EXPERIMENTAL INVESTIGATION OF PROPELLER JET INDUCED SCOURS

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Abstract

This paper describes an experimental study aiming at the investigation of the temporal evolution of propeller jet induced scours taking into account the effect of different propulsion systems. Time series of scour depths are presented which were obtained in experiments carried out with a stern scale model (1:16) equipped with different propulsion systems, a Kaplan propeller in Kort nozzle and double rudder and a Wageningen B-series propeller with central rudder, respectively, and identical boundary conditions (underkeel clearance, number of revolutions, draft). Preliminary results are used to show the reproducibility of the experiments and to highlight the influence of the propulsion system on scour depth and geometry.

Introduction

One of the consequences of increases in barge size and motor power in recent years has been an increased attack of waterways boundaries. Especially the fast-moving turbulent propeller jet induced by sailing and maneuvering vessels can cause severe damage to the bed as well as quay structures. However, compared to investigations of scouring at bridge abutments, piers, and weirs, only a limited number of studies exist in which the scouring action of a propeller jet has been investigated in detail.

These studies, carried out in both the laboratory and the field, revealed the significance of vessel related parameters such as engine power, propeller characteristics, rudder arrangement, vessel type and underkeel clearance for the temporal evolution of scour depth as well as equilibrium scour depth (e.g. Gebers 1911, Hitzler 1938, Felkel & Steinweller 1972, FAS 1974, VWS 1975, Blaauw & van de Kaa 1978, VWS 1984, Hamill 1988, Hamill et al. 2001). This is due to the fact that the setup of the propulsion system, in combination with the ship's stern, has a great influence on the dispersion characteristics of the propeller jet and hence on the associated near bed flow field. For example, a central rudder behind a propeller splits the jet into two streams with one stream being directed towards the bottom (e.g., Krey 1914, Hamill et al. 2001, BAW 2005) causing a larger flow attack of the bed compared to an identical situation without rudder. Moreover, the hydrodynamics of the propeller jet depend on propeller characteristics such as propeller diameter, hub diameter, propeller surface area, and pitch ratio (e.g., Oebius 1984, Hamill & Johnston 1993, Lam et al. 2011). As a consequence, the jet is characterized by prevailing axial, radial, and tangential velocity components, which are not constant in the radial and tangential direction (Blaauw & van de Kaa 1978). For moving vessels, the velocity field is influenced additionally by the vessel induced wave system, return flows, and drawdown. However, over a longer period of time, the heaviest flow attack on the bottom can be expected in manoeuvring situations (Verhey 1983).

The significance of vessel related parameters for the accurate determination of the jet related bottom attack shows the complexity of vessel induced scour depth forecasting. Although the topic of propeller jet induced scouring has been investigated since 1900 (see Spitzer et al. 2012a, b), there is still no generally applicable approach available that adequately considers vessel related parameters. For example, different scour depths can be observed for identical geometrical boundary conditions (water depth, sediment size, and canal geometry) when the flow attack is caused by different vessel types or propulsion systems, even if the jet is characterized by an identical efflux velocity u_0. Therefore, it is not surprising that existing computational approaches yield results which vary by an order of magnitude when they are tested with independent data (e.g., Aberle & Söhngen 2008).

Consequently, there is a need for a more accurate method for the prediction of propeller jet induced scouring processes taking into account peculiarities of the propulsion system. For this purpose, a scale model study is currently carried out in the hydraulic laboratory of the Leichtweiß-Institut für Wasserbau at the Technische Universität Braunschweig, Germany. The objective of this paper is the description of the experimental setup and the presentation of preliminary results of the ongoing study.

Experimental Setup

The scale-model study (1:16) is carried out in a 2 m high, 5 m wide, and 15 m long basin with a an observation-window at the side enabling visual inspection of the scour process. Absorbers are installed at the side-walls of the basin to minimize the influence of backflow effects as well as waves resulting from the propeller jet. For the erosion tests, a 0.335 m high, 3.0 m long and 3.6 m wide false bottom is installed in the middle of the tank (Figure 1). The false bottom contains a 1.24 m wide recess area which is, for the present experiments, filled with quartz sand (d_{50} = 0.8 mm) and gravel (d_{50} = 4 mm), respectively.

