SIMPLE BUT ACCURATE CALCULATION METHOD FOR VESSEL SPEED IN A MINIMUM CAPACITY LOCK

by

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ABSTRACT

The increase of vessel size puts pressure on the maximum allowed vessel dimensions in various inland waterways and locks. Waterway authorities are increasingly challenged to allow vessels with dimensions that exceed the design specifications of the lock. Besides the risk of collision with the sill or the lock head, there is also the aspect of the time required to sail in and out of the lock.

This paper presents a desk study, prototype measurements, and verification and calibration of a simple but accurate calculation method based on the Schijf`s method for vessel speed (and squat) in the very confined water (blockage ratio: k< 0.7) in a minimum capacity lock. The calculation method has been verified with prototype vessel speed measurements from five locks and one ship lift.

As such this paper is a contribution to the understanding of the consequences of larger vessel sizes in the existing lock infrastructure, focussing on the vessel speed during sailing in and out of the lock and the subsequent increase of the lock-cycle time.

1 Introduction

1.1 Enlarging of the Twentekanaal and Lock Delden

The Twentekanaal in the eastern part of The Netherlands was opened in 1933. Originally the canal was constructed for CEMT Class IV vessels with a draft of 2,6 m. After more than half a century the Dutch government decided to upgrade the canal to CEMT Class Va vessels. In 2010 the 1st Phase of the enlarging of the Twentekanaal was completed. The 1st phase covered the western part of the Twentekanaal, some 30 km from the River IJssel up to Lock Delden, see Figure 1.

The 2nd Phase of the enlarging of the canal (from Lock Delden up to Enschede and the branch to Almelo) has been scheduled for the next decennium.

This enlarging comprises the widening and deepening of the canal profile, but does not include Lock Delden.

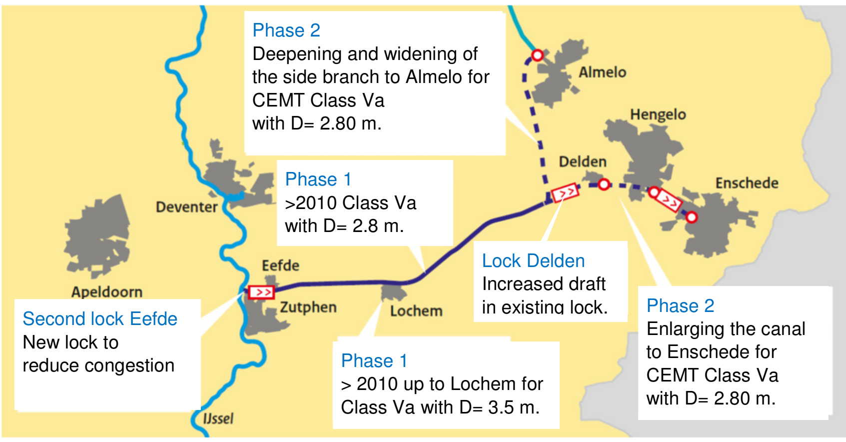

Figure 1: Situation Twentekanaal in the eastern part of the Netherlands

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1.2 Investigation Twentekanaal after completion of Phase 1

After the opening of the 1st Phase the pressure of the shipping industry grew to allow Class Va container vessel in the enlarged canal. In view of this demand, the authorities investigated the possibility of Class Va vessels with draft limitation. Since the cross-section of the canal east of Lock Delden has not yet been increased, the specialist of Rijkswaterstaat advised not to increases the maximum wet cross-section of the vessels above the existing 25 m² (=9.5 m * 2.6 m, corresponding to the beam and max allowed draft of CEMT Class IV vessels) as this would cause significant wearing of the slopes of the canal.

Maintaining the maximum wet cross-section of 25 m², results for Class Va vessels in a maximum allowed draft of 2.2 m (=25 m² / 11.4 m). The authorities followed this advice and in 2008 Class Va vessels were allowed with a maximum draft of 2.2 m. For Lock Delden this increase of the vessel class resulted in a significant decrease of the minimum beam clearance, whereas, the maximum blockage ratio in the lock remained unchanged. The minimum beam clearance forces the skipper to line up accurately for the lock and to sail with great care. However, since the blockage ratio of the vessel in the lock remains unchanged, the new access policy had hardly any impact on the lock entry and departure speed, and therefore, on the lock-cycle time.

