Bowthruster-Induced Damage
A physical model study on bowthruster-induced flow

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Preface

This report is the final product of my Master’s Thesis at Delft University of Technology, within the specialisation Hydraulic Engineering at the Faculty of Civil Engineering and Geosciences. It is entitled:

“Bowthruster-Induced Damage: A physical model study on bowthruster-induced flow”

This research took place in the Fluid Mechanics Laboratory, where a physical scale model of a ship, fitted with a bowthruster, was built. The question as to the behaviour of the flow caused by a bowthruster directed at a vertical quay wall is one of many facets. This study focuses on the verification of a numerical model, using a physical model, for velocities just above the basin floor. This is only a small part of the ongoing research done at Delft University of Technology on this subject, but is, nevertheless, a step in the right direction in the understanding of bowthruster-induced damage.

Hereby, I would like to express my gratitude to the staff of the laboratory, whose practical assistance was of vital importance. I would also like to thank the members of my graduation committee: Henri Fontijn, Rob Booij, Henk Jan Verhagen, Jelle Olthof and Marcel Stive, for their constant support and guidance.

Brendan Nielsen
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Abstract

During the last decade the developments in the shipping industry have primarily been characterised by an increase in capacity. As a result of the increased power of modern ships, harbours are experiencing problems with regard to bottom protection. Larger and more powerful propellers cause higher flow velocities and thus more damage to existing harbour bottoms. Modern ships often not only possess main propellers at the rear of the ship but also bow and stern thrusters, allowing the ship to manoeuvre independently, without the help of a tugboat. These secondary thrusters tend to be the cause of damage to bottom protection layers.

Over the last couple of years a series of researches has been done on the topic of bowthruster-induced flow velocity and damage. These were based primarily on in-situ tests and physical laboratory models. A numerical model was also designed in a Computational Fluid Dynamics package called Phoenics. In this model a ship called the ‘Pride of Rotterdam’ was used as a prototype situation and scaled to 1:25. This numerical model was used to design a physical model in the Fluid Mechanics Laboratory of Delft University of Technology.

The aim of this research is to validate and adapt the numerical model using the physical model.

The measurement apparatus used in this research is the electromagnetic velocity meter (from now on referred to as ‘EMS’). This is a very sensitive instrument, which tends to experience a lot of interference if positioned too close to a solid object. In this research the velocity was measured three centimetres above the basin floor, and in some places three centimetres under the ship. It was unclear what the extent of the interference of the basin floor is. Therefore, an extensive calibration of the different EMS-probes was undertaken in a calibration flume. Calibration graphs for the four main orientations of the three EMS-probes were the result of this calibration procedure. From these graphs can be seen that the EMS gives accurate results at low flow velocities. For higher flow velocities the EMS is reasonably accurate, with a relatively small deviation from the theoretical value. Calibration tests were also done to investigate the sensitivity of the EMS to deviation in placement height. These tests showed that the EMS is more sensitive to deviations toward the basin floor than to deviations in the direction of the ship bottom, although the EMS proved to be less sensitive to these deviations than initially presumed.

After the calibration procedure was completed, tests were done using the physical model. The tests done were twofold. Firstly, observations were done using injected purple dye. At predefined nodal points in the area around the ship, estimations were made of the horizontal flow velocities and directions with the aid of a stopwatch. These observations were mapped out to form a flow field, which gave a reasonably complete picture of the horizontal flow velocities at three centimetres above the basin floor. These observations were followed by the actual flow velocity measurements using the EMS. At three predefined points under the
ship the velocity was measured by three fixed EMS-probes. A movable probe was used to measure the velocity at a number of points around the ship. Judging from the flow field produced by the observations, it was considered unnecessary to make measurements at all nodal points, especially for the points further away from the bowthruster. Here the density of the measurements was lower than for the areas immediately around the bowthruster. This proved also to be far more practical because of the fact that the procedure is very time-consuming and that the time available for these tests was limited. These measurements produced a flow field very similar to the flow field from the observations.

The existing numerical model used by Van der Laan was evaluated and adapted to better represent the outcome of the physical model. Firstly the dimensions and orientation were adapted to the values of the physical model. The calculation grid in the numerical model was also adapted so as to avoid discontinuities. An investigation was done to identify the optimal number of iterations. This was found to be 1000. The resulting flow field of the numerical model was subsequently compared to that of the physical model. This comparison shows a mildly similar flow pattern. In the area at the quay wall in front of the bowthruster, the velocity is alike, both in direction and size. The area around and under the bowthruster shows flow velocities of similar orders of magnitude as the numerical model but the flow direction differs considerably. In the areas further away from the bowthruster, the opposite is the case. The flow velocities in the numerical model are much larger than in the physical model, while the flow direction shows much similarity.

From this research can be concluded that, although there are similarities between the outcomes of the two models, the present numerical model does not yet sufficiently represent the physical situation. For a more reliable numerical model, additional investigation is required in order to understand the performance of the model and to identify the weaknesses thereof.
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1 Introduction

Marine transport is constantly undergoing development in order to comply with the ever-changing demands of the international market. During the last decade the developments in the shipping industry have primarily been characterised by an increase in capacity. Ships are becoming larger and deeper, with higher freight capacity. This, in turn, has an effect on the demands on the harbours. Harbour basins have to be deepened, quay walls lengthened and approach channels widened. As a result of the increased power of modern ships, harbours are experiencing problems with regard to bottom protection. Larger and more powerful propellers cause higher flow velocities and thus more damage to existing harbour bottoms.

An additional development aggravating this problem is that modern ships often not only possess main propellers at the rear of the ship but also bow and stern thrusters (respectively at the front and back of the ship) perpendicular to the ship’s axis. These secondary propellers allow the ship to manoeuvre independently, without the help of a tugboat. They are used especially for manoeuvres such as berthing and de-berthing.

Large ships, such as ferries, use their propellers to manoeuvre in harbours. The function of the main propeller at the rear of the ship is predominantly for forward thrust, but can aid a manoeuvre by changing the direction of the rudders. This, however, produces only limited manoeuvrability. Stern thrusters are found at the back of the ship in a duct perpendicular to the axis of the ship. The functions of these two types of thrusters can be combined by a rotate-able thruster, such as an azipod or a hydrojet. The bowthruster, like the stern thruster, is situated in a duct perpendicular to the ships axis, but is located at the front of the ship. Figure 1.1 shows a diagram of a cross section of the bow of a ship with a side view of a bowthruster.

The force produced by the bowthruster, combined with its distance to the centre of gravity of the ship, results in a large momentum, causing the front of the ship to be turned away from the quay wall. After this has happened, the main propellers are used for forward thrust in order to sail away. As a result of the increase in the size and engine power of the bowthrusters, the flow velocities against the quay walls and at the harbour basin floors in front of the quay walls have increased considerably over the last few years. Because the harbours bottoms are often not designed for these extreme velocities, this can lead to increased bottom erosion and possibly to quay wall failure. This bottom erosion can be minimised by placing a well dimensioned...
harbour bottom protection.

The relevance of this research can be seen by the fact that that a PIANC, the International Naval Association, initiated ‘Working Group’ #48 in 2004 to investigate and collect information on this topic in order to publish guidelines for bottom protection in harbours at vertical quay walls. At the moment the guidelines are not sufficient to design bottom protection. Guidelines made by PIANC ‘Working Group’ #22 in 1997 proved to be inadequate and are not used by harbour authorities. In Rotterdam, for example, the harbour engineers have developed their own method of designing the bottom protection based on experience, but in practice this proves to be rather conservative. In Antwerp concrete slabs are used in order to overcome this problem. This is a simple, yet very expensive, solution.

Insight into bowthruster-induced flow and the resulting damage is as yet still insufficient to be able to take appropriate cost-effective measures to protect harbour basin floors.
2 Problem Analysis

2.1 Problem Description

These days, harbours are being faced more and more with the rapid scale increase of the shipping sector. Larger ships mean deeper harbour basins, larger unloading capacities and better bottom protection. One of the effects of this scale increase is that many large ships no longer need tugboat assistance in order to berth or de-berth. With the aid of bowthrusters, in combination with the main propellers, ships are able to manoeuvre much easier than before. When de-berthing, a ship uses its bowthruster(s) to propel itself away from the quay wall, which results in a strong turbulent current towards the quay wall. In the case of a vertical quay wall this results in a strong reflection and high currents at the harbour bottom in front of and under the ship. If the necessary precautions are not taken, this can result in scour and possibly undermining of the quay wall. Figure 2.1 shows the working of a bowthruster and the scour hole which can be caused when the harbour bottom is insufficiently protected.

Many different types of bottom protection are used in harbours. The most common type is a stone rubble layer. The most important facet in the dimensioning of this type of bottom protection is the stone stability. Stone instability causes damage to the bottom protection layer. This damage can be limited by using stones with a larger diameter. Up until now, harbours have been estimating stone size by experience, rules of thumb and general stone stability formulas, as there is not yet sufficient insight into what is actually happening on the harbour floor as a result of bowthrusters. This often leads to large error margins and over dimensioned bottom protection layers.

Bottom protection in harbours faced with the bowthruster induced damage has gained much international interest over the last couple of years. In the Netherlands various researches have been done in order to investigate this problem. Blokland did various in situ tests for propeller wash against vertical quay walls (See Blokland, 1996). He used the main propeller of a tugboat to imitate the bowthruster of a larger ship. Physical models were also used to investigate this problem. Bok made use of a simple water jet to investigate stone stability at a quay wall (Bok, 1996). Van Veldhoven and Schokking both investigated the damage caused by a bowthruster (modelled by a propeller in a tube) on a rubble mound slope (Van Veldhoven, 2002 and Schokking, 2002). In these researches a small enclosed model was used, resulting in substantial interference from circulation flow. De Jong investigated the use of a computer programme to make a numerical model of a bowthruster at a vertical quay wall.
This research shows that the computer programme which was used is suitable for modelling bowthrusters. Building further on the results of De Jong, Van der Laan made a numerical model of a harbour basin with a schematised model ship, fitted with a bowthruster (Van der Laan, 2005). Using this model, Van der Laan determined the minimum size of the measuring domain in which the boundary effects on the flow pattern near to the bowthruster are negligible. An exact physical replica of the numerical model was built.

The results given by the numerical model are to be validated by the physical model. Because of the complexity of the Computational Fluid Dynamics (CFD) package used, many different scenarios can be modelled, using different boundary conditions and computational settings. It is therefore to be expected that the outcome of the physical model will differ a great deal from this first outcome of the numerical model.

2.2 Objectives

The objectives of this research are twofold and are formulated as such:

1. To map out the flow field close to the basin floor in the physical model for the maximum initial velocity of the bowthruster.
2. To evaluate and adapt the existing numerical model to better represent the physical situation.

The following steps will be undertaken in order to achieve these goals:

1a. Observing and recording the flow behaviour three centimetres above the basin floor with the aid of injected purple dye. This should give a general overview of the flow field and a first estimation of the flow velocities and directions at the predefined nodal points.

b. Measuring the average flow velocities and directions with the aid of electromagnetic velocity meters at the three predefined positions under the model ship (for the coordinates see Van der Laan (2005)).

c. Measuring the average flow velocities and directions with the aid of electromagnetic velocity meters in the area around the model ship. These results should validate the observations in step 1a.

2a. Evaluating the numerical model and correcting errors in the computational input. In this error analysis, input with regard to computational procedure such as grid size and number of iterations will be evaluated.

b. Evaluating the input of physical parameters in the computational model. The intention behind this step is to try to find a way to better model the physical situation at hand. In this step the results of the physical model are compared to the numerical model.

2.3 Outline of the Report

The research described in this report is divided into two parts, the physical analysis and the evaluation of the numerical model. The build-up of this report is therefore as follows:

Chapter 3 gives a brief summary of previous researches done and some relevant theory about bowthrusters. This helps to place this research in the context of recent developments and provides a theoretical basis for further research.
In chapter 4 a description is given of how the physical model is used to gain insight into the flow field close to the basin floor. This is done by first making observations with the aid of injected purple dye and, secondly, by measuring the size and direction of the flow velocity with the aid of electromagnetic velocity meters.

Chapter 5 deals with the numerical model. In this chapter an evaluation of the existing model will be made, after which the possible changes will be dealt with in order to better simulate the physical situation. The outcomes of the physical model and the numerical model are also compared in this chapter. This gives a brief overview of the results, showing the areas where the models give similar outcomes and where there are discrepancies.

This is followed by the conclusions and recommendations of this research, given in chapter 6.
3 Background Information

3.1 General

This chapter deals with the theory behind a ducted propeller jet against a vertical quay wall. Much research has been done in this field. Firstly a look will be taken at the theory behind the propeller wash. After this a short summary of relevant researches will be given. Finally, the prototype situation will be discussed and the method used to translate this into a scale model.

3.2 The Initial Velocity of a Propeller Wash

In this research the term “initial velocity” refers to the flow velocity directly in front of the opening of the propeller duct. Assuming that the flow velocity is uniform across the cross section of the duct, the volumetric flow coming out of the duct can be determined by the following equation:

\[ Q = U_0 \cdot \pi \cdot R^2 = U_0 \cdot \frac{\pi}{4} \cdot D_p^2 \quad [\text{m}^3/\text{s}] \quad (3.1) \]

where:
- \( U_0 \) = initial flow velocity directly in front of the propeller duct [m/s]
- \( R \) = radius of the propeller duct [m]
- \( D_p \) = diameter of the propeller duct [m]

And if there are no further disturbances in the water, the following can be derived from the energy balance:

\[ P_d = \rho_w \cdot U_0^2 \cdot Q \quad [\text{W}] \quad (3.2) \]

where:
- \( P_d \) = the generated power [W]
- \( \rho_w \) = density of water [kg/m^3]

Substituting (3.1) into (3.2) produces:

\[ P_d = \rho_w \cdot U_0^3 \cdot \frac{\pi}{8} \cdot D_p^2 \quad [\text{W}] \quad (3.3) \]

Rewriting eq. (3.3) to \( U_0 \) produces:

\[ U_0 = 1.37 \cdot \left( \frac{P_d}{\rho_w \cdot D_p^2} \right)^{\frac{1}{3}} \quad [\text{m/s}] \quad (3.4) \]

Eq. (3.4) can be used to calculate the initial flow velocity directly in front of a bowthruster, given the installed power and diameter of the bow-thruster.
3.3 What do we already know about Bowthrusters?