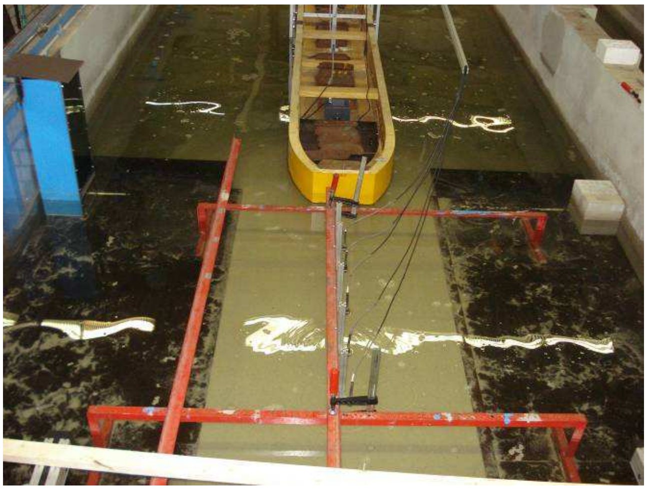

Figure 1: View of the basin, vessel, and sediment bed.

The scouring experiments are carried out in a maneuvering situation with a 5 m long, 0.7 m wide and 0.4m deep scale model of a stern of an inland vessel commonly found on the river Rhine. The vessel is firmly attached to a frame over the sediment bed preventing its movement around the vertical and transverse axis (Figure 2). A wire attached to a drag force sensor holds the ship in its longitudinal position and enables the measurement of the propeller thrust. The propeller torque is measured with a torque-sensor. The number of revolutions of the 440 V DC-motor installed in the ships-body powering the propeller can be adjusted continuously between 0 and 1660 rpm and can directly be related to the rpm of the propeller n_p.
In order to study the effect of different propulsion systems on scour development, two different four blade brass propellers (Kaplan propeller in Kort-nozzle and Wageningen B-series propeller with a diameter of D_p = 111 mm) and rudders (115 mm high central and double rudder with a web width of 19 mm, respectively) can be installed to the vessel. Taking into account relevant propulsion systems, the Kaplan propeller is mainly used with the double rudder (Figure 3) and the Wageningen-propeller with the central rudder (Figure 4).

Figure 2: Detailed view of the ship's holding frame (left: in dry conditions; right: during vessel operation).

Figure 3: Kaplan propeller in a Kort nozzle with double-rudder.

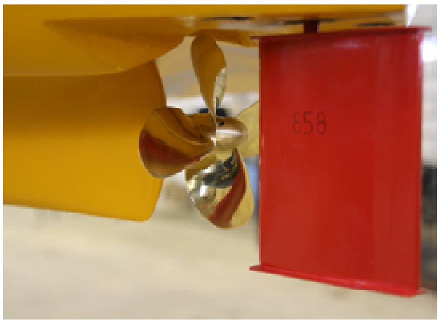

Figure 4: View of the Wageningen-propeller with central rudder.

During the experiments the rudders are fixed in an angle of 0° and the experiments are carried out with different propeller rpm's, drafts, and distances h_p of the propeller axis to the sediment bed (ranging from h_p = 102.8 - 177.8 mm) (Figure 5).
After the positioning of the ship, the sediment bed is scoured in reduplicative time intervals (Δt = 10, 20, 40 s etc.) up to a total load time of 2h (note that some experiments are carried out with different load times). Following each interval, five characteristic points of the scour are manually measured subaqueous using point gauges (Points P1, P7, P8, P9 and P12 in Figure 6). These measurements are used to determine the temporal evolution of the scour geometry (depth, length and, width).