1.3 Investigation Lock Delden for Phase 2

After the completion of the 2nd Phase of the enlarging of the Twentekanaal the maximum draft for the Class Va vessels will be increased to 2.8 m. In 2016 an investigation was started on the effects of the increased draft on Lock Delden. The first findings of the desk study are summarized in Table 1.

Lock and vessel			1933		2008	Future	Minimum lock	
Dimension and clearance			**Lock**	**Class IV**	**Class Va**	**Class Va**	**RVW(2017)**	
Length of lock	L_{lock}	[m]	133				125	
Length of vessel	L	[m]		85	110	110		110
Length clearance	LC	[m]		48	23	23		15
Lenght clearance ratio	k_{LC}	[%]		56%	21%	21%		14%
Width of lock	W_{lock}	[m]	12				12.5	
Beam of vessel	B	[m]		9.50	11.40	11.40		11.40
Beam Clearance	BC	[m]		2.50	0.60	0.60		1.10
Beam clearance ratio	k_{BC}	[%]		26%	5%	5%		10%
Depth of lock	D_{lock}	[m]	3.34				3.5	
Draft of vessel	T	[m]		2.60	2.20	2.80		2.80
Underkeel Clearance	UKC	[m]		0.74	1.14	0.54		0.70
Under keel clearance ratio	k_{UKC}	[%]		28%	52%	19%		25%
Blockage ratio	k	[%]		62%	63%	80%		73%
Schijf's method: limiting speed	v_{lim}	[m/s]		0.77	0.74	0.29		0.46
operational speed	v_{op}	[m/s]		0.65	0.63	0.25		0.39
water level depression	z_{op}	[m]		0.20	0.19	0.11		0.15
Lock entry time	T_{entry}	[s]		204	212	542		322
	T_{entry}	[min]		3.4	3.5	9.0		5.4

Table 1: Lock dimension and increasing vessel dimensions and lock entry time

With the acceptance of Class Va with draft of 2.8 m two of the lock clearances and the blockage ratio (indicated in Table 1 in red) are beyond the values recommended in the Waterway Guidelines (RVW,2017) for a minimum capacity lock.

PIANC (2015) states, that if the blockage ratio is 0.75 or higher, special measures have to be taken for safe passage. A vessel that enters a lock with a large blockage ratio and a high speed creates a wave in front of her bow. This wave propagates through the lock and is subsequently reflected at the lock gate. The returning waves can become significantly high, that the entering vessel is pushed back in reverse direction.

In addition, PIANC (2015) states that with small clearances, the entry and exit times are generally longer and depend increasingly on pilot skills, assistance by bow thrusters and the availability of guiding structures.

Questions that arise for situation with Class Va vessels in Lock Delden are:

- Is the UKC still positive and safe? Or does the vessel touch (or even damage) the lock sill?
- Is the vessel able to sail in and out of the lock with acceptable speed?
- Is the increase of the locking cycle time acceptable?

To investigate these questions a desk study on the lock entry speed and lock-cycle time has been performed (RWS-ON,2016) and the impact for Lock Delden has been reported (RWS-PPO,2016).

1.4 Previous investigations on vessel speeds in locks

In an investigation on the hydraulic forces on mitre gates, Vrijburcht (1994) compared the approach speed of vessels entering a lock, with the limiting speed according to Schijf's method (Schijf,1949 and Jansen and Schijf, 1953). He analysed measured vessel speeds and found that just before the bow enters the lock, vessel with speeds 2 to 4 times higher than the limiting speed in the lock generate huge translatory waves in the lock. Vrijburcht (2000) describes the translatory waves generated during the lock entry and departure manoeuvre and proposes an equation for the maximum speed when the bow of the vessel enters the lock.

An overview of the longitudinal dynamics of ship entry and departure at locks has been presented by Spitzer and Söhngen (2013). They summarise investigations in Germany and other countries including numerical solutions of ship dynamics and field and model measurement data. In this paper the vessel speed in the lock is compared to the limiting speed according to Schijf's method.