3.3.1 General

Over the last few years bowthruster induced damage has been the subject of much interest. Many researches have been undertaken to gain insight into the performance of (ducted) propellers and the possible ways to model their effects on the surroundings. In the following, a summary of some of these researches is given. The researches of Van Veldhoven, Schokking, de Jong and Van der Laan, are part of a research programme initiated by and performed at Delft University of Technology.

3.3.2 Schmidt and Römisch (1993)

Schmidt and Römisch did experiments with a scale model in order to investigate the effect of a bowthruster jet against a vertical quay wall. In this research the development of the jet flow and its reflection against the quay wall were investigated, in which the influence of the quay and the keel clearances on the flow velocity at various points was determined. In addition to the velocity measurements, erosion measurements at the bottom were done.

When a bowthruster (a ducted propeller) is directed towards a quay wall, five zones are distinguished by Schmidt and Römisch, as is depicted in Figure 3.1.

Fig. 3.1 Five zones in front of a quay wall, as defined by Schmidt and Römisch (1993)

Zones 1 and 2: Flow establishment and established flow

According to Römisch, the velocity field is dependent on the ratio between the distance from the propeller (x) and its diameter (D_p). From experiments done by Schmidt (1998) a solution was derived which is valid for bowthrusters:

\[
\frac{U_{x,max}}{U_0} = 2.0 \left( \frac{x}{D_p} \right)^{-1.0} \quad [-]
\]

where: \(U_{x,max} = \) maximum velocity at a distance x from the propeller [m/s]

Equation 3.5 is only valid for the established-flow zone (Zone 2). For the zone of flow establishment (Zone 1) it is assumed that \(U_{x,max} = U_0\). This leads to a length of the zone of flow establishment of \(x_0 = 2.0 \cdot D_p\). This is much smaller than a free propeller jet which is derived to be \(x_0 = 2.6 \cdot D_p\) (see Schokking (2002)).

Zone 3: The pressure zone

This zone is where the jet hits the wall. The kinetic energy is converted into pressure, which finds its maximum where the velocity is zero. The conversion of the flow velocity to pressure takes place over a distance of 0.3·L [m] in front of the wall. As can be seen in Figure 3.1 L is the distance in metres between the quay wall and the beginning of the duct of the bowthruster.
Zone 4: Radial wall jet zone

Zone 4 is characterised by the conversion of the pressure back to kinetic energy, flowing radially from the pressure point. At \( z = 0.3 \cdot L \) [m] the flow velocity reaches its maximum again.

Zone 5: Bottom

According to Römisch (1975) the velocity decrease as a result reflection is negligible. The velocity at the bottom is therefore equal to the velocity just in front of the quay wall. Submitting \( L \) into equation 3.5 gives us:

\[
\frac{U_{s,max}}{U_0} = 2.0 \left( \frac{L}{D_p} \right)^{-1.0} [-] \tag{3.6}
\]

where \( L \) is the distance from the quay wall [m].

Römisch defined a bottom stability parameter, \( B \), as follows:

\[
B = \frac{U_{\text{max,bot}}}{\rho_s - \rho_w} \cdot \sqrt{\frac{\rho_s}{\rho_w}} \tag{3.7}
\]

where

\[
\rho_s = \text{sediment density} \quad [\text{kg/m}^3] \\
\rho_w = \text{water density} \quad [\text{kg/m}^3]
\]

According to Römisch, \( B_{\text{crit}} = 1.25 \) represents the start of erosion.

3.3.3 Blokland (1994)

In collaboration with the municipal harbour company of Rotterdam, Blokland did in situ tests with the propeller wash of a tugboat against a vertical quay wall in the Benelux harbour basin of Rotterdam Harbour. The main propeller of the tugboat had approximately the same size and power as a bowthruster of a large container ship.

Current velocities were measured within 3.5 m from the vertical quay wall, caused by a propeller jet perpendicular to the quay wall and by a jet with an angle of 16 degrees with respect to the quay wall. Stone movements were also measured for the jet perpendicular to the quay.

The results of these measurements were compared with the theoretical relations for current velocities and stone transport. (Blaauw and van der Kaa, 1978, Waterloopkundig Laboratorium, 1993, Romisch and Fuehrer, 1993, Paintal, 1971).

In this research Blokland defined the following relations for flow velocity close to the bottom:

\[
U_{b,max} = 2.8 \cdot \frac{U_0 \cdot D_0}{x_{pq} + h_{pb}} \quad [\text{m}] \quad \text{for} \quad \frac{x_{pq}}{h_{pb}} \geq 1.8 \quad [-] \tag{3.8}
\]

\[
U_{b,max} = 1.0 \cdot \frac{U_0 \cdot D_0}{h_{pb}} \quad [\text{m}] \quad \text{for} \quad \frac{x_{pq}}{h_{pb}} < 1.8 \quad [-] \tag{3.9}
\]

where:

\[
U_{0,max} = \text{maximum bottom velocity flow averaged over time} \quad [\text{m/s}] \\
D_0 = \text{diameter of the bowthruster} \quad [\text{m}] \\
x_{pq} = \text{distance between the bowthruster and the quay wall} \quad [\text{m}] \\
h_{pb} = \text{distance between the axis of the bowthruster and the harbour bottom} \quad [\text{m}]
\]
He determined the stability of the bottom material using the parameters of Shields ($\Psi_{cr}$) and of Izbash ($\beta_{iz}$) for the critical water velocity. As critical value, Blokland suggests to make use of either Römisch’s findings on the parameter of Izbash, or Verheij’s findings on the parameter of Shields:

The sediment is therefore stable in the following cases:

$$B_{iz,cr} = 2.5 \text{ to } 3.75$$  \hspace{1cm} (Römisch, 1993)

or

$$\Psi_{cr} = 0.03 \text{ (no movement) to } 0.04 \text{ (some movement)}$$  \hspace{1cm} (Verheij, 1983)

### 3.3.4 Van Veldhoven (2002)

Van Veldhoven’s M.Sc. research at Delft University of Technology centred around different ways in which a bowthruster could be modelled in a physical model. The question was investigated whether a simple water jet could be used instead of a ducted propeller to physically model a bowthruster. He investigated the stability of a rubble mound slope under the influence of a simple water jet and a propeller wash. Using the physical model, calculations were made of the initial flow velocity, the flow field, flow velocities close to the slope and the stability of the stones on the slope.

The most important observation made by Van Veldhoven is that the stability of the stones under attack from a ducted propeller differs greatly from the stability when a simple water jet is used. He concluded that a bowthruster could not be modelled in a physical model by a simple water jet.

### 3.3.5 Schokking (2002)

Schokking continued the research work done by Van Veldhoven and carried out two investigations, viz.

- The stability of stones in propeller-induced jet wash on a slope. For these tests the same physical model was used as Van Veldhoven.
- The scour effects of bow- and main thrusters in Dutch inland waterways. A case study was done in the Amsterdam-Rhine Canal, a 70 kilometre long canal leading from Amsterdam to Tiel.

The experimental model was used to derive insight into the influence of the duct of a bowthruster. Velocity measurements in a jet, induced by a free propeller, were carried out and compared to similar measurements taken in a jet which was induced by a ducted propeller. The results show that the velocity in a free propeller jet decreases faster than the velocity in a ducted propeller jet, although both jets diverge at a similar angle. It was found that due to this difference in velocity decrease, the damage on the slope is considerably larger for a ducted propeller jet than for a free propeller jet. It was also found that the maximum damage occurs at the toe of the slope, whilst the jet axis, carrying the largest velocities, hits the slope much higher. Figure 3.2 shows a photo of the physical model used by Schokking and Van Veldhoven, as well as a diagram of the cross section of the model.
With the case study in the Amsterdam-Rhine Canal, Schokking focused on berthing places only, since bowthrusters are mainly used at these locations. For 15 locations along the Amsterdam-Rhine Canal bathymetry maps were analysed to find trends in scour and to relate these to the use of bow- and main thrusters.

Based on these results, Schokking identified two different types of berthing places, viz. uniform (long) and non-uniform (short) berthing places. At uniform berthing places, scour tends to be shallow and widely spread, usually not endangering the sheet pile structure. At non-uniform berthing places, scour tends to be more severe, since vessels berth in a more consistent manner, thereby creating scour at specific, concentrated spots.

The measured depth of some of the scour holes was compared to the calculated scour depth for the location investigated. This comparison shows that the calculation methods of Römisch (1977) and Ducker & Miller (1996) produce results similar to the measured results.

### 3.3.6 De Jong (2003)

De Jong’s research focussed on making a numerical model in order to compute flow velocity (patterns) caused by bowthrusters at vertical quay walls. Using a CFD-package, called Phoenics, he started off by investigating the correct way to model a bowthruster. In order to correctly model a propeller wash, de Jong found that a swirl had to be added to a simple water jet in the form of tangential flow velocities and that a core had to be added in the axis of the propeller.

De Jong based his research on the findings of Van Veldhoven (2002) and Schokking (2002). First of all, simulations were done in order to compare the simple water jet, the free propeller wash and the ducted propeller wash. He showed that these three types could easily be modelled in the numerical model by a standard k-ε turbulence model. Figure 3.3 shows a diagram of the input of the physical model used by Van Veldhoven and Schokking (see Figure 3.2) into the numerical model.

This model was translated into a scenario with a vertical quay wall and was simulated for two different situations, viz. one in which the keel clearance was taken into account and one in which the keel clearance was neglected. The same scale of the model, as was used by Van Veldhoven and Schokking, was implemented, although certain changes were made:
• Only one scenario for the distance of the propeller to the quay wall was investigated.
• The breadth of the model was increased in order to lessen the effect of unwanted circulations.
• At both the outer boundaries the boundary condition was changed to an outflow boundary so that the water could flow away much easier.

Figure 3.4 shows these changes, and Figure 3.5 shows the output thereof.

![Diagram of the computational input for a vertical quay wall](image)

The maximum flow velocities calculated by the numerical model just above the bottom were compared to the present calculation methods for this particular situation. It is questionable whether this comparison leads to any usable results, as the numerical model uses maximum velocities while in the calculation methods it is the average velocities that are used.

3.3.7 Van der Laan (2005)

The aim of Van der Laan’s research was to design a numerical model in which flow velocities caused by a ship’s bowthruster can be calculated for various different situations. The results of this model were later be verified by means of a physical model.

The prototype ship used for this research was the ‘Pride of Rotterdam’ which has two bowthrusters, each with a diameter of 2.5m. A simplification of the prototype was made and the main dimensions were scaled to the model dimensions (1:25). In Phoenics a numerical model was designed in which the bottom flow velocities could be determined. These flow velocities were used to define the domain area in such a way that the interference in the flow would be limited as much as possible. These interferences are a result of the reflection of the water against the domain boundaries.

Firstly, a large domain was created in which the whole ship could be placed. In this domain area, a comparison was made between an open and a closed domain, in which the open domain allowed in- and outflow through its boundaries. From these calculations, Van der Laan concluded that a closed domain gives a reasonably good representation of an open flow.
The large domain is subsequently demarcated in such a way that an optimal smaller domain is defined. The results of the numerical model show that interferences caused by circulation currents are minimal. Van der Laan concludes that a small domain calculation can be used in order to make a comparison with the prototype situation. Figure 3.6 shows the large domain, as defined by Van der Laan, and the first step in demarcating the model to the smaller domain.

![Fig. 3.6 Large domain defined in Phoenics by Van der Laan (2005), showing the first step in the demarcation process.](image)

Using the results from the demarcation analysis, a physical model was built in the Fluid Mechanics Laboratory at Delft University of Technology. Van der Laan used the numerical model to define three significant positions under the model ship in which physical measurements were made. The comparison of these measurements to the calculated values at the given points did not give conclusive results. This is because these three points do not give a complete picture of the flow field. The results at the three points, however, give an indication that the computer model does not produce an accurate representation of the outcome of the physical model.

### 3.4 Developing the Model

#### 3.4.1 The Prototype Situation

The ship on which this research has been based is called the ‘Pride of Rotterdam’, a ferry with a length of 215 m and 2 bowthrusters with diameter 2.5 m. In Van der Laan (2005) the choice for this ship as prototype is explained. In the prototype situation, we consider a situation in which the ship is lying parallel to the quay wall with the duct of the bowthruster perpendicular to the quay wall. In this research a static situation is considered. Even though the bowthruster is in use, we assume that the ship stays in its original position. In Figure 3.7 a simplified cross section of the prototype situation is given in order to illustrate the various terms.

In order to investigate the most extreme situation, the parameters are selected in such a way that the highest possible velocities will be induced. It is assumed that the highest velocities will occur when the quay and keel clearances have their smallest values, and when the
bowthruster’s maximum power is used. The keel clearance is the distance between the underside of the ship and the basin floor. According to PIANC (The International Naval Association) in its guidelines of 1997 the keel clearance must be at least 1 m, but under certain circumstances this can be reduced to 0.6 m. Because of the foreseen limitations of the measurement apparatus, this value is chosen at 1.5 m. The term ‘quay clearance’ here does not refer to the distance of the ship from the quay wall, but to the distance between the beginning of the duct of the bowthruster to the quay wall. Because specific dimensions of the Pride of Rotterdam are not given, the length of the bowthruster duct is estimated using guidelines given by PIANC (1997), which say that the length of the duct of a bowthruster is 29% of the maximum breadth of the ship.

![Fig. 3.7 Cross section of the prototype situation](image)

The maximum installed power of one of the bowthrusters is 2000 kW, giving us a maximum initial flow velocity in the propeller duct ($U_0$) of 9.37 m/s, calculated from equation (3.4).

### 3.4.2 Making the scale model

A scale of 1:25 is chosen for the scale model, because this proved to be practical in this situation. The dimensions of the model are scaled geometrically, according to equation (3.5).

$$\frac{n_L}{L_p} = \frac{L_m}{L_m}$$

(3.5)

where

- $n_L = \text{geometrical scale value} = 25$ [-]
- $L_p = \text{characteristic length of the prototype [m]}
- L_m = \text{characteristic length of the model [m]}

The most relevant dimensions are the keel clearance (scaled to 0.06 m), the quay clearance (scaled to 0.5 m) and the bowthruster diameter (scaled to 0.1 m). For the time being, the bowthruster diameter is scaled geometrically. Further study about the turbulence will prove whether this is founded.

