2),(4),(7) and (9) that the effective outflow opening D_0 equals 1m. Moreover, for Equation (2) an equivalent D_0 value has been estimated resulting in a coefficient of 10.8 instead of 12.4.

The figure shows that the decrease due to the Lips water jet is closer to the results for the conventional propeller jet than to the results of the Kamewa water jet. The decrease is faster than in the case of a free jet. The flow velocities in the jet axis of the Lips jet are about 50% higher than for the conventional propeller. Results for Hamilton jets are comparable with the Lips results (Anonymus, 1996).
The decrease of the flow velocities in the Kamewa jet are slower than in the free jet. It is assumed that the differences between the two types of jets has to do with the difference in power, but this requires more research. The maximum power of the Lips jets is 750 kW, while the power of the Kamewa jets is 25 MW.

The diffusion shows a similar result: the Lips jets resemble conventional propeller jets (see Figure 5), while the Kamewa jets are close to the free jets (Figure 4).
In other words: the characteristics of flow fields in hydro jets regarding the decrease of the maximum flow velocity in the jet axis and the diffusion in radial direction, seem to depend on the installed power. More data is required to solve this issue in order to derive reliable prediction equations.

4. Counter measures against flow velocities

The high flow velocities may result in scour and instability of quay walls if no proper measures are taken. It means that a designer has to decide to accept scour and to assure the stability of the structure, or to protect the bed against scour. Relevant areas in this aspect are: quay walls, revetments at turning basins, and ramps.

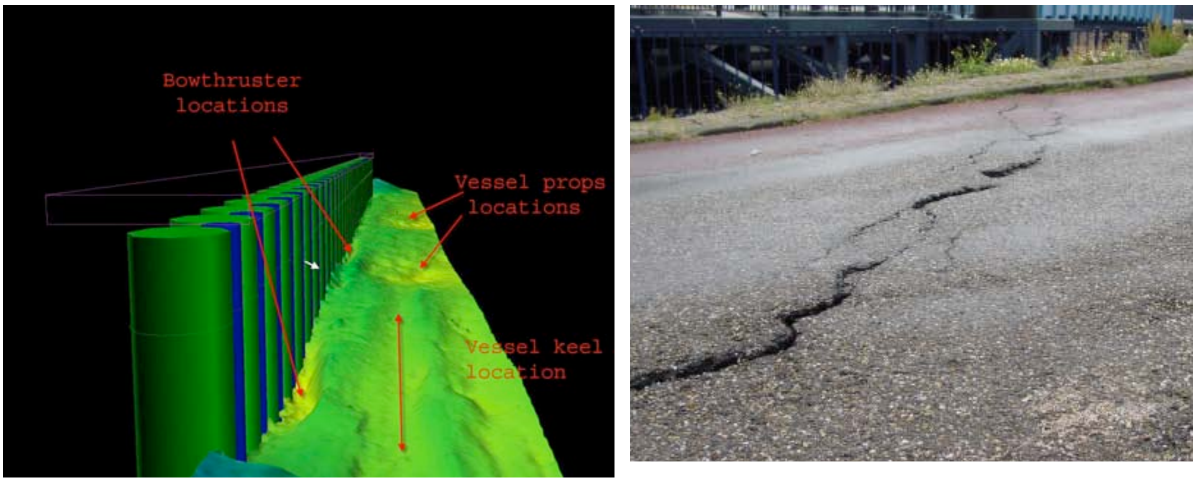

Figure 8. Observed erosion in front of a quay wall (left) and cracks in the road (right)

The main distinction in design philosophies is between:

A. Design to **protect the bottom** in front of the structure in order **to avoid scour** from occurring, or
B. Design to **protect the structure** in order **to avoid negative impacts** to the structure resulting **from scour**

Although in both cases the ultimate goal and result is the protection of the structure, in some cases the designer could decide to accept anticipated scour near the structure but secure the structural integrity in a different way, which in certain cases may be more cost-effective and suitable. It may be more effective and appropriate to design the structure for greater depths taking into account that deep scour holes may develop in front of it, than it would be to put all focus of the design in avoiding any movement or erosion of bed material. Alternatively, a third option of design philosophy could be to focus attention on avoiding scouring forces to happen, which is briefly addressed later in this section.

This design philosophy issue is not much different from the usual design question what level of damage to accept in order to optimize a design for long-term functionality and cost-effectiveness over the lifetime of the structure. The answer to that question is highly dependent on the specifics of a situation, and will have to be considered by the designer. Relevant factors that will have to be taken into account are:

- Cost (for both initial construction as well as maintenance)
- Environmental aspects (considerations related to allowing large movements of bed material versus installation of for example a hard bottom protection)
- Options to -and ease of- performing monitoring and any needed maintenance
- Risk to the structure if scour would be more than an acceptable level and/or not detected in time
- Impacts and possibility of performing repair work in case damage to the structure would occur
- Effects on deepening or other berth modifications potentially required in future years
- Any other potential functions of the local bottom (e.g. nearby slopes, buried utilities/outfalls, etc.)

Design methods are available for both design philosophies A and B. Here, equations are presented for design philosophy B meaning that the flow velocities might be higher than the threshold value of loose bed material resulting in erosion of material and finally the development of a scour hole. The depth S of the scour hole created by the jet can be computed with (Römisch et al, 2009):

$$\frac{S}{d_{85}} = \frac{h_p}{d_{85}} C_{ad} C_{m,r} \left[a_\alpha \frac{B}{B_{crit}} - 1 \right] \tag{11}$$

with $a_\alpha = 0.65$ and $C_{m,r} = 0.3$ and $C_{ad} = 17 \left(\frac{h_p}{d_{85}} \right)^{-1} + \left[0.9 \frac{B}{B_{crit}} - 1 \right] \leq 1.0$

with $B = \frac{V_{bed}}{\sqrt{d_{85} g \Delta}}$ and $B_{cr} = 1.2$

where d_{85} = characteristic diameter of bed material exceeded by 15% of the material (m), h_p = distance between outflow opening and the bed (m).

5. Conclusions

The characteristics of flow fields in hydro jets have been compared with the flow fields generated by conventional propeller jets and circular free jets. Equations have been derived describing the flow fields for two types of hydro jets, a high-powered jet and a low-powered jet. Based on the comparison the following conclusions can be drawn:

- There are significant differences between the high-powered jet and the low-powered jet regarding the decrease of the flow velocities in the jet axis and the diffusion of the jet which perhaps can be explained by the difference in power.
- The low-powered jet resembles the flow field of a conventional propeller jet, although the flow velocities are about 50% higher.
- The high-powered jet resembles the flow field of a circular free jet.

It is recommended to collect more data of hydro jets in order to obtain reliable prediction equations for the flow fields.

Acknowledgements

Rijkswaterstaat, Centre for Public Works is gratefully acknowledged for providing data of the Harlingen ferry.

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