The Panama Canal Commission performed prototype measurements of vessel speeds in the Miraflores upper west lock (Povirk and Rush,1999). In the Miraflores lock the longitudinal culverts are used for the return flow of the vessel to increase the vessel speed in the lock.

1.5 Desk study and prototype measurements

The present paper focusses on the vessel speed in the lock. The lock entry speed has been studied with the method described by Schijf (1949) and Jansen & Schijf (1953) as described in Section 2.2. According to this approach the possible speed of a vessel is a function of the blockage ratio and the water depth in the lock (see Section 2.1 for definitions). Where sailing in a canal can be characterised as sailing in confined water with a blockage ratio of: $0.1 < k < 0.2$, sailing in a lock should be characterised as sailing in extremely confined water with blockage ratio of $k > 0.5$.

From the desk study (RWS-ON,2016) and the calculation of the vessel speed the following can be concluded:

- The time required for a loaded Class Va vessel to enter the Lock Delden is significantly longer than for smaller vessels.
- If the maximum approach speed of 0.3 m/s (=1 km/hr) is respected, a loaded Class Va can be locked safely through the existing navigation Lock Delden.
- The vessel speed that is judged safe by skippers is significantly higher than the advised operational vessel speed (and even higher than the limited vessel speed computed with Schijf's method).

To verify the conclusions of the desk study, a verification study which incorporates prototype measurements near Lock Delden was executed. This finally resulted in a better understanding of the consequences of larger vessel size in the existing lock infrastructure, and an method for the accurate calculation of vessel speeds for a vessel in locks with high blockage ratio.

2 Definitions and calculation methods

In Section 2 the basic definitions and calculation methods used in this paper are presented:

1. Definition of the clearances and clearance ratios between the lock and the vessel;
2. Schijf's method for the calculation of the vessel speed in the lock; and
3. Determination of maximum vessel speed for safe entry of locks according to skippers.

Modifications on Schijf's method are presented in Section 5.1

2.1 Definitions of clearances and blockage ratio

The clearances between lock and vessel are related to the size of the vessel, whereas the blockage ratio is related to the wet cross-section of the lock, as defined below:

Length clearance: $LC = L_{lock} - L$, and length clearance ratio: $k_{LC} = LC/L$, with:

L_{lock} = Length of lock [m]
L = Length of vessel [m]

Beam clearance: $BC = W_{lock} - B$, and beam clearance ratio: $k_{BC} = BC/B$, with:

W_{lock} = Width of lock [m]
B = Beam of vessel [m]

Under-keel clearance: $UKC = D_{lock} - T$, and under-keel clearance ratio: $k_{ukc} = UKC/T$, with:

D_{lock} = Water depth in lock [m]
T = Draft of vessel [m]

Blockage ratio: $k = A_s / A_{lock}$ with:

A_{lock} = Wet cross-section of the undisturbed lock ($A_{lock} = W_{lock} \cdot D_{lock}$)
A_s = Wet cross-section of the vessel ($A_s = B \cdot T$)

2.2 Schijf's method for a Lock

At the bow of a sailing vessel water is constantly pushed aside, while at the same time an equal discharge of water is supplemented behind the vessel at the stern. This displacement of water from the bow to the stern induces a flow along and under the vessel, called the return flow. The return flow induces a water level depression around the vessel which results in a sinkage of the vessel compared to the still water level.

The speed of the vessel is limited by the return flow around the vessel hull. As the return flow increases (i.e. speed of the vessel increases), the water level depression increases until it reaches its maximum related to Froude. When this critical water level depression is reached, further increase in discharge of the return flow is not possible. This is a physical limit on the maximum speed of a vessel in the lock.

A vessel exceeding the limiting speed in the lock entrance creates a high translatory wave (Vrijburcht,1994). This wave, after reflection at the dead end of the lock and back at the bow significantly decelerates the vessel. Prototype measurements in the Lüneburg ship lift indicated that the average speed of the vessel in the lock is almost independent of the approach speed (Spitzer and Söhngen, 2013). This because of the physical limitation on the maximum discharge in the return flow.