In order to correctly scale the dynamic variables, the scaling law of Froude is used, in which the value of the Froude number should be the same for the scale model as for the prototype situation. The Froude number is defined by equation (3.6).

$$Fr = \frac{U^2}{g \cdot L}$$

(3.6)

where

- $Fr = \text{Froude number [-]}
- U = \text{characteristic flow velocity [m/s]}

Fig. 3.7 Cross section of the prototype situation

The maximum installed power of one of the bowthrusters is 2000 kW, giving us a maximum initial flow velocity in the propeller duct ($U_0$) of 9.37 m/s, calculated from equation (3.4).
\( L \) = characteristic length [m]

Equating the Froude values produces the following:

\[
Fr_p = Fr_m \quad \Rightarrow \quad \frac{U_p^2}{g \cdot L_p} = \frac{U_m^2}{g \cdot L_m} \quad \Rightarrow \quad \left( \frac{U_p}{U_m} \right)^2 = \left( \frac{L_p}{L_m} \right) \quad \Rightarrow \quad n_U = \sqrt{n_L}
\] (3.7)

where

\( n_U \) = velocity scale value [-]
\( Fr_p \) = Froude number for the prototype situation [-]
\( Fr_m \) = Froude number for the physical model situation [-]

This leads to an initial velocity for the scale model of \( U_0 = 1.87 \) m/s. In the model set-up a value of 1.5 m/s is used, because it is expected that the model apparatus cannot produce higher velocities than this. From equation (3.3) we see that an initial flow velocity of 1.5 m/s corresponds to 52\% of the maximum power. This is the same value as is used by Van der Laan for the numerical model.
4 Observations and Measurements in the Physical Model

4.1 General

This chapter describes the methods used to gain insight into the flow near the bottom in the physical model. The method used to do this is two-fold, namely observing the behaviour of injected dye and measuring the flow velocities and directions using electromagnetic velocity meters.

4.2 Description of the Physical Model

In the Fluid Mechanics Laboratory of Delft University of Technology, a physical copy of the numerical model, as described in section 3.3.7, was built. The basin has the following internal dimensions: $h \times l \times b = 70 \times 600 \times 500 \text{ cm}^3$. The walls of the basin are made of bricks and are plastered on the inner side. The floor is made of concrete, covered by PVC sheets and sealed with a sealant. The result is a relatively smooth, horizontal floor.

The model ship, with dimensions $h \times l \times b = 64 \times 350 \times 40 \text{ cm}^3$ is placed in the physical model in the same way as in the numerical model, with an underkeel clearance of 6 cm and a quay clearance of 50 cm. In Figure 4.1 a diagram of the layout of the physical model is given. In Figure 4.2 a photo of the actual set-up is given.
The bowthruster is modelled by a PVC cylinder (internal diameter 10 cm) with a propeller mounted inside which is powered by an electric motor (see Figure 4.3). For the sake of this research only the maximum initial velocity \( U_{0,\text{max}} \) will be modelled. As is described in Van der Laan (2005) \( U_{0,\text{max}} = 1.5 \, \text{m/s} \), which corresponds to 850 revolutions per second of the electric motor.

Fig. 4.2 Photo of actual set-up

For the sake of the positioning of both the movable velocity meter and the injection tube, a grid was drawn on the floor in the physical model. In the area immediately next to the ship, a grid of 20 * 20 cm was drawn. In the area further away from the ship the grid was 20 * 50 cm. See figure 4.4.

Fig. 4.3 Electric motor (left) and model of bowthruster (right)

Fig. 4.4 Diagram of grid in physical model

Bowthruster-Induced Damage
4.3 Observations

In order to get an overall view of the flow field and a first estimation of the flow velocities and directions, observations were made using the injection of purple dye (KMnO$_4$ – potassium permanganate, which was dissolved in water), at 3 cm above the bottom. This is the same distance as is used in the numerical model.

Firstly, general observations were made in order to get an overall view of the flow field and to identify the main flow directions. This was done in order to quickly identify the flow patterns and characteristic points. This process is characterised by the injection of large quantities of dye over a large area and then observing the patterns formed by the dye. For example, in the area to the right of the ship, a line of dye can be ‘drawn’ close to the bottom, resulting after some time in the pattern shown in Figure 4.5. In both photos the dye is injected along the line X = 4.3 m. In the left photo, the dye is seen to be moving in the positive X-direction (for Y = 3.5 m to 5 m), while in the right photo, it is moving in the negative X-direction (for Y = 5.2 m to 6 m). At about Y = 5.1 m, where the dye is darker than the rest (see the photo on the right), we can see a ‘turning point’ in the flow where the water shows little movement.

Fig. 4.5 Photos of injected line of dye

Similar observations were done in other regions around the ship, producing a general picture of the flow behaviour.

The second type of observation made, using the potassium permanganate dye, is the injection of small amounts of dye at each node of the grid in order to make an estimation of the flow velocity and direction. For each node a series of injections were done in order to estimate the general flow direction. Once this was done, the flow velocity is estimated. This is done with the aid of a stopwatch. The time is measured that it takes for an injected ‘cloud’ to travel 20 cm. This is repeated 5 times per node and the average of these values is recorded.

In order to illustrate this process, a few examples are given.
Figure 4.6 shows a continuous stream of injected dye at point $X=3.7$ m; $Y=1.3$ m. From the photograph the direction of flow can clearly be seen. In this case the water flow has a direction of $335^\circ$, where the negative x-axis represents $0^\circ$ and the angle increases in a clockwise direction. This is, however, a snapshot in time and does not represent the flow direction averaged over time. When observing this point over a longer period of time, we see that the average flow direction is $345^\circ$.

Figure 4.7 shows a series of photos of an injected cloud at the same point. Although these photos alone are not sufficient to deduce the flow velocity, they give an indication of how a cloud of dye can be followed.
The region in front of the bowthruster is the region of most interest for the question at hand. In this region, however, it proved rather difficult to make clear photographs of the injected dye, because of the large degree of turbulence and high flow velocities. Figure 4.8 is a photo of dye injected approximately at point X=4.5 m; Y=3.3 m. It shows a general flow direction of 135°.

The above-mentioned process is repeated for all of the 71 nodes shown in the Figure 4.4. The results of these observations are plotted as vectors in Figure 4.9. A larger view of Figure 4.9 as well as a table with the vector values is given in Appendix B1, Table A12 and Figure A15. This flow pattern gives a qualitative indication of the flow velocities and flow directions. The values given should by no means be treated as accurate measurements.
4.4 Measurements

In order to verify the results of the observations given above, a series of measurements were made with electromagnetic velocity meters. Where the observations give an overall first impression, the measurements should give reasonably accurate values for the size and direction of the flow velocity. Because of the limited added value of measuring in all the nodal points, as well as the fact that the measurements are very time consuming, it was deemed inefficient to do measurements at every point on the grid.

The area immediately around the bowthruster is considered the most important area of interest. This is because it is here that the highest flow velocities occur, as well as the most fluctuation in the flow direction. Because in this area the flow field is relatively complex, it proved quite difficult to make a sound observation. Therefore, in this area each nodal point was measured. Further from the bowthruster, the flow fields are of less interest and are also less complex. In these areas a limited number of measurements were done.

The above-mentioned considerations result in a measurement plan, as is seen in Figure 4.10.

![Fig. 4.10 Measurement Plan](image)

4.4.1 Placing the EMS

For the measurements, four EMS probes will be used. Three of these were fixed probes (EMS5, EMS12 & EMS7) and the fourth (EMS10) was a movable probe.

The three fixed probes were to be placed in the predetermined positions laid out in Van der Laan (2005). For the coordinates of these EMS positions see also Figure 4.10. These probes were to measure the flow velocities in the X- and Y-directions under the ship at these three specific points. The movable probe was used to measure the flow velocities at all the other points outside the ship.

In order to place the probes exactly 3 cm above the basin floor, point gauges were used. For the three fixed probes, these point gauges were fixed directly to the model ship (hence the name ‘fixed probes’). For the fixed probes it proved possible to place these probes with an accuracy of ±1 mm. For the movable probe, however, this was not the case. The point gauge was fixed to a tripod which showed a certain degree of flexibility. It was therefore be assumed that the distance to the basin floor had a deviation of ±2 mm.
Figure 4.11 shows a diagram of the position of the probe under the ship (left), as well as a photo of the actual probe after it was placed (right).

Figure 4.12 shows two photos of how the EMS-probes had been mounted in the model ship.

4.4.2 The Output of the EMS

The output of the EMS is in the form of ASCII-code. This code is divided into three output variables, viz. the elapsed time, the voltage differences in the X-direction and in the Y-direction. In order to translate this code into average flow velocities, the following method was used:

A. The values of the EMS-output for still water in the X-direction were averaged
   \( \overline{V_{X_0}} = \frac{\sum V_{X_0,a}}{n} \).
B. The values of the EMS-output for flowing water in the X-direction were averaged
   \( \overline{V_{X_1}} = \frac{\sum V_{X_1,a}}{n} \).
C. The average value for still water was subtracted from the average value for flowing water
   \( \overline{V_X} = \overline{V_{X_1}} - \overline{V_{X_0}} \).
D. This value was translated from volts into flow velocity [cm/s], by multiplying it by a factor 10. This is the average flow velocity in the X-direction \( \overline{U_X} \).
E. Steps A.-D. were repeated for the Y-direction, producing \( \overline{U_Y} \).
F. From the two average flow velocities per direction, the overall average flow velocity and direction were calculated, using Pythagoras's Law:

\[ U = \sqrt{(U_X)^2 + (U_Y)^2} \]  
and \[ \alpha = \arctan \left( \frac{U_X}{U_Y} \right) \]  

(4.1)

4.4.3 Measurements under the Ship

The first series of measurements done were the measurements under the ship. Three identical measurements were made in order to check the accuracy and the reproducibility of the measurements.

Each measurement that was made took exactly ten minutes. Firstly stationary water is measured for one minute. Then the motor is switched on. After the motor has been running for nine minutes, the measurement is stopped and the motor switched off. Because it takes approximately one to two minutes for the flow field to develop, this leaves us with seven minutes of actual measurements. In Appendix A, where the calibration procedure is described, we see that measurements were made of stationary water, before and after each measurement of streaming water. For the measurements in the model set-up, however, measurements of stationary water, after the flowing state, were not made. This is because, after turning off the motor, it takes about four to five minutes before the water in the basin becomes reasonably still.

In Table 4.1 a summary of the results of these tests is given.

<table>
<thead>
<tr>
<th>Measurement #</th>
<th>EMS1 (Y = 3.05 m)</th>
<th>EMS2 (Y = 2.3 m)</th>
<th>EMS3 (Y = 1.3 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Velocity</td>
<td>Direction [°]</td>
<td>Flow Velocity</td>
<td>Direction [°]</td>
</tr>
<tr>
<td>[cm/s]</td>
<td></td>
<td>[cm/s]</td>
<td></td>
</tr>
<tr>
<td>01</td>
<td>10.06</td>
<td>2.01</td>
<td>3.46</td>
</tr>
<tr>
<td></td>
<td>130</td>
<td>42</td>
<td>334</td>
</tr>
<tr>
<td>02</td>
<td>9.90</td>
<td>2.13</td>
<td>3.20</td>
</tr>
<tr>
<td></td>
<td>129</td>
<td>54</td>
<td>344</td>
</tr>
<tr>
<td>03</td>
<td>9.63</td>
<td>2.10</td>
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<tr>
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<td>130</td>
<td>53</td>
<td>352</td>
</tr>
<tr>
<td>Average</td>
<td>9.86</td>
<td>2.08</td>
<td>3.78</td>
</tr>
<tr>
<td></td>
<td>129</td>
<td>50</td>
<td>343</td>
</tr>
</tbody>
</table>

Table 4.1 Results of measurements under the ship

When comparing this outcome to Van der Laan (2005), we see that his outcomes differ somewhat to the outcomes given in Table 4.1. This shows the large variability in the flow caused by the bowthruster. For more accurate results, a large number of tests must be undertaken. Van der Laan’s series of tests are possibly not sufficient to give accurate results for \( U_0 = 1.5 \) m/s.

4.4.4 Measurements around the Ship

EMS10 (the movable probe) was used to do the measurements indicated in the Measurement Plan in Figure 4.10 for the points around the model ship. This probe was mounted via a point gauge to a tripod. This tripod could be moved to different positions. The point gauge allowed the height of the probe above the basin floor to be accurately determined.

For each measurement the following procedure was followed:
1. The position of the tripod was determined such that the probe was directly above the nodal point where the measurement was to be made.
2. The orientation was determined. The line across the top of the EMS ‘box’ was visually aligned to the appropriate Y-gridline.
3. The height of the probe was adjusted to 30 mm above the basin floor. This was done by lowering the probe to the floor using the point gauge and then raising it by 24.5 mm (30 mm – 5.5 mm)\(^1\).

4. The ten-minute measurement, as is explained under 4.4.3, was made.

5. The water was allowed 5 minutes to come to a reasonable standstill, while steps 1 to 3 were repeated for the following point.

Because of problems with the apparatus, it was not always possible to make full ten-minute measurements for each point. Those measurements for which this occurred where later repeated. The repeated tests, however, proved that the shorter tests were not as inaccurate as was previously assumed. This can be seen by the fact that the results of the shorter tests (usually approximately 5 minutes long) do not deviate much from the results of the longer tests.

In addition to these tests, a second series of tests was done for the points of interest in the area on the quay side of the ship in front of the bowthruster.

Figure 4.13 gives a visual overview of the results of these tests. The vectors given represent the size and direction of the flow velocities measured by the electromagnetic velocity meter three centimetres above the basin floor at the predetermined nodal points. In Appendix B2, a complete overview of the EMS measurements are given in Table B2. In Table B3 a summary of the average result per point is given, as well as a larger view of Figure 4.13 in Figure B3.

\[\text{Fig 4.13 Plot of results of the measurements}\]

### 4.4.5 Interpretation of the Results

For some of the results of the measurements, some doubt exists as to whether a suitable method was used to calculate the flow velocity from the EMS-output. This will be illustrated using two examples of the output of the EMS at two characteristic points, viz. X = 4.9 m; Y = 2.7 m and X = 4.7 m; Y = 2.7 m. The method which was used to calculate the average flow velocity is explained in paragraph 4.3.2.

\[1\] The thickness of the probe is 11 mm and the distance between the underside of the probe to the reference level is 5.5 mm (see figure 4.11).
These points fall in the area on the quay side of the ship in front of the bowthruster. In this area there is a lot of turbulence and the flow velocity and direction show a lot of variability. This can be seen by the graph given in Figure 4.15.