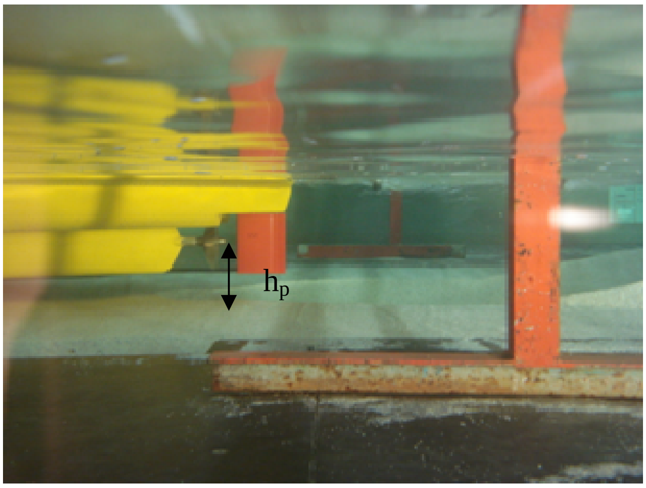

Figure 5: Definition of h_p.

After completion of the experiment, the water is drained from the tank and a total of 14 characteristic scour points are surveyed to determine the final scour geometry including the geometry of the deposited crest (Figure 6). These data, which are not discussed in the present paper, will be used in our future analyses to study the resulting scour geometry in more detail.

Additional experiments without interrupting the scour process are carried out to investigate the effect of the interval-loads. Complementary experiments with duration of 24 h are used to estimate scour depth at near equilibrium conditions.

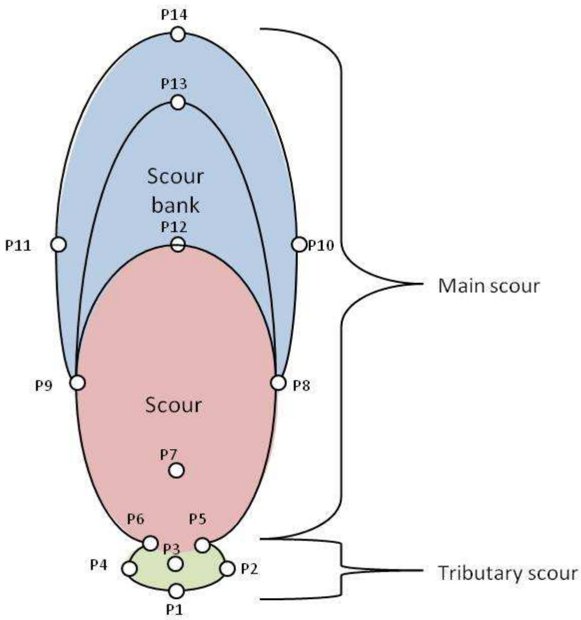

Figure 6: Distinctive points of scour. The tributary scour, which has only been observed in experiments with the sand bed, is located directly below the propeller.

Preliminary results

Figure 7a shows the temporal evolution of the scour depth in the gravel sediment for an experiment carried out with the Kaplan propeller in Kort-nozzle and double rudder (h_p = 102.8 mm, n_P = 22.3 1/s, maximum draft). The figure also contains scour depths of non-interrupted experiments carried out with identical boundary conditions and load periods of t_E = 10, 1200, and 7200 s.

Similarly, Figure 7b shows the temporal evolution of the scour depth in the sand sediment for experiments carried out with the Wageningen-propeller and central rudder as well as the Kaplan propeller in Kort nozzle and double rudder (h_p = 102.8 mm, n_p = 22.3 1/s, maximum draft). The experiments with the Wageningen-propeller were carried out with total load periods of t_E = 20470 s (two experiments) and t_E = 86400 s (first interruption after 12600 s) while the total load period of the Kaplan propeller experiment was t_E = 5110 s.