The limiting speed (or critical speed) can be computed from the following equations originally derived by Schijf (1949) and Jansen and Schijf (1953). The equations have been derived for a vessel with a prismatic amidships cross-section over the total length of the vessel, sailing at constant speed and in a straight and prismatic canal section. The limiting vessel speed V_{lim} can be iterated from:

$$\frac{V_{lim}}{\sqrt{gD_{lock}}} = \left(\frac{2}{3}\right)^{3/2} \left\{1 - \frac{A_S}{A_{lock}} + \frac{1}{2}\left(\frac{V_{lim}}{\sqrt{gD_{lock}}}\right)^2\right\}^{3/2} \tag{1}$$

With:

V_{lim} = limiting vessel speed in the lock [m/s]
g = acceleration of gravity [m/s^2]

The corresponding return flow U_{lim} (m/s) around the vessels hull at limiting speed:

$$\frac{U_{lim}}{\sqrt{(gD_{lock})}} = \sqrt{\frac{2}{3}\left(1 - \frac{A_S}{A_{lock}} + \frac{1}{2}\left(\frac{V_{lim}}{\sqrt{(gD_{lock})}}\right)^2\right)} - \left(\frac{V_{lim}}{\sqrt{(gD_{lock})}}\right) = \left(\frac{V_{lim}}{\sqrt{(gD_{lock})}}\right)^3 - \left(\frac{V_{lim}}{\sqrt{(gD_{lock})}}\right) \tag{2}$$

The limiting water-level depression z_{lim} around the vessel's hull:

$$\frac{z_{lim}}{D_{lock}} = \frac{1}{3}\left(1 - \frac{A_S}{A_{lock}} - \left(\frac{V_{lim}}{\sqrt{(gD_{lock})}}\right)^2\right) \tag{3}$$

Sailing a vessel at a speed close to V_{lim} is not very realistic. In practice most of the vessels will not go much faster than about 80 % of this limiting speed due to the high power required and the associated fuel consumption for a further increase of speed (PIANC,2015). A more realistic maximum vessel speed is often set at 85% of the limiting speed. For more realistic sailing speeds $V < V_{lim}$ the return flow U can be iterated from:

$$\frac{\alpha(V+U)^2-V^2}{2gD_{lock}} - \frac{U}{V+U} + \frac{A_s}{A_{lock}} = 0 \quad (4)$$

With:

- U = return flow in the lock [m/s]
- V = vessel speed in the lock [m/s]
- α = Correction factor for non-uniform distribution of the return flow ($\alpha = 1.4 - 0.4\frac{V}{V_{lim}}$)

And the water-level depression z from:

$$z = \frac{\alpha(V+U)^2-V^2}{2g} - \frac{V^2}{2g} \quad (5)$$

The above method has initial been applied for calculation of the vessel speed in the locks.

2.3 Safe vessel entry speed

The operational vessel speed is often set at 85% of the limiting speed. However, a German study (VBD, 1993) has included the judgement of pilots to analyse the safety of the lock entering manoeuvre. It was found that a safe entry is determined by factors such as the approach speed, the draft ratio ($D_{lock}/T = 1 + k_{UKC}$) and the area ratio ($n = 1/k$).

These studies have been re-evaluated for the UKC ratio: $0.07 \leq k_{UKC} \leq 0.60$ and blockage ratio: $0.595 \leq k \leq 0.885$ which led to the results shown in Figure 2 (BAW,2005).

The graph presents an estimate for the safe entry speed ratio ($= v_{safe}/\sqrt{g \cdot D_{lock}}$) as function of the under-keel clearance ratio k_{UKC} and the beam ratio k_{BC}.

Note that in Figure 2 the definitions of the ratios have been adopted to the ratios defined in Section 2.1 of this paper.