Figure 4.14 shows a relatively stable flow, while Figure 4.15 shows a large degree of variability. Although the flow velocity in Figure 4.15 averaged over time is relatively small ($u=1.91$ cm/s – see appendix B2, Table A14) compared to the flow velocity calculated from Figure 4.14 (11.94 cm/s), it shows an output with a deviation from the still-water value in the same order of magnitude as Figure 4.14. We can therefore conclude that the flow velocity, averaged over time, does not always give a good indication of what is happening.

Figure 4.15 gives rise to a few questions.
1. Has the flow field had enough time to fully develop?
2. Does the flow demonstrate an instable equilibrium at this point?
3. If so, does this instable equilibrium have a cyclic character?
4. How can we better represent the instantaneous flow velocities?

In order to find answers to these questions, an additional series of tests was done for longer time periods. Point (4.7, 2.7), of which a 'short' measurement is given in Figure 4.15, is examined. In addition to the 10-minute measurement that had already been done, 20- and 30-minute measurements were done. The output of the EMS for these tests is given in Figure 4.16.
These results shed some light on the above-mentioned questions.
1. From the 20- and 30-minute measurements can be concluded that in the first 10 minutes the flow field is indeed fully developed. This can be seen by the fact that the average value of the first ten minutes does not increase or decrease later on in the same measurement series.
2. The question about an instable equilibrium cannot be sufficiently answered by Figure 4.16. We do, however, see that there is a form of instability which seems to centre around an average value. This suggests an instable equilibrium.
3. A similar conclusion can be found about the cyclic character, although deeper analysis than simply a visual examination must be made to give an adequate answer to this question.
4. The answer to this question can be found in the method used to find the average flow velocity. This will be explained here.

In paragraph 4.3.2 the method used to calculate the average flow velocity is explained. This method is summarized in equation 4.1. For the sake of clarity; this method will be called Method 1.

\[ U = \sqrt{\left(\frac{U_x}{U_y}\right)^2 + \left(\frac{U_x}{U_y}\right)^2} \] \hspace{1cm} (4.1)

\[ \alpha = \arctan\left(\frac{U_x}{U_y}\right) \]

Method 1, however, does not adequately describe the magnitude of the instantaneous flow velocities. Therefore a different method is chosen to calculate the average flow velocities. This method differs from the method explained in 4.4.2 in such that the flow velocity and direction is first calculated per time unit. These velocities and directions are then averaged. This method is summarised in Equation 4.2 and is called Method 2.

\[ U = \sqrt{\left(\frac{U_x}{U_y}\right)^2 + \left(\frac{U_x}{U_y}\right)^2} \] \hspace{1cm} (4.2)

\[ \alpha = \arctan\left(\frac{U_x}{U_y}\right) \]

In Table 4.2 the results of these calculations for the two characteristic points are given. In the same table the standard deviations of these values are also given.

<table>
<thead>
<tr>
<th></th>
<th>Point 1 (X = 4.9 m; Y = 2.7 m)</th>
<th>Point 2 (X = 4.7 m; Y = 2.7 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Method 1</td>
<td>Method 2</td>
</tr>
<tr>
<td>( U )</td>
<td>11.94 cm/s</td>
<td>12.2 cm/s</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>294°</td>
<td>293°</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>4.12 cm/s</td>
<td>4.51 cm/s</td>
</tr>
<tr>
<td>Relative S.D. (Percentage of ( U ))</td>
<td>35%</td>
<td>34%</td>
</tr>
</tbody>
</table>

Table 4.2 Comparison between different calculation methods

From these results can be seen that the difference between the two methods have very little effect on the results for the measurements at Point 1, while for Point 2 Method 2 gives totally different results than Method 1. This can possibly be explained by the standard deviation. The relative standard deviation calculated for Point 2 is far higher than that for Point 1. This was expected, because the plot in Figure 4.15 is much more irregular than the plot in Figure 4.14. The flow velocity calculated by Method 2 for point 2 is higher than for Method 1. This value better represents the magnitude of the instantaneous flow velocities represented in Figure 4.15. The flow direction calculated by Method 2 for Point 2, is also consistent to the flow direction found by the observations (see section 4.3).

Therefore, it can be concluded that Method 2 gives a better representation of a flow field than Method 1. In areas of little fluctuation, both methods give similar results, while in areas of
much fluctuation, Method 2 gives better results. Therefore, Method 2 should be implemented in further analysis of flow velocity data.

4.5 Comparison between the Observations and the Measurements

Figure 4.17 shows the result of superimposing the results of the measurements on the results of the observations. As can be seen, the general picture produced by the measurements is largely similar to that of the observations.

Fig. 4.17  Vector Representation of Measurement Results (orange) superimposed on the Observation Results (blue)
4.6 Error Analysis

4.6.1 Observations

The results of the observations give an indication of the order of magnitude of the flow velocity and general direction of flow. It goes without saying that these results have a large error margin.

With regard to the flow velocity the estimated error is dependent on the flow velocity itself. The higher the velocity, the smaller the relative error is. For velocities above 10 cm/s the error of observation is estimated at ±20%. For values smaller than 2 cm/s, this error is estimated at ±100%. For flow velocities between 2 and 10 cm/s the errors lie somewhere in between these two values (they can be estimated by extrapolation). The reason that the velocity is difficult to estimate at low velocities, is because of the following. While timing the interval in which the water flows 20 cm (intervals of more than 10 seconds), the flow field may change direction a bit, or slow down or speed up. A smaller distance can be timed (e.g. 10 cm) but this also increases the relative error.

With regard to the flow direction, two different scenarios have to be examined, viz. situations where a stable equilibrium has developed and where an instable equilibrium is present. In points where a stable equilibrium has developed (for example in the area around point X = 3.9 m; Y = 0.9 m), the flow direction can be estimated with an accuracy of ±10°. In points where an instable equilibrium has developed, this error is much larger and is estimated at ±30°.

A critical note has to be made with regard to the average flow direction recorded in Figure 4.9. In cases where an instable equilibrium has developed, it is questionable whether an average flow direction gives us any useful information. For example, at point (4.7,1,5) an instable equilibrium seemed to develop. The flow seemed to have two main flow directions, viz. 240° and 300°, randomly changing very abruptly between the two flow directions. An average flow direction of 270° is therefore only a mathematical average and not a representation of the actual situation.

4.6.2 Measurements

Error calculated from Calibration Curves

In Appendix A3, pp. 71 – 73, the calibration curves for the three fixed EMS probes is given. As can be seen from these curves, a similar trend is observed for all four orientations of all three the probes. The absolute deviation from the theoretical value given by the pressure-difference meter is, for all the cases, in the same order of magnitude. For these reasons, it can be assumed that the movable EMS (EMS10), which was not calibrated in the calibration flume, exhibits similar behaviour.

The average deviations of the EMS readings from the values given by the pressure-difference meter are deduced from the results in Appendix A3, Tables A8 – A10. These are shown in Table 4.3 for three relevant velocities.
Flow velocity \((V_{\text{ems}})\) | Average absolute deviation \(V_{\text{ems}}\) from \(V_{\text{orifice}}\) | Average percentage deviation \(V_{\text{ems}}\) from \(V_{\text{orifice}}\)  
--- | --- | ---  
5 [cm/s] | 0.14 [cm/s] | 2.8 [%]  
10 [cm/s] | 0.43 [cm/s] | 4.3 [%]  
15 [cm/s] | 0.9 [cm/s] | 6.5 [%]  

Table 4.3 Error Analysis Calibration Curves

**Error as a result of Vertical Deviation of EMS position**

In Appendix A3, pp. 74 and 75, the results of the sensitivity study of the EMS to vertical displacement are given. As can be seen the output shows a similar trend for all four orientations. The EMS shows greater sensitivity to displacement towards the bottom than away from the bottom. This was expected because the measuring volume of the EMS is found in a region under the probe.

The tests were done for large placement deviations of up to 10 mm. In the actual model setup it proved possible to place the probes with greater accuracy. In section 4.4.1 (Placing the EMS) the expected deviations of placement are given. For the fixed probes this is ±1 mm and for the movable probe this is ±2 mm. The average percentage deviation of the EMS output for ±2 mm placement deviation is ±3% of the EMS output. For a placement deviation of ±1 mm, no tests were done. It is therefore assumed that the error will be 1.5% of the EMS output (half of the error for ±2 mm placement deviation).

**Total Error**

The individual errors can be added up. In Table 4.4 these errors are summarised.

<table>
<thead>
<tr>
<th>Flow velocity ((V_{\text{ems}})) [cm/s]</th>
<th>Error Calibration Curves [%]</th>
<th>Error Vertical deviation [%]</th>
<th>Total Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.8</td>
<td>1.5 Fixed Probes</td>
<td>4.3 Fixed Probes</td>
</tr>
<tr>
<td>10</td>
<td>4.3</td>
<td>1.5 Fixed Probes</td>
<td>5.8 Fixed Probes</td>
</tr>
<tr>
<td>15</td>
<td>6.5</td>
<td>1.5 Fixed Probes</td>
<td>8 Fixed Probes</td>
</tr>
</tbody>
</table>

Table 4.4 Total Measurement Errors

To illustrate the errors given in Table 4.4 the measurement results of all the points along the \(X = 4.9\) m line (next to the quay wall) have been plotted, as well as the error intervals calculated by interpolation of the errors given in Table 4.3. See Figure 4.18.
Fig. 4.18 Example of Measurements and Errors at X = 4.9 m

As can be seen from Figure 4.18 the errors are found to be larger for higher flow velocities. This is in accordance with Table 4.3 and the calibration curves found in Appendix A3, pp. 71 - 73.
5 Evaluation and Adaptation of the Numerical Model

5.1 General

As is explained in section 3.3.7, Van der Laan developed a numerical model using a Computational Fluid Dynamics (CFD) software package called Phoenics. In this chapter a critical look will be taken at this model, focussing especially on the input parameters. A short comparison will also be made to the measurements in the physical model, highlighting the similarities and the differences between the two outputs.

5.2 Domain dimensions and orientation

The most obvious difference between the numerical model and the physical model is that the one is the mirror image of the other. The reason that the physical model was not built with the same orientation as the numerical model is explained in Van der Laan (2005). This difference in orientation will not have any influence on the outcome of the numerical model other than that the flow field will have to be mirrored in order to compare it to the flow field of the physical model. For reasons of clarity the numerical model was redesigned in the correct orientation. This avoids any possible misinterpretation.

The smaller domain defined by Van der Laan, used in the numerical model, has the following dimensions: \( l \times b \times h = 5.2 \times 4.0 \times 0.63 \text{ m}^3 \). The physical model, that was subsequently built, was slightly larger in size, viz. \( 6.0 \times 5.0 \times 0.63 \text{ m}^3 \). This is because there was more space available in the laboratory and a larger basin means less interference as a result of circulation flow. This difference in dimensions between the physical model and the numerical model could have lead to differences in the flow pattern. These differences were expected to be very small because the smaller domain was already defined with the intention of creating a basin large enough to minimise the interference. Nevertheless, in order to rule out all possible sources of inaccuracies, the domain size in the numerical model was adapted to that of the physical model.
Figure 5.1 shows the difference in dimensions and orientation between the numerical model developed by Van der Laan and the adapted numerical model based on the physical model.

![Figure 5.1 Van der Laan’s numerical model (left) and the numerical model adapted to the physical model (right)](image)

### 5.3 The Calculation Grid

A possible source of errors in the calculation of the numerical model was found in the calculation grid pattern. In general a calculation made with a denser grid pattern gives a more accurate calculation, although it considerably increases the calculation time. A method used to decrease the calculation time, while retaining the desired accuracy, is using a denser grid in the areas of interest and a larger grid elsewhere. This, however, cannot be done arbitrarily. In order to avoid discontinuities in the calculation, the size difference in adjacent cells should not be much larger than a factor 2. This means that in order to go from a small to a large grid, this often has to be done in a few steps.

When looking at the left hand diagram in Figure 5.2, the grid on the left side of the diagram is seen to be about 10 times larger than on the right side, with an abrupt transition between the two areas. Also in the X-direction abrupt transitions are present. In order to avoid discontinuities as a result of the grid size, the horizontal grid was given a uniform spacing, with a grid size of 10x10 cm (see the right hand diagram in Figure 5.2). An increase in the calculation time was expected. Although the area under the ship was now left with a less dense grid, this was considered acceptable as the breadth of the ship was still a factor 4 larger than the grid spacing.
For the vertical grid, a similar situation was found, with an arbitrary difference in cell sizes (see Figure 5.3 (left)). For example, a cell in the region under the ship has a height of 0.67 cm. In the adjacent region the cell height is 10 cm. This is a factor 15 larger.

In the adaptation of the vertical grid, a grid with increasing size in the positive Z-direction was chosen. For the region under the ship, a dense grid was chosen with cell height 1.5 cm. This is the region in which the calculation is of most importance for this research. For increasing values of Z, the grid size was gradually increased. This was done in order to reduce the calculation time. Figure 5.3 (right) shows the adapted grid with gradually increasing cell size in the positive Z-direction.
5.4 Iterations

In the numerical model used by Van der Laan, a convergence criterion of 1% was used. It is unclear whether the number of iterations used (n = 500) is sufficient to be able to meet this criterion. For the new situation, with an adapted domain size and grid pattern, an additional analysis of the number of iterations was done.

In order to determine the optimal number of iterations (n) for this situation, a calculation was performed using the adapted computer model for 5 different values of n, ranging from 50 to 10 000. For each calculation a plot was made of the horizontal velocity along the line X = 4.3 m; Z = 0.03 m (halfway between the ship bottom and the basin floor, along the centre line of the ship), as a way of comparison between the different calculations. These plots can be seen in Figure 5.4.