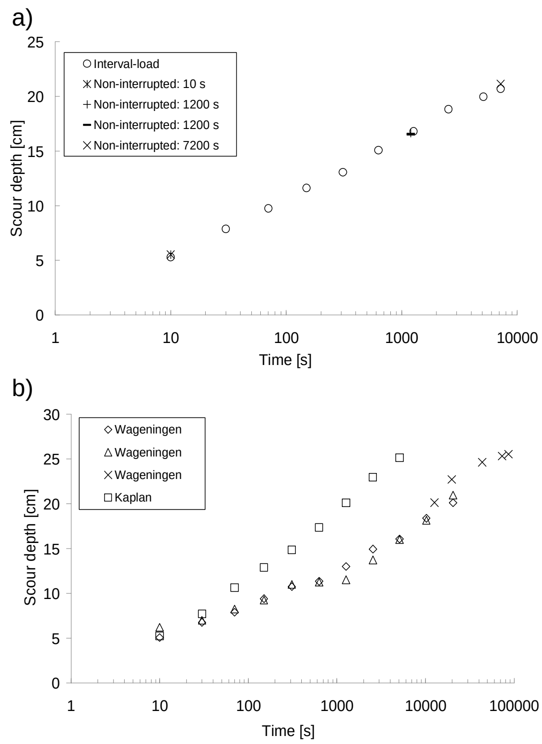

Figure 7: Scour depth as a function of time for experiments carried out with identical boundary conditions (interval and non-interrupted experiments); a) Kaplan propeller, gravel-bed; b) Wageningen and Kaplan propeller, sand bed.

The comparison of the scour depths caused by the same propulsion system reveals similar scour depths for identical load periods showing that the interval load has a negligible effect on the scour depth (Figure 7a). Moreover, the good agreement of the time series of the Wageningen-propeller in Figure 7b shows the reproducibility of the experiments, which has also been confirmed in our further experiments.

The semi-logarithmic plotted time series in Figure 7 show that, for load periods $t < 10000$ s, scour depth ε was linearly related to the load period, i.e. $\varepsilon = f(\ln(t))$ which is in agreement with findings reported in the literature (e.g., Hamill 1988). For large load periods ($t > 43600$ s; Figure 7b), the scour depth reached almost a constant value indicating near equilibrium conditions after a load time of 24 h.

Figure 7 also reveals relative large scour depths after relatively short load periods. For example, the scour depth after a load period of 10 s corresponded approximately to 25% - 33% of the scour depth at near equilibrium conditions. A similar result was reported by Hamill (1988) showing that starting vessels, although imposing only a time-limited load of several seconds, can have a significant impact on the bed topography. In this context, Felkel & Steinweller (1972) found in their field and laboratory experiments that the scour depth after a load period of 5 min corresponded to approx. 75 % of the scour depth after 50 min load period. A similar result was obtained in our study, for which the scour depth after t = 310 s, i.e. approx. 5 min, corresponded to 69% - 80% of the scour depth observed after 42.5 min.

Our experiments also showed the expected influence of n_p, h_p, and sediment size on scour depth. Comparing the scour depths caused by the same propulsion system with identical n_p (i.e., identical jet efflux velocity) showed that ε increased with decreasing h_p as the near bed flow velocity increases with decreasing distance of the propeller axis to the bed (e.g. Fuehrer et al. 1981). Similarly, for identical h_p but different n_p it was found that scour depth decreased with decreasing n_p due the decreasing efflux velocity (Figure 8; note that the time series reveal once more $\varepsilon = f(\ln(t))$). The effect of the sediment size was that larger scour depths were observed in sand than in gravel (see Figure 7a, b).

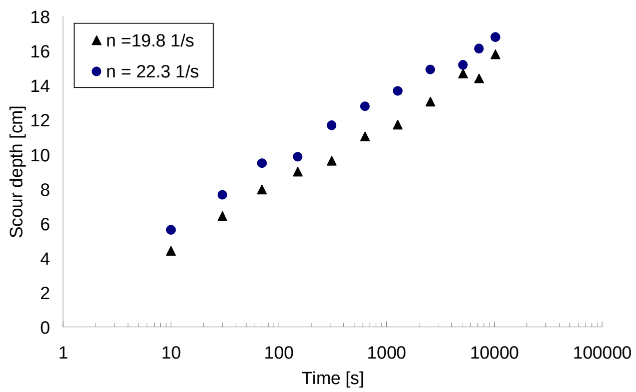

Figure 8: Time series of scour depths in gravel for Wageningen-propeller with central rudder for identical draft and h_p but different propeller revolutions n.