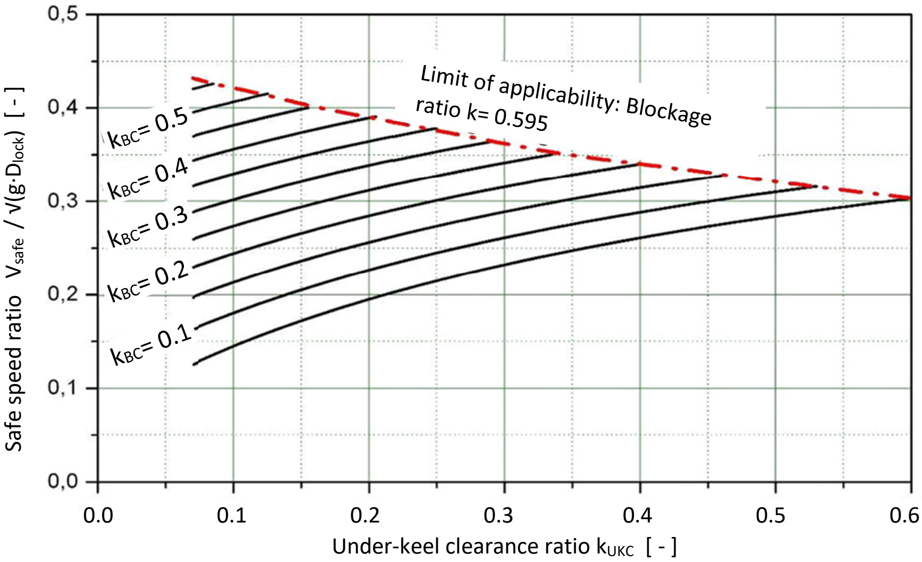

Figure 2: Safe speed at lock entry manoeuvre (BAW,2005)

The Class IV and Class Va vessels in Table 1 have a blockage ratio in between the limits of applicability of Figure 2. Therefore, Figure 2 can be used to determine the safe entry manoeuvre speed for these vessels in Lock Delden. The safe speed for the vessels entering Lock Delden (RWS-ON, 2016) turned out to be about 3 to 4 times higher than the limiting speed calculated with Schijf's method. From this comparison it turns out that both the limiting and the operational vessel speed are considered to be safe.

As mentioned in Section 2.2, if the vessel enters the lock with the speed that is considered safe, but higher that the limited speed, the vessel will induce a wave in the lock chamber that runs through the lock and will be reflected at the dead end of the lock. Once the reflected wave returns at the bow of the vessel, the vessel will be slowed down significantly. To avoid these fluctuations in the vessel speed the skipper is advised to reduce his speed in the approach to the lock to less than the limiting speed in the lock.

3 PROTOTYPE MEASUREMENTS

3.1 Objective of the measurements

The objective of the prototype measurements is to measure the impact of the increase of the maximum draft for a Class Va from 2.20 m to 2.80 m on the locking process in Lock Delden. To get prototype data for a range of blockage ratios and limit the risk of grounding the vessel, the prototype measurements were executed for two drafts. The first measurements were done with draft of 2.6 m (original design depth of the channel) and finally with the future maximum of 2.8 m. During the prototype test, the following information has been collected from the prototype vessel:

- Position and speed of the vessel during normal navigation in the canal before, during and after the locking process, including entering/departure in the lock and the locking itself.
- The under-keel clearance in the lock head and above the sill and in the lock;
- The lock-cycle time.

In addition, the prototype dimensions of the lock have been measured accurately in situ.

3.2 Lock Delden

Lock Delden is situated in the Twentekanaal 36 km from the junction with the IJssel River. The lock heads have been made of concrete and the lock chamber is created with sheet pile walls. Lock Delden has two lift gates between towers pairs. The main dimensions of the lock are presented in Table 2:

Dimension of lock		
Length	lock structure	159 m
	lock chamber between gates	140 m
	utilised length for vessels	133 m
Width		12.05 m
lock lift		6.00 m

Levels and water depth		Lower lock head
Water level	normal	NAP +10.00 m
	minimum	NAP + 9.90 m
Sill level		NAP + 6.56 m
Minimum water depth lower lock head		3.34 m

Levels and water depth		Upper lock head
Water level	normal	NAP +16.00 m
	minimum	NAP + 15.90 m
Sill level		NAP + 12.25 m
Minimum water depth upper lock head		3.65 m

Table 2: Lock dimensions and water depths

Figure 3: Lock Delden from West to East

3.3 Measurement plan

The Twentekanaal from Lock Delden up to Hengelo has been presented in Figure 4. Lock Delden (Km 36,32) is approximately 2 km from the junction with the branch to Almelo (Km 32) and approximately 8 km from the CTT (Km 44). The water bed bottom in this 10 km section of the canal and the lock has been surveyed beforehand to verify the water depth.