From Figure 5.4 can be seen that the values for n = 1,000 and n = 10,000 are virtually identical. Although this could indicate that 1,000 iterations is sufficient to adequately calculate the flow field, still some doubt exists. Judging from the positions of the five curves, it seems as though the output has an oscillatory nature. This can be illustrated by the following. If one looks at the right hand side of the graph in Figure 5.4, the curve for n = 50 iterations is far from the curve for n = 1,000 (which sounds logical); the curve of n = 100 is much closer than that of n = 50, while for n = 500 it is further away again. This seems illogical. The question that then arises is whether the calculation shows some form of oscillation and whether it is not just pure coincidence that the values for n = 1,000 and n = 10,000 are similar.

Further calculations were done for values of n in between the values that had already been investigated, viz. for n = 700 and n = 2000. As can be seen from Figure 5.5 the graphs produced by these calculations are also almost identical to the graph for n = 1,000. This indicates that the calculation process does not have an oscillatory character as was deemed possible, and that for values of n > 700, the numerical model exhibits no further convergence. For further calculations n = 1,000 was used.
This process is also illustrated by the output of the calculation convergence given by Phoenics, as is given in Figure 5.6 for 1,000 iterations (left) and for 100 iterations (right). For 1,000 iterations, we see in the left sub-plot that the output of the 4 variables have reached reasonably constant values (horizontal lines) and that the largest value of the convergence errors (indicated by the top value in the red oval) is 1.1% which is (virtually) the convergence criterion. For 100 iterations (right) we see that the convergence is not met by far. The left sub-plot also shows that the plots of the different variables still show a lot of variability (not yet horizontal).
5.5 Boundary Conditions

The output of the numerical model gives rise to the question whether the boundary conditions have been defined properly. Figure 5.7 shows a section of the flow field next to the left-hand border in the numerical model. From this figure can be seen that the flow is not hindered much by the solid wall present in the model. This can be seen by the fact that the flow vectors indicate that the water is flowing through the wall (in the area marked by the oval). This indicates that here the boundary conditions may not be properly defined.

Fig. 5.7 Detail of flow field next to left-hand boundary

In Phoenics, defining the input parameters can be done in two different ways. The first way is by compiling an input file, called a Q1-file. This is the most efficient way of working but it requires more insight into the working of the programme. The second way is by using a user-friendly interface, developed to visually input all parameters. This method is easier to understand but does not contain all the features of Phoenics as is the case when using the Q1-file.

In the development of this particular model, the second method was used. The boundary conditions were put in as solid objects, viz. four walls and a basin floor. In the input menu no further provision was made to define the boundary conditions. This seems to be in line with the above-mentioned suspicion that the boundary conditions are not sufficiently defined. Although the Q1-file was not used to input the parameters, Phoenics automatically generates this file from the input parameters. In Appendix C the Q1-file, generated by Phoenics, is given. Under the heading 'Boundary and Special Sources' the Q1-file reports that 'No patches are found'. This seems to confirm the suspicion that the boundary conditions are not properly defined, although it is highly unlikely that no boundary conditions are present, as the Q1-file suggests.

The problem of defining the boundary conditions needs to be further investigated. A possible solution for this problem is inputting the boundary conditions in the existing Q1-file.
5.6 Comparison with the Physical Model

After implementation of the above-mentioned adaptations, the numerical model can be compared to the physical model. This will be done in two different ways. Firstly, a visual comparison will be done in section 5.6.1, in which the flow patterns are compared, focussing mainly on the flow direction. Secondly, a comparison will be done of the absolute flow velocities, given in section 5.6.2.

5.6.1 Visual Comparison – Flow direction

Figure 5.8 gives an overview of the results of the physical model (above) and the numerical model (below). In these diagrams only the region next to the quay wall is depicted. This is the region in which the highest flow velocities occur.

It is important to note that in the diagrams given in this section, the sizes of the vectors of the physical model are not comparable with those in the numerical model. The only comparison done on size from the flow patterns, is of different regions within the same model.

In order to be able to clearly describe the similarities and differences between the flow fields generated by the physical and numerical models, four areas of interest have been identified and denoted in Figure 5.9.

![Flow fields measured in the physical model (above) and calculated in the numerical model (below) at 3cm above the basin floor.](image)

Fig. 5.8 Flow fields measured in the physical model (above) and calculated in the numerical model (below) at 3cm above the basin floor.

![Diagram defining the four areas of interest](image)

Fig. 5.9 Diagram defining the four areas of interest
Area 1 - Behind the ship

Figure 5.10 depicts the output of the numerical model (left) and the physical model (right) in Area 1. The position of Area 1 is depicted by the red rectangle in the inlay of Figure 5.10 and in Figure 5.9.

In this area can be seen that both models show a relatively uniform flow field. The direction of the flow is, however, slightly different in the two models. In the numerical model the water has a prominent flow direction of about $300^\circ$, while in the physical model this is about $345^\circ$. This difference can possibly be attributed to the fact that the boundary conditions are not properly defined in the numerical model, as is explained in section 5.5. In the physical model we see that the water flow is indeed affected by the left hand boundary. In the numerical model this is not the case.

In general, the flow patterns in the two different models show similar traits, especially in direction of the flow velocity, as well as with respect to the general pattern formed.

Area 2 - Alongside the ship

Figure 5.11 shows the output of the two models in Area 2, the area between the ship and the quay wall. This area is denoted by the red rectangle in the inlay in Figure 5.11. In this area we see a similar discrepancy between the models as in Area 1.

The flow direction is generally in the same direction, although there is a slight difference in direction. The physical model shows a flow pattern with main flow direction being $270^\circ$ (parallel to the quay wall), although close to the left wall the effect of the boundary can be
seen. The numerical model gives an average flow direction of 290°, and the boundaries show less influence on the flow direction. As previously mentioned, this can be attributed to the fact that the boundary conditions may not be adequately defined.

Area 3 - In front of the ship

The flow patterns produced by the numerical and physical models in Area 3, are depicted in Figure 5.12. The inlay shows the position of the area being considered. In both models generally the same flow pattern is present. Above the red-dotted line we see an area in which the flow is directed diagonally towards the quay wall. This is the result of the drag effect of the inflow of the propeller. In the numerical model, this cannot be seen, as the velocities here are lower than below the red line, but the direction is consistent with the above. Below the red-dotted line we see the flow as result of the reflection of the propeller wash against the quay wall. The red-dotted line represents the position where these two currents meet and where the water flow makes a sharp change in direction.

In the area below the red-dotted line, the flow patterns of the numerical model and the physical model are consistent in direction, with an average flow direction of 80°. For the area above the line, a similar situation is present. Although the direction is generally similar, the magnitude is of a different order. This can be seen by the fact that in the numerical model the flow velocities are much smaller above the red line than below it. In the physical model the flow velocities above the red line are of the same order as below this line. This seems to indicate a lack of drag effect, suggesting that the inflow side of the propeller is not correctly modelled. As a result of the relatively small flow velocities above the red line, compared to the larger velocities below, we see that the position of the line in the numerical model is also not accurate. It is slightly further away from the quay wall than in the physical model.

In the physical model we also see the influence of the right-hand boundary, while in the numerical model the water flow is little affected by this boundary.

Area 4 - Around the bowthruster

Area 4, the area around the bowthruster, is by far the most complicated to evaluate, because of the complex flow the bowthruster induces in this area. From the flow patterns given in Figure 5.13, a few characteristic similarities and differences will be discussed. In the inlay, area 4 is the area marked with a red rectangle.
In the area immediately in front of the quay wall, the flow velocities and directions of the numerical and physical models are alike in direction and similar in magnitude. This is the most significant area for this research, as it is here that the highest flow velocities occur in both models. This result is therefore very satisfactory.

![Diagram of the outputs of the numerical model (left) and the physical model (right) in area 4 (see inlay)](image)

In the area immediately under the front end of the ship, where the bowthruster is located, we see a significant difference between the two models. In the numerical model, the main flow direction is perpendicular to the quay wall (180°), while in the physical model this is 150°. This is a crucial difference between the two models, as this is the origin of the flow field and it has an effect on the rest of the flow field. In the numerical model the flow under the bowthruster does, however, show a very slight asymmetry in the correct direction.

In the area depicted above the ship (on the inflow side of the bowthruster), we also see a large discrepancy between the models. As discussed above for the top half of Area 3, the area on the inflow side of the bowthruster shows much smaller velocities in the numerical model than in the area below the red line. In the physical model, the order of magnitude of the flow velocities on the inflow side of the bowthruster is the same as in other areas around the ship (such as Areas 1 & 2). The reason given for this discrepancy is the same as already stated above. This is that the inflow of the ducted propeller is possibly not correctly modelled.
5.6.2 Comparison of the Flow Velocities

In Figure 5.14 the flow velocities from the numerical and physical model are plotted for six different lines parallel to the quay wall. This gives a general impression of the differences between the two models. The values plotted for the physical model are horizontal flow velocities, while for the numerical model these are 3-dimensional flow velocities. Although the values of the numerical model contain 1 dimension more than those measured by the physical model, a comparison will nevertheless be made between the two models. This gives a general impression of the flow velocities. In the area under the ship the vertical component of the flow velocity can be neglected. Here, the two models show the most similarity in magnitude of flow velocity.

The most obvious difference between the results is that the numerical model generally gives much higher values than the physical model. This is especially the case for regions further away from the bowthruster.

For the regions around the bowthruster (Y = 2.95 m) we see that the flow velocities measured in the physical model generally have the same order of magnitude as in the numerical model. The plots also seem to have the same shape. For example, in plots a. through c., we see that both the physical and numerical models have a peak at the position of the bowthruster, with virtually the same shape. In plot f. the two graphs also have the same shape, with an inverted peak at the position of the bowthruster.

Fig. 5.14 Comparison between the horizontal flow velocities calculated by the numerical model (blue) and measured in the physical model (red) at 3 cm above the basin floor.
Plot f. represents an area in the model which is most significant to this research. It is here that the highest flow velocities are measured (reaching 16 cm/s). It is these velocities that will be investigated in further research about scour at quay walls. Plot f. shows a similar velocity distribution for the numerical model as for the physical model. The only difference here is the magnitude of the flow velocity. This is a reasonably satisfying result.

The large difference in the magnitude of the flow velocities between the two models in the areas further away from the bowthruster shows that the numerical model still needs a lot of work.
6 Conclusions and Recommendations

6.1 General

Based on the previous two chapters, this chapter discusses the conclusions that have been drawn and the recommendations that have been made. They are divided into two main categories:

Conclusions and recommendations concerning:
- The results of the physical model investigation (Objective 1).
- The numerical model (Objective 2).

6.2 The Physical Model (Objective 1)

Conclusions
1. The EMS probes give accurate results at low flow velocities. For higher flow velocities the EMS is reasonably accurate, with a relatively small deviation from the theoretical value.
2. The injected purple dye gave a good first estimation of the horizontal flow velocities and directions close to the basin floor. A complete flow field was mapped out with the results of these observations.
3. It was possible to place the EMS probes under the ship with an accuracy of 1 mm.
4. The accuracy of the placement of the movable EMS probe was 2 mm.
5. The results of the EMS measurements were mapped out in a similar way as for the observations. The resulting flow field has the same characteristics as that of the observations, with generally the same flow pattern.
6. When processing the output of the EMS, a simple averaging is not sufficient to calculate the flow velocity and direction. This is because of the turbulent character of the water in front of the bowthruster. The average flow velocity should therefore be calculated according to: 

\[ U = \sqrt{(U_X)^2 + (U_Y)^2} \]

and the average flow direction according to: 

\[ \alpha = \arctan\left(\frac{U_X}{U_Y}\right) \]

Recommendations
1. The resulting flow field produced by the EMS measurements is calculated using simple averaging of the ASCII-code. This, however, should be done with the method described in conclusion no. 5. All results should first be rewritten.
2. The measurements that were made were only used to identify the average flow velocity and direction. The output of the EMS shows varying degrees of variability.
Further investigations should be done, using the existing measurement results, into the turbulent character of the flow created by the bowthruster.

3. The flow velocities measured at the basin floor only give a two-dimensional picture of the flow field. Further measurements have to be done with a 'bent' EMS to be able to measure the vertical component of the flow velocity. However, a measuring apparatus that measures in three dimensions is preferred.

6.3 The Numerical Model (Objective 2)

Conclusions
1. The domain size and orientation of the numerical model were adapted to represent the physical model.
2. The calculation grid was adapted in such a way that no discontinuities could occur in the calculation. The model was given a uniform grid size of 10 cm in the X- and Y-directions. In the vertical direction (Z), the chosen grid size is small in the area close to the bottom (1.5 cm) and increases steadily in size towards the top.
3. The optimal number of iterations for this calculation was found to be 1,000. A larger value than this does not increase the accuracy of the calculation, but only increases the calculation time.
4. The boundary conditions were found to be badly defined. This can be seen by the fact that the water seems to flow through the outer boundaries.
5. The numerical model produces a similar flow pattern as the physical model. In the area directly in front of the quay wall at the position of the bowthruster, the flow direction is virtually identical to the physical model. The order of magnitude of the velocity is also the same. In the area under the ship, where the bowthruster is located, the flow shows a different behaviour to the physical model. In the physical model the flow is diagonal, whereas in the numerical model it is virtually perpendicular to the quay wall. The physical model shows that the flow velocities on the inflow side and the quay side of the ship are of the same order. The numerical model, however, shows a large discrepancy between the two. The average flow velocity is much larger on the quay side than on the inflow side.
6. A comparison of the magnitude of the flow velocities shows that, in the area immediately around the bowthruster, the numerical model produces values that are similar in magnitude to those in the physical model. In areas further removed from the bowthruster, the numerical model produces velocities that are far higher than the physical model.