The influence of the propulsion system on scour development can be discussed on the basis of Figure 7b which reveals significant differences between the Wageningen and Kaplan time series. In general, these differences are in agreement with findings reported in the literature that propeller characteristics and the rudder type have a significant impact on scour depth (e.g., Gebers 1911, Hitzler 1938, Fuehrer & Römisch 1977, Oebius 2000, Hamill et al. 2001, BAW 2005, Aberle & Söhngen 2008).

However, it is interesting to note that the scour caused by the Kaplan propeller was, for comparable load periods and boundary conditions, always deeper than the scour caused by the Wageningen propeller (this difference has been verified in further experiments). Originally we expected, for identical efflux velocities, larger scour depths for the Wageningen propeller with central rudder than for the Kaplan propeller with double-rudder due to the splitting of the jet at the central rudder. Thus, larger near bed velocities were expected for the central rudder setup (e.g., Fuehrer et al. 1981, BAW 2005) and consequently, assuming that bed shear stress is proportional to the squared near bed velocity, larger bed shear stresses and hence scour depths. Currently, we can only speculate that the observed differences for the two propulsion systems are related to differences in the near bed turbulence characteristics of the jet, which again have a significant impact on bed shear stress. In order to quantify the influence of the propulsion system on near bed velocities and turbulence characteristics it is therefore planned to measure the near bed turbulent flow field with Particle-Image Velocimetry (PIV) in future experiments.

The effect of the propulsion system and associated jet characteristics on the scouring process was not only related to scour depth but also to scour geometry. Our experiments showed that the Kaplan propeller scours were rather broad and characterized by a certain asymmetry that was related to the orientation of propeller rotation (Figure 9).

Figure 9: Scour geometry resulting from Kaplan propeller with double rudder.

On the other hand, the scours induced by the Wageningen propeller with central rudder were more symmetric and, compared to the Kaplan scour, slim (Figure 10). These differences, which were also confirmed in our further experiments, reveal once more the significant influence of the propulsion system on the scour process.

Finally, it is worth mentioning that small bed forms and tributary-scours were observed in the experiments. As can be seen in Figures 9 and 10, the bed forms were mainly observed at the scour ridge and above the initial bed height at the beginning of the experiments. However, bed form development could only be observed during sand-bed experiments.

A tributary-scour located directly below the propeller (see Figures 6, 9, and 10) was observed in both the sand- and gravel-bed experiments. Visual inspections during the experiments showed that the tributary-scours were caused by up-flowing water (water sucked towards the propeller) and that their size depended on h_p. The tributary-scours grew in time and, after a certain time, merged with the main-scour (e.g., Figure 10).

Figure 10: Scour geometry resulting from Wageningen-propeller with central rudder.

Conclusions

This paper described the setup and preliminary results of an ongoing experimental study aiming at the investigation of the temporal evolution of propeller jet induced scours taking into account different propulsion systems. The preliminary results show the reproducibility of the experiments and, in accordance with the literature, that propeller characteristics and rudder arrangement have a significant effect on scour development and scour geometry.

The observed differences in scour geometry and the unexpected result that the Kaplan propeller caused, for identical boundary conditions, larger scour depths than the Wageningen-propeller will be investigated in more detail in our upcoming experiments. In these experiments, the near bed propeller-jet hydraulics which will be measured using PIV in order to quantify the influence of the propulsion system on the near bed flow field and bed shear stress. Moreover, the experimental data will be used to develop a novel approach for the determination of propeller jet induced scour depth as a function of time taking into account propeller jet characteristics.

Acknowledgments

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