Recommendations
1. The boundary conditions are not properly defined. Before any further calculation can be undertaken, these conditions have to be better defined. This will probably have to be done by editing the Q1-file which is automatically generated by Phoenics from the already inputted variables. This could have a profound effect on the pattern of the flow field.
2. The discrepancy between the inflow and outflow sides of the numerical model has to be investigated. It is suspected that the inflow side of the bowthruster is not correctly modelled.
3. The mistakes in the numerical model, such as far higher flow velocities further away from the bowthruster and a wrong orientation of the main flow direction under the bowthruster, should further be investigated. No further recommendation can be done at this point as to the reasons for these discrepancies.
### Nomenclature

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\text{opening}}$</td>
<td>Cross sectional area under the ship in the calibration flume</td>
<td>m²</td>
</tr>
<tr>
<td>$A_{\text{pipe}}$</td>
<td>Upstream internal cross section of the pipe</td>
<td>m²</td>
</tr>
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<td>$B$</td>
<td>Stability parameter of Römisch</td>
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<td>$B_{\text{crit}}$</td>
<td>Critical value of the stability parameter of Römisch</td>
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<td>$C$</td>
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</tr>
<tr>
<td>$L_p$</td>
<td>Value of the characteristic length in the prototype situation</td>
<td>m</td>
</tr>
<tr>
<td>$L_t$</td>
<td>Length of propeller duct</td>
<td>m</td>
</tr>
<tr>
<td>$n_L$</td>
<td>Geometrical scale value</td>
<td>-</td>
</tr>
<tr>
<td>$n_u$</td>
<td>Velocity scale value</td>
<td>-</td>
</tr>
<tr>
<td>$P_d$</td>
<td>Power generated by the bowthruster's engine</td>
<td>W</td>
</tr>
<tr>
<td>$Q$</td>
<td>Volumetric flow from a ducted propeller</td>
<td>m³/s</td>
</tr>
<tr>
<td>$Q_{\text{flume}}$</td>
<td>Volumetric flow in calibration flume</td>
<td>l/s</td>
</tr>
<tr>
<td>$Q_v$</td>
<td>Volume rate of flow through the pipe</td>
<td>m³/s</td>
</tr>
<tr>
<td>$R$</td>
<td>Radius of the propeller duct</td>
<td>m</td>
</tr>
<tr>
<td>$Re_D$</td>
<td>Reynolds number referred to D</td>
<td>-</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Draught of ship</td>
<td>m</td>
</tr>
<tr>
<td>( U )</td>
<td>Average flow velocity calculated from the EMS-output</td>
<td>cm/s</td>
</tr>
<tr>
<td>( U )</td>
<td>Upstream flow velocity through pipe</td>
<td>m/s</td>
</tr>
<tr>
<td>( U )</td>
<td>Characteristic flow velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>( U_m )</td>
<td>Characteristic flow velocity in the model situation</td>
<td>m/s</td>
</tr>
<tr>
<td>( U_p )</td>
<td>Characteristic flow velocity in the prototype situation</td>
<td>m/s</td>
</tr>
<tr>
<td>( U_{orifice} )</td>
<td>Average flow velocity under the ship in the calibration flume measured using the orifice</td>
<td>cm/s</td>
</tr>
<tr>
<td>( U_{vol} )</td>
<td>Average flow velocity under the ship in the calibration flume measured using the volumetric method</td>
<td>cm/s</td>
</tr>
<tr>
<td>( U_{ems} )</td>
<td>Average flow velocity under the ship in the calibration flume measured using the EMS</td>
<td>cm/s</td>
</tr>
<tr>
<td>( U_0 )</td>
<td>Initial flow velocity in front of the propeller</td>
<td>m/s</td>
</tr>
<tr>
<td>( U_{0,max} )</td>
<td>Maximum initial velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>( U_{x,max} )</td>
<td>Maximum velocity at a distance x from the propeller</td>
<td>m/s</td>
</tr>
<tr>
<td>( U_{max,bot}, U_{b,max} )</td>
<td>Maximum flow velocity at the bottom averaged over time</td>
<td>m/s</td>
</tr>
<tr>
<td>( \overline{U}_X )</td>
<td>Average flow velocity in the X-direction calculated from the EMS-output</td>
<td>cm/s</td>
</tr>
<tr>
<td>( \overline{U}_Y )</td>
<td>Average flow velocity in the Y-direction calculated from the EMS-output</td>
<td>cm/s</td>
</tr>
<tr>
<td>( \overline{V}_{X0} )</td>
<td>Average value of the EMS-output for still water in the X-direction</td>
<td>V</td>
</tr>
<tr>
<td>( \overline{V}_{X1} )</td>
<td>Average value of the EMS-output for flowing water in the X-direction</td>
<td>V</td>
</tr>
<tr>
<td>( \overline{V}_X )</td>
<td>Average difference between the EMS-output for flowing water and still water in the X-direction</td>
<td>V</td>
</tr>
<tr>
<td>( x )</td>
<td>Distance from the propeller</td>
<td>m</td>
</tr>
<tr>
<td>( x_{pq} )</td>
<td>Distance between the bowthruster and the quay wall</td>
<td>m</td>
</tr>
<tr>
<td>( z )</td>
<td>Distance of propeller axis to the bottom of the ship</td>
<td>m</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Average flow direction calculated from the EMS-output</td>
<td>°</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Flow coefficient</td>
<td>-</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Diameter ratio</td>
<td>-</td>
</tr>
<tr>
<td>( \beta_{iz} )</td>
<td>Stability parameter of Izbash</td>
<td>-</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>Expansibility factor</td>
<td>-</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Kinematic viscosity of fluid</td>
<td>m&lt;sup&gt;2&lt;/sup&gt;/s</td>
</tr>
<tr>
<td>( \rho_w )</td>
<td>Density of water</td>
<td>kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>( \rho_s )</td>
<td>Sediment density</td>
<td>kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>( \Psi_{cr} )</td>
<td>Critical Shields stability parameter</td>
<td>-</td>
</tr>
</tbody>
</table>
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Appendices

A. Calibration of the Measuring Apparatus
   A1. The Calibration Procedure
   A2. Calibration Measurements
   A3. Calibration Results

B. Observations and Measurements in Physical Model
   B1. Observation Results
   B2. Measurements

C. Phoenics Output File (Q1-file)
A. Calibration of the Measuring Apparatus
A1. The Calibration Procedure

Introduction

In order to be able to determine the flow velocities, a variety of different measuring devices can be used. In this case the Electromagnetic Velocity Meter (EMS) was chosen. The choice for this apparatus is explained in Van der Laan (2005), Appendix D.

An EMS consists of a long rod, with at the one end the signal-processing equipment and at the other end an ellipsoid-shaped disk (see Figure A1). The disk has a diameter of approximately 3 cm and a thickness of 1.1 cm. Four electromagnetic sensors are placed on it, in such a way that the EMS is able to measure the voltage difference in two different directions (the X- and Y-direction). This voltage difference is a measure for the flow velocity, as shall be seen later. The voltage difference is measured in a certain measuring volume, located around the underside of the EMS-probe. The manufacturer does not give a clear definition of this measuring volume. It remains therefore unclear as to what the size and shape is thereof.

In general the flow is hindered by the disk because of its size. This, however, can mostly be neglected, because the size of the domain in which is measured is usually much larger than the size of the disk. For the case at hand, the EMS will be used to measure the flow velocity in an opening under the model ship (keel clearance) of 6 cm, approximately 3 cm from the bottom. The thickness of the disk is therefore not insignificant and could cause an error in the absolute value of the flow velocity and the direction thereof. It is also unclear how the EMS will react to the fact that it is placed so close to the bottom. It is a known fact that this could cause inaccuracies, but the extent thereof is unclear. For these reasons an extensive calibration of the EMS was undertaken.
The Calibration Flume

In the Fluid Mechanics Laboratory a calibration flume was designed and built, in order to calibrate the EMS for the specific situation of measuring under the model ship. The calibration flume was designed in such a way that the volumetric flow through the flume could be measured. The flow velocity calculated from this volumetric flow is compared to the velocity given by the EMS. In such a way the output of the EMS can be checked as to whether it gives the correct values.

In Figure A2 a diagram is given of the calibration set-up.

The calibration flume is 4 m long, 40 cm wide and has an internal height of 25.1 cm. The end of the flume is closed off by a sharp-crested weir resulting in a water depth in the flume of about 14.7 cm, depending on the size of the volumetric flow. In the calibration flume a 40 cm segment of the cross section of the model ship is duplicated with an underkeel clearance (ukc) of 5.8 cm. The water flow is directed perpendicular to the longitudinal axis of the ship and flows under the ship.

The EMS-probe is placed through a hole in the bottom of the ship in the same way as it will be placed in the main set-up (3 cm under the bottom of the ship). The height of the EMS is adjustable. Because the ship segment can be easily removed from the calibration flume, it is possible to place the EMS with an accuracy of 0.5 mm. The EMS can also be rotated 360° in order to be able to measure the horizontal flow velocities given by the EMS for the four main orientations (+/-X and +/-Y).

In order to regulate the amount of water flowing into the flume, two valves are placed in the inflow pipe. The first valve is used to regulate the amount of water entering the system, the second valve functions as an open and shut 'switch'.

Fig. A2 Calibration set-up
The Procedure

Two methods were used in order to verify the outcome of the EMS, viz. by means of an orifice plate and by volumetric measurements.

Orifice Plate

Between the two valves mentioned above a measuring orifice is placed, which acts as a pressure-difference meter. An orifice is a device used to measure volumetric flow, whereby the difference between the pressures upstream and downstream is a measure for the volumetric flow. This pressure difference is measured with a manometer.

The characteristic formula (ISO-norm) used to calculate the volumetric flow from the pressure difference across the orifice is given by:

\[ Q_v = \alpha \frac{\pi}{4} d^2 \sqrt{2g\Delta h} \]  

(A.1)

with:

\[ \alpha = CE \]  

(A.2)

\[ C = 0.5959 + 0.0312 \beta^{2.1} - 0.1840 \beta^8 + 0.0029 \beta^{2.5} \left[ \frac{106}{Re_D} \right]^{-0.75} \]  

(A.3)

\[ E = \left(1 - \beta^4\right)^{-1/2} \approx 1.075 \]  

(A.4)

\[ \beta = \frac{d}{D} \approx 0.6 \]  

(A.5)

\[ Re_D = \frac{UD}{\nu} \]  

(A.6)

\[ \varepsilon = 1 \]

\[ d = 0.05039 \text{ m} \]

\[ D = 0.0831 \text{ m} \]

\[ \nu = 10^{-6} \text{ m}^2/\text{s} \]

\[ A_{pipe} = \frac{1}{4} \pi D^2 \approx 0.0054 \text{ m}^2 \]  

(A.7)

\[ U = \frac{Q_v}{A_{pipe}} \]  

(A.8)

where

- \( Q_v \): Volume rate of flow [m³/s]
- \( \alpha \): Flow coefficient [-]
- \( C \): Coefficient of discharge [-]
- \( E \): Velocity of approach factor [-]
- \( \beta \): Diameter ratio [-]
- \( Re_D \): Reynolds number referred to D [-]
- \( \varepsilon \): Expansibility factor [-]
- \( d \): Diameter of orifice [m]
- \( D \): Upstream internal pipe diameter [m]
- \( \nu \): Kinematic viscosity of fluid [m²/s]
- \( A_{pipe} \): Upstream internal cross section of the pipe [m²]
- \( U \): Upstream flow velocity through pipe [m/s]
Determining the volumetric flow from the pressure difference is an iterative process because the volumetric flow \(Q_v\) is found on both sides of the equation. The value for \(\alpha\) is dependent on the value of the Reynolds number, which in its turn is dependent on the flow velocity \(U\), thus also on the volumetric flow \(Q_v\). In this case an orifice with a \(\beta\)-value of 0.6 is used. The characteristic graph from the above-mentioned ISO-formula for this specific case is plotted in Figure A3. Here the volumetric flow is translated into the average velocity under the ship. Because of the high flow velocities under the ship and the short distance over which it travels, it can be assumed that the flow has a plug-shaped velocity profile. Therefore, the flow velocity, averaged over the cross sectional flow area under the ship, can be compared to the velocities measured by the EMS in its measuring volume.

![Characteristic Graph Measuring Orifice (\(\beta=0.6\))]  

Fig. A3 Characteristic graph measuring orifice (\(\beta \approx 0.6\))

**Volumetric Measurements**

The second method of checking the validity of the EMS-measurements is a volumetric check. The water that flows over the spillway, flows into the funnel and then ends up in the measuring reservoir. The volumetric flow can be calculated from the time taken to fill the reservoir. The reservoir used has a volume of 586 litres.
Measurements in the calibration flume

Calibration curves

In the model set-up three EMS-probes will be used. Because there is a certain variability between the EMS, all three have to be calibrated. For each EMS measurements are done in the range for which the EMS will be used in the model set-up. Measurements are done for five different flow velocities. For each velocity a measurement is done for the four main directions (±X and ±Y). This results in four calibration curves for each of the three EMS. For each separate measurement done, the EMS output is compared to the output of the orifice and the volumetric output. The volumetric measurement was only used in the first series of tests. This is because this method appeared to be very time-consuming and less reliable than the output of the orifice.

Figure A4 is an example of the output of the EMS (E12, for a flow velocity in the positive X-direction with a pressure difference of 61.4 cm water column).

From this graph the average difference in voltage between stagnant water (before and after the measurement) and the average value during flow, can be calculated. This difference in voltage can be translated into flow velocity. In the table below an example is given of the EMS-output for E12 in the positive X-direction. This is compared to the values calculated from the orifice and volumetric output. The peaks seen in the output in the Y-direction are as a result of respectively increase (acceleration) and decrease (deceleration) of the flow in the X-direction, causing large fluctuations in the Y-direction.

<table>
<thead>
<tr>
<th>E12 (+X)</th>
<th>Orifice</th>
<th>Volumetric</th>
<th>EMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δh [cm wc]</td>
<td>Q\textsubscript{flume} [l/s]</td>
<td>A\textsubscript{opening} [m\textsuperscript{2}]</td>
<td>U\textsubscript{orifice} [cm/s]</td>
</tr>
<tr>
<td>2.9</td>
<td>1.00682</td>
<td>0.0234</td>
<td>4.30</td>
</tr>
<tr>
<td>7.2</td>
<td>1.57268</td>
<td>0.0234</td>
<td>6.72</td>
</tr>
<tr>
<td>19.4</td>
<td>2.56408</td>
<td>0.0234</td>
<td>10.96</td>
</tr>
<tr>
<td>24.6</td>
<td>2.88360</td>
<td>0.0234</td>
<td>12.32</td>
</tr>
<tr>
<td>61.4</td>
<td>4.53718</td>
<td>0.0234</td>
<td>19.39</td>
</tr>
</tbody>
</table>

Table A1 Example of Experimental results

The flow velocity calculated from the EMS-output is plotted against the flow velocity calculated from the output of the orifice. This results in a calibration curve, as is depicted in Figure A5. The blue line represents the calibration results and the grey line is the theoretical line representing a 1:1 relationship between the output of the orifice and the EMS. In the respective Appendices A2 and A3 the experimental results and the calibration curves for the different orientations of the EMS are given.
Sensitivity of EMS placement

As stated above, the EMS can be placed with an accuracy of 0.5 mm under the bottom of the model ship in the calibration flume. This, however, does not need to be the case for the actual model set-up, as this model ship is fixed in position. Measuring under the ship is therefore not an easy task. To be able to predict the behaviour of the EMS under the ship, one must therefore know something about the sensitivity of the EMS with regard to its distance from the bottom of the ship. A number of experiments was done in the calibration flume for varying distances of the EMS from the ship bottom, at a constant flow velocity of 11 cm/s (according to the orifice measurement). These experiments are given by the numbers 124 - 127 and 136 – 159 in Appendix A2. An example of the outcome of these experiments is given in Figure A6.

The complete record of the calibration experiments and the results thereof is given in Appendices A2 and A3.
Error analysis

In order to get an idea of how accurate the results are, an error analysis was done for the results from the EMS and the orifice.

**EMS**

The value for the error margin of the EMS is given in the EMS user manual. This is set by the manufacturer at ±1% of the total measuring range. In this case, a range of 1 m/s was used. The error margin for the EMS is therefore ±1 cm/s. In Figures A7 and A8 and Appendix A3 this error margin is plotted. This error margin is absolute. Therefore the relative error is larger for lower flow velocities.

---

![Calibration EMS E12 (EMS orientation in channel: +X)](image)

*Fig. A7 Example of a calibration curve showing the absolute error of the EMS*

![Variation EMS-position (EMS orientation in channel: +X)](image)

*Fig. A8 Sensitivity of EMS for distance from the bottom, with the absolute EMS error*
Orifice

In order to calculate the error margin of the orifice, the ISO-formula is used. The error is calculated by a ‘Taylor series’–type development of the ISO-formula, in which the individual errors of each variable, multiplied by their partial derivatives, add up to the total error of Q.

A summary of this process is given in Table A2. As mentioned above, this process is iterative, as can be seen by the fact that Q, is needed to calculate the value of the Reynolds number. In the last two columns, an example is given for \( \Delta h = 15 \) cm.

<table>
<thead>
<tr>
<th>Var.</th>
<th>Dim.</th>
<th>Value</th>
<th>Error</th>
<th>Example (( \Delta h = 15 ) cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta h )</td>
<td>m</td>
<td>variable</td>
<td>0.004</td>
<td>0.15</td>
</tr>
<tr>
<td>( Q_v )</td>
<td>m(^3)/s</td>
<td>variable</td>
<td>1% of ( Q_v )</td>
<td>2.2581\times10^{-3}</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>-</td>
<td>1</td>
<td>0.0001</td>
<td>1</td>
</tr>
<tr>
<td>d</td>
<td>m</td>
<td>0.05039</td>
<td>0.0001</td>
<td>0.05039</td>
</tr>
<tr>
<td>D</td>
<td>m</td>
<td>0.0831</td>
<td>0.0001</td>
<td>0.0831</td>
</tr>
<tr>
<td>( v )</td>
<td>m(^3)/s</td>
<td>( 10^{-4} )</td>
<td></td>
<td>10(^{-6} )</td>
</tr>
<tr>
<td>U</td>
<td>m/s</td>
<td></td>
<td></td>
<td>0.416342054</td>
</tr>
</tbody>
</table>

\[
U = \frac{Q_v}{\sqrt[4]{\pi D}}
\]

\[
\Delta U = \Delta Q_v \frac{dU}{dQ_v} + \Delta D \frac{dU}{dD}
\]

\[
= \Delta Q_v \left( \frac{4}{\pi D} \right) - \Delta D \left( \frac{8 Q_v}{\pi D^2} \right)
\]

<table>
<thead>
<tr>
<th>Var.</th>
<th>Dim.</th>
<th>Value</th>
<th>Error</th>
<th>Example (( \Delta h = 15 ) cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_e )</td>
<td>-</td>
<td>( \frac{UD}{\nu} )</td>
<td></td>
<td>34598.02467</td>
</tr>
<tr>
<td>( \beta )</td>
<td>-</td>
<td>( \frac{d}{D} = 0.6 )</td>
<td></td>
<td>0.606377858</td>
</tr>
<tr>
<td>( E )</td>
<td>-</td>
<td>( E = \left( 1 - \beta^4 \right)^{1/2} = 1.075 )</td>
<td></td>
<td>1.075330335</td>
</tr>
<tr>
<td>( C )</td>
<td>-</td>
<td>( C = 0.5959 + 0.0312\beta^{2.1} - 0.1840\beta^6 ) + ( 0.0029\beta^{2.5} \left[ \frac{10^6}{Re_D} \right]^{-0.75} )</td>
<td></td>
<td>0.613799647</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>-</td>
<td>( \alpha = CE )</td>
<td></td>
<td>0.66003738</td>
</tr>
<tr>
<td>( Q_v )</td>
<td>m(^3)/s</td>
<td>( \frac{\pi d^2 \sqrt{2gh}}{4} )</td>
<td></td>
<td>2.2581\times10^{-3}</td>
</tr>
</tbody>
</table>

Table A2 Summary of the process of error calculation of the orifice, including an example for \( \Delta h = 15 \) cm.
In Figure A9 and Appendix A3 these error margins are plotted in the calibration curves.

From these plots can be seen that the absolute value of the calculated error is larger at lower flow velocities than at higher velocities.

Figure A10 shows the characteristic graph for the measuring orifice as is given in Figure A3. In the same graph the relative error is plotted. This shows that the smaller the velocity under the ship, the higher the relative errors. For a flow velocity of about 4 cm/s, the relative error is about 7%. For smaller flow velocities (as will be the case in the actual model set-up), the relative velocities will be even higher.

Additional errors, such as the error in the measurement of the flume and ship dimensions, were found to be of little importance.
Conclusions

Calibration curves

In Appendix A3, a complete record of the calibration curves is given, consisting of 4 calibration curves per EMS for the four main orientations. Although we see from these twelve curves a slight variability between the different EMS-probes, as was to be expected, a general trend can be observed. For flow velocities up to 10 to 12 cm/s, the EMS give readings which fall within the calculated error margin (see Appendix A3). Above this value the deviation of the EMS output is larger than the calculated error margin. However, this deviation is never larger than 10%.

We can conclude that for flow velocities under 12 cm/s the EMS is suitable to measure the flow velocity in a confined space close to the bottom, as is the case here. For velocities above this value there is some deviation. Nevertheless, the EMS still gives reasonably accurate results.

Sensitivity EMS-output with respect to the distance from the flume bottom

As can be seen from Appendix A3, the closer the EMS probe comes to the bottom of the flume, the greater the deviation of its output from the value calculated from the orifice. For the closest position to the bottom which was measured (20 mm from the bottom), the EMS shows a deviation from the orifice value of approximately 10%, as opposed to 5% at 30 mm from the bottom, where the probe is to be placed. (This is consistent with the calibration curve of E5 at 11 cm/s.)

The maximum deviation from the value given by the orifice falls within a reasonable error margin. We can conclude that the EMS is not very sensitive to its positioning and that a few millimetres give an acceptable error. Even though we know that the positioning of the EMS in the physical model cannot be done with as much accuracy as in the calibration flume, it will not be as large as 10 mm. The expected accuracy with which the EMS will be placed is in the region of 1 to 2 mm.
## A2. Calibration Measurements

<table>
<thead>
<tr>
<th>Date</th>
<th>Name</th>
<th>Orientation</th>
<th>Output Orifice [cm water column]</th>
<th>Time volumetric measurement [s]</th>
<th>EMS#</th>
</tr>
</thead>
<tbody>
<tr>
<td>04-01-05</td>
<td>01</td>
<td>+X</td>
<td>3.6</td>
<td>N/A</td>
<td>E12</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>-X</td>
<td>3.65</td>
<td>N/A</td>
<td>E12</td>
</tr>
<tr>
<td></td>
<td>03</td>
<td>+Y</td>
<td>3.6</td>
<td>N/A</td>
<td>E12</td>
</tr>
<tr>
<td></td>
<td>04</td>
<td>-Y</td>
<td>3.6</td>
<td>N/A</td>
<td>E12</td>
</tr>
<tr>
<td></td>
<td>05</td>
<td>+X</td>
<td>10.3</td>
<td>N/A</td>
<td>E12</td>
</tr>
<tr>
<td></td>
<td>06</td>
<td>-X</td>
<td>10.3</td>
<td>N/A</td>
<td>E12</td>
</tr>
<tr>
<td></td>
<td>07</td>
<td>+Y</td>
<td>10.3</td>
<td>N/A</td>
<td>E12</td>
</tr>
<tr>
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<td>+X (3.2cm)</td>
<td>19.8</td>
<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>145</td>
<td>-X (3.2cm)</td>
<td>19.85</td>
<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>146</td>
<td>+Y (3.2cm)</td>
<td>19.8</td>
<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>147</td>
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<td>19.8</td>
<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>148</td>
<td>+X (3.4cm)</td>
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<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>149</td>
<td>-X (3.4cm)</td>
<td>19.85</td>
<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>150</td>
<td>+Y (3.4cm)</td>
<td>19.8</td>
<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>151</td>
<td>-Y (3.4cm)</td>
<td>19.8</td>
<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>152</td>
<td>+X (4.0cm)</td>
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<td>N/A</td>
<td>E5</td>
</tr>
<tr>
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<td>-X (4.0cm)</td>
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<td>N/A</td>
<td>E5</td>
</tr>
<tr>
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<td>+Y (4.0cm)</td>
<td>19.85</td>
<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>155</td>
<td>-Y (4.0cm)</td>
<td>19.8</td>
<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>156</td>
<td>+X (2.0cm)</td>
<td>19.8</td>
<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>157</td>
<td>-X (2.0cm)</td>
<td>19.8</td>
<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>158</td>
<td>+Y (2.0cm)</td>
<td>19.8</td>
<td>N/A</td>
<td>E5</td>
</tr>
<tr>
<td>159</td>
<td>-Y (2.0cm)</td>
<td>19.8</td>
<td>N/A</td>
<td>E5</td>
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Table A3 Overview of the calibration experiments
## A3. Calibration Results

### Comparison calibration output

<table>
<thead>
<tr>
<th>Orifice</th>
<th>Volumetric</th>
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<tbody>
<tr>
<td>Δh [cm]</td>
<td>Q\textsubscript{flume} [l/s]</td>
</tr>
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<td>---------</td>
<td>----------------</td>
</tr>
<tr>
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<td>7.2</td>
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### Table A4 Calibration Results for E12 (series 1)

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<tr>
<th>EMS</th>
<th>Δ\textsubscript{Volt} [V]</th>
<th>U\textsubscript{flume} [cm/s]</th>
<th>Δ\textsubscript{Volt} [V]</th>
<th>U\textsubscript{flume} [cm/s]</th>
<th>Δ\textsubscript{Volt} [V]</th>
<th>U\textsubscript{flume} [cm/s]</th>
<th>Δ\textsubscript{Volt} [V]</th>
<th>U\textsubscript{flume} [cm/s]</th>
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<td>4.01</td>
<td>0.41333</td>
<td>4.13</td>
<td>0.41145</td>
<td>4.11</td>
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<tr>
<td>0.652392</td>
<td>6.52</td>
<td>0.61234</td>
<td>6.12</td>
<td>0.62517</td>
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<td>1.20169</td>
<td>12.02</td>
<td>1.19351</td>
<td>11.94</td>
<td>1.24324</td>
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</tr>
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<td>20.40</td>
<td>2.01121</td>
<td>20.11</td>
<td>2.00211</td>
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### Table A5 Calibration Results for E12 (series 2)

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<th>EMS</th>
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<td>Δh [cm]</td>
<td>Q\textsubscript{flume} [l/s]</td>
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<td>---------</td>
<td>----------------</td>
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<td>1.35755</td>
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<td>1.87589</td>
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<td>15.20</td>
<td>2.27291</td>
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<td>20.85</td>
<td>2.65710</td>
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<td>3.65938</td>
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<td>4.50406</td>
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<td>81.23</td>
<td>5.21332</td>
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### Table A6 Calibration Results for E7

<table>
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<th>EMS</th>
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</thead>
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<td>Δp [cm]</td>
<td>Q\textsubscript{flume} [l/s]</td>
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<td>---------</td>
<td>----------------</td>
</tr>
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<td>5.05</td>
<td>1.32115</td>
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<td>10.28</td>
<td>1.87364</td>
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<tr>
<td>20.55</td>
<td>2.63813</td>
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<tr>
<td>44.40</td>
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<td>78.95</td>
<td>5.14029</td>
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### Table A7 Calibration Results for E5
### Errors and Deviations

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<tr>
<th>Flow velocity [cm/s]</th>
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<th>Percentage error [%]</th>
<th>Absolute error [cm/s]</th>
<th>Percentage error [%]</th>
<th>Average percentage deviation EMS to Orifice [%]</th>
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<tr>
<td>4.79</td>
<td>2.15</td>
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<td>1</td>
<td>20.87</td>
<td>0.22</td>
</tr>
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<td>5.80</td>
<td>1.77</td>
<td>30.58</td>
<td>1</td>
<td>17.24</td>
<td>0.16</td>
</tr>
<tr>
<td>8.02</td>
<td>1.29</td>
<td>16.10</td>
<td>1</td>
<td>12.47</td>
<td>1.15</td>
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<td>9.71</td>
<td>1.08</td>
<td>11.08</td>
<td>1</td>
<td>10.30</td>
<td>1.57</td>
</tr>
<tr>
<td>11.36</td>
<td>0.93</td>
<td>8.21</td>
<td>1</td>
<td>8.81</td>
<td>3.16</td>
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<tr>
<td>15.64</td>
<td>0.71</td>
<td>4.53</td>
<td>1</td>
<td>6.39</td>
<td>4.63</td>
</tr>
<tr>
<td>19.25</td>
<td>0.61</td>
<td>3.15</td>
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<td>8.50</td>
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Table A8 Errors and Deviations for E12

<table>
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<th>Absolute error [cm/s]</th>
<th>Percentage error [%]</th>
<th>Absolute error [cm/s]</th>
<th>Percentage error [%]</th>
<th>Average percentage deviation EMS to Orifice [%]</th>
</tr>
</thead>
<tbody>
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<td>17.71</td>
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<td>8.01</td>
<td>1.29</td>
<td>16.14</td>
<td>1</td>
<td>12.49</td>
<td>4.22</td>
</tr>
<tr>
<td>11.27</td>
<td>0.94</td>
<td>8.32</td>
<td>1</td>
<td>8.87</td>
<td>5.98</td>
</tr>
<tr>
<td>16.51</td>
<td>0.68</td>
<td>4.11</td>
<td>1</td>
<td>6.06</td>
<td>7.37</td>
</tr>
<tr>
<td>21.97</td>
<td>0.55</td>
<td>2.52</td>
<td>1</td>
<td>4.55</td>
<td>9.93</td>
</tr>
</tbody>
</table>

Table A9 Errors and Deviations for E7

<table>
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<tr>
<th>Flow velocity [cm/s]</th>
<th>Absolute error [cm/s]</th>
<th>Percentage error [%]</th>
<th>Absolute error [cm/s]</th>
<th>Percentage error [%]</th>
<th>Average percentage deviation EMS to Orifice [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.54</td>
<td>1.86</td>
<td>33.60</td>
<td>1</td>
<td>18.07</td>
<td>3.90</td>
</tr>
<tr>
<td>7.90</td>
<td>1.31</td>
<td>16.57</td>
<td>1</td>
<td>12.66</td>
<td>4.47</td>
</tr>
<tr>
<td>11.07</td>
<td>0.95</td>
<td>8.62</td>
<td>1</td>
<td>9.03</td>
<td>6.05</td>
</tr>
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<td>15.60</td>
<td>0.71</td>
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<td>1</td>
<td>6.41</td>
<td>8.57</td>
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<tr>
<td>21.96</td>
<td>0.55</td>
<td>2.52</td>
<td>1</td>
<td>4.55</td>
<td>11.21</td>
</tr>
</tbody>
</table>

Table A10 Errors and Deviations for E5
**Calibration curves**

![Calibration curves for E12](image)

**Fig. A11** Calibration curves for E12
Fig. A12 Calibration curves for E7
Fig. A13 Calibration curves for E5
**Sensitivity EMS to its distance from the bottom of the channel**

<table>
<thead>
<tr>
<th>Distance from channel bottom [cm]</th>
<th>+X [cm/s]</th>
<th>-X [cm/s]</th>
<th>+Y [cm/s]</th>
<th>-Y [cm/s]</th>
<th>Orifice [cm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>12.335</td>
<td>12.544</td>
<td>12.525</td>
<td>12.423</td>
<td></td>
</tr>
<tr>
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<td>11.776</td>
<td>12.355</td>
<td>12.324</td>
<td>12.265</td>
<td></td>
</tr>
<tr>
<td>2.8</td>
<td>11.820</td>
<td>12.017</td>
<td>12.167</td>
<td>12.016</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>12.075</td>
<td>12.212</td>
<td>11.338</td>
<td>11.330</td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>11.504</td>
<td>12.121</td>
<td>11.565</td>
<td>11.437</td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>11.399</td>
<td>11.630</td>
<td>11.531</td>
<td>11.435</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>11.136</td>
<td>11.065</td>
<td>11.052</td>
<td>10.640</td>
<td>11.069</td>
</tr>
</tbody>
</table>

Table A11 Sensitivity EMS to its distance from the basin floor
Fig. A14 Sensitivity curves of EMS for distance from basin floor.

Variation EMS-position (EMS orientation in channel: +Y)

Variation EMS-position (EMS orientation in channel: -Y)

Variation EMS-position (EMS orientation in channel: +X)

Variation EMS-position (EMS orientation in channel: -X)
B. Observations and Measurements in the Physical Model
## B1. Observation Results

### Observations [Velocities & Directions]

| Y-coordinate [m]  | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 | 2.1 | 2.3 | 2.5 | 2.7 | 2.9 | 3.1 | 3.3 | 3.5 | 4 | 4.5 | 5 | 5.5 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| X-coordinate [m]   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 3.5               | 3   | 3   | 3   | 2.9 | 2.9 | 2.8 | 2.5 | 2   | 1   | 1   | 1.5 | 1.5 | 1.4 | 1.4 | 1.3 | 1.25| 1   | 0.8 | 0.5 | 1   |
|                   | 350 | 350 | 350 | 345 | 345 | 345 | 345 | 350 | 0   | 70  | 105 | 150 | 165 | 165 | 155 | 155 | 150 | 125 | 105 | 95  | 345 |
| 3.7               | 3.3 | 3.3 | 3.3 | 3   | 3   | 3   | 3   | 2.5 | 2   | 1   | 1   | 1.5 | 1.5 | 1.4 | 1.4 | 1.3 | 1.25| 1   | 0.8 | 0.5 | 1   |
|                   | 0   | 350 | 350 | 350 | 345 | 345 | 345 | 350 | 350 | 45  | 130 | 135 | 135 | 135 | 135 | 135 | 150 | 130 | 110 | 95  | 345 |
| 3.9               | 3.5 | 3.5 | 3   | 3.4 | 3.4 | 3.3 | 3.3 | 3   | 3   | 1   | 2.5 | 5   | 4   | 3.5 | 3   | 2.8 | 2.3 | 2   | 0.5 | 1.5 |
|                   | 0   | 350 | 350 | 345 | 340 | 340 | 340 | 345 | 350 | 30  | 45  | 90  | 120 | 135 | 135 | 125 | 135 | 135 | 125 | 105 | 345 |
| 4.1               | 3.6 | 3.7 | 3.8 | 3.9 | 4   | 4   | 4   | 4   | 3.5 | 3   | 3   | 3   | 7   | 7.5 | 6   | 3.5 | 2.4 | 2   | 0.5 | 2   |
|                   | 0   | 350 | 350 | 345 | 340 | 340 | 340 | 345 | 350 | 45  | 150 | 150 | 133 | 133 | 135 | 150 | 150 | 160 | 150 | 350 |
| 4.3               |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
|                   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 4.5               | 3.6 | 3.7 | 3.8 | 3.9 | 4   | 4   | 4   | 4   | 4   | 4   | 4   | 4   | 4   | 4   | 4   | 4   | 4   | 4   | 4   | 4   | 2   | 0.5 | 2.5 |
|                   | 0   | 350 | 350 | 345 | 340 | 340 | 340 | 345 | 350 | 45  | 60  | 80  | 95  | 95  | 95  | 95  | 95  | 135 | 135 | 135 | 140 | 170 |
| 4.7               | 1.5 | 2   | 2.2 | 2.5 | 2.7 | 3.5 | 4   | 4   | 5   | 1   | 2   | 1   | 0.5 | 7   | 7.5 | 8   | 0   | 5   | 3.5 | 3   |     |
|                   | 350 | 330 | 310 | 290 | 270 | 270 | 270 | 270 | 280 | 300 | 310 | 280 | 225 | 200 | 200 | 135 | 135 | 135 | 135 | 130 | na  | 80  |
| 4.9               | 0.5 | 1   | 2   | 2.2 | 2.5 | 3.5 | 4   | 6   | 7   | 9   | 10  | 10  | 13  | 16  | 14  | 15  | 16  | 18  | 12  | 7   | 6   | 5   |
|                   | 345 | 315 | 295 | 275 | 275 | 275 | 275 | 275 | 280 | 280 | 285 | 285 | 285 | 290 | 290 | 300 | 310 | 60  | 70  | 75  | 75  | 80  |

Black = velocity [cm/s]  
Gray = direction [°]

Table B1 Observation Results
B2. Measurements

Fig. B2 Diagram of Measurement Plan
<table>
<thead>
<tr>
<th>Date</th>
<th>Name</th>
<th>X-coordinate</th>
<th>Y-coordinate</th>
<th>Velocity [cm/s]</th>
<th>Direction [degrees]</th>
<th>Remark</th>
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<td>3,05</td>
<td>10,06</td>
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</tr>
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<td>334</td>
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<tr>
<td>06-04-05</td>
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Table B2 Overview of Measurements done

- Fan belt broke at 5:30 mins
- Probe in wrong position
- EMS-probe fell in water
- Bowthruster-Induced Damage
| Y-coordinate [m] | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 | 2.1 | 2.3 | 2.5 | 2.7 | 2.9 | 3.1 | 3.3 | 3.5 | 4  | 4.5 | 5  | 5.5 |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 3.5             | 1.54| 1.41| 1.07|     |     |     |     |     |     |     |     |     |     |     |     | 0.98|     |     |     |     |     |
|                 |     | 358 | 7   | 12  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 3.7             |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 3.9             | 2.69| 2.39| 1.41| 1.11| 1.5 | 2.03| 2.31| 1.71| 0.77| 0.91| 1.4 |     |     |     |     |     |     |     |     |     |     |
|                 | 347 | 3   | 23  | 46  | 87  | 123 | 156 | 189 | 182 | 156 | 186 |     |     |     |     |     |     |     |     |     |     |
| 4.1             | 2.79| 2.5 | 2.06| 1.5 | 1.79| 2.58| 4.88| 1.79| 2.46| 1.74 |     |     |     |     |     |     |     |     |     |     |     |
|                 | 346 | 7   | 20  | 50  | 71  | 73  | 98  | 126 | 154 | 207 |     |     |     |     |     |     |     |     |     |     |
| 4.3             |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
|                 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 4.5             |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
|                 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 4.7             |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
|                 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 4.9             |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

**Measurements [Velocities & Directions]**

- **Black = velocity [cm/s]**
- **Gray = direction [°]**

*Table B3 Measurement Results*
Fig. B3 Vector Representation of Measurement Results
Fig. B4 Vector Representation of Measurement Results (orange) superimposed on the Observation Results (blue)
C.  Phoenics Output File (Q1-file)
Bowthruster-Induced Damage

**Group 1. Run Title**

`TEXT(12/05/05 - Uo=1.5 - 1000 iterations )`  

**Group 2. Transience**

`STEADY = T`  

**Group 3, 4, 5 Grid Information**

`RSET(M,50,61,15)`  

**Group 6. Body-Fitted coordinates**

**Group 7. Variables: STOREd,SOLVEd,NAMEd**

`ONEPHS = T`  

`NAME(150) = EPKE`  

*Solved variables list*  

`SOLVE(P1 ,U1 ,V1 ,W1 )`  

*Stored variables list*  

`STORE(EPKE)`  

*Additional solver options*  

`SOLUTN(P1 ,Y,Y,Y,N,N,Y)`  

`TURMOD(KEMODL)`  

**Group 8. Terms & Devices**

`DIFCUT = 0.000000E+00`  

**Group 9. Properties**

`PRESS0 = 1.000000E+05`  

`TEMP0 = 2.730000E+02`  

`SETPRPS(1, 67)`  

`DVO1DT = 1.180000E-04`  

`PRT (EP ) = 1.314000E+00`  

**Group 10. Inter-Phase Transfer Processes**

**Group 11. Initialise Var/Porosity Fields**

**Group 12. Convection and diffusion adjustments**

**Group 13. Boundary & Special Sources**

**Group 14. Downstream Pressure For PARAB**

**Group 15. Terminate Sweeps**

`LSWEEP = 1000`
SARAH = 5.000000E-03
RESFAC = 1.000000E-02

************************************************************
Group 16. Terminate Iterations
************************************************************

************************************************************
Group 17. Relaxation
************************************************************
RELAX(P1 ,LINRLX, 1.000000E+00)
RELAX(KE ,LINRLX, 5.000000E-01)
RELAX(EP ,LINRLX, 5.000000E-01)
KELIN = 3

************************************************************
Group 18. Limits
************************************************************
VARMAX(U1 ) = 1.000000E+01 ;VARMIN(U1 ) =-1.000000E+01
VARMAX(V1 ) = 1.000000E+01 ;VARMIN(V1 ) =-1.000000E+01
VARMAX(W1 ) = 1.000000E+01 ;VARMIN(W1 ) =-1.000000E+01

************************************************************
Group 19. EARTH Calls To GROUND Station
USEGRD = T ;USEGRX = T
GENK = T
ASAP = T

************************************************************
Group 20. Preliminary Printout
ECHO = T

************************************************************
Group 21. Print-out of Variables
OUTPUT(P1 ,N,N,Y,Y,N,Y)
OUTPUT(KE ,N,N,Y,Y,N,Y)
OUTPUT(EP ,N,N,Y,Y,N,Y)
OUTPUT(EPKE,N,N,Y,N,Y,N)

************************************************************
Group 22. Monitor Print-Out
IXMON = 44 ;IYMON = 30 ;IZMON = 2
NPRMON = 100000
NPRMNT = 1
TSTSWP = -1

************************************************************
Group 23. Field Print-Out & Plot Control
NPRINT = 100000
NUMCLS = 8
NXPRIN = 1
IXPRF = 10 ;IXPRL = 10
NYPRIN = 1
IYPRF = 4 ;IYPRL = 73
NZPRIN = 1
IZPRF = 5 ;IZPRL = 5
ISWPRF = 1 ;ISWPRL = 100000
ITABL = 3
No PATCHes used for this Group

************************************************************
Group 24. Dumps For Restarts

GVIEW(P,0.000000E+00,0.000000E+00,1.000000E+00)
GVIEW(UP,-1.000000E+00,0.000000E+00,0.000000E+00)

> DOM, SIZE, 5.000000E+00, 6.000000E+00, 6.300000E-01
> DOM, MONIT, 4.350000E+00, 2.925000E+00, 2.250000E-02
> DOM, SCALE, 1.0000000E+00, 1.0000000E+00, 1.0000000E+00
> DOM, SNAPSIZE, 1.000000E-02
> DOM, VECSCALE, 1.000000E-01
> GRID, RSET_X_1, 41, 1.000000E+00,G
> GRID, RSET_X_2, 4, 1.000000E+00
> OBJ, ROTATION24, 1
> OBJ, TYPE, PRESSURE_RELIEF
> OBJ, PRES_RELIEF, 1.000000E+03, 0.000000E+00
STOP