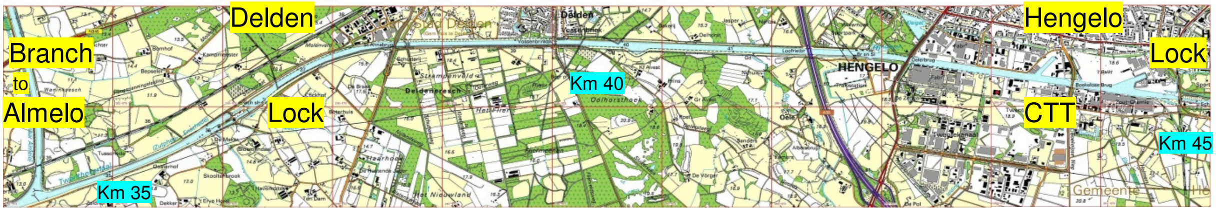

Figure 4 Twentekanaal: section for prototype test

During the night the traffic on the canal is low, especially in the weekend. During one night the Class Va container vessel could make two roundtrips passing the lock four times. Therefore, the prototype test was scheduled for a night in the weekend: Friday 31 March up to Saturday morning 1 April 2017. The vessel turned near the Combi Terminal Twente (CTT) and at the junction with the canal branch to Almelo. The vessel is loaded with containers to the required draft at the CTT in Hengelo and sailed up and down the Twentekanaal (Figure 4) once with a draft of 2.6 m and once with a draft of 2.8 m

3.4 Prototype vessel characteristics

The prototype vessel is a Class Va container vessel that has been scheduled on a roundtrip between the Port of Rotterdam and the CTT in Hengelo on a regular basis since 2008. The skipper of the vessel is therefore very familiar with the Twentekanaal. The main characteristics of the prototype vessel are[4]:

Main characteristics of the vessel		
Year of construction		2006
Hull		bulk / containers
Length		110 m
Beam		11.45 m
Maximum draft		3.50 m
Capacity	cargo	3080 Ton
	containers	208 TEU
Main engine		Caterpillar 1699 Hp (1249 kW)
Bow thruster		2 * DAF 430 Hp (2 * 316 kW)

Table 3: Vessel characteristics

Figure 5: Prototype vessel with containers

3.5 Instruments and data registration

The vessel has been equipped with instruments to register the manoeuvring actions of the skipper, and to measure the position of the vessel. The manoeuvring actions have been captured in the wheel house by video. The video registration (see Figure 6) has been analysed with video capturing software to create time series of the registration. Recordings have been made of:

1. Main engine: rpm, load factor and the fuel consumption;
2. Ruder: ruder angle; and
3. Bow thruster: rpm and direction.

[4] Source.: http://www.binnenvaartcruises.nl/schepen/martinique and https://www.binnenvaart.eu/motorvrachtschip/3057-anne-marijke.html .

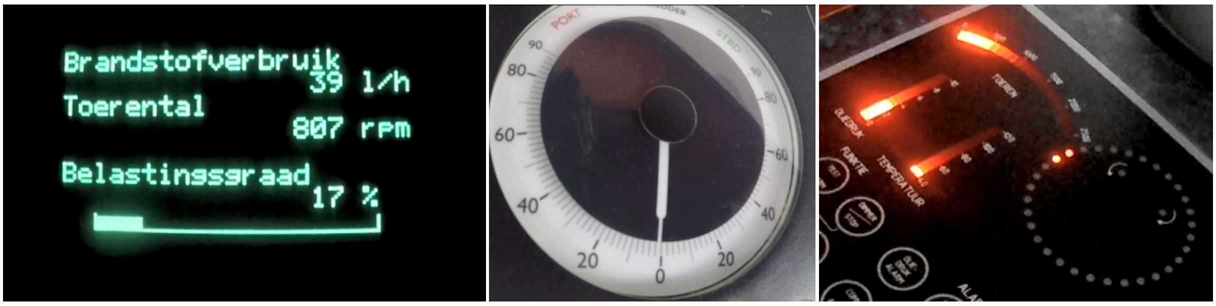

Figure 6: Video registration of meters of main engine, ruder and bow thruster

The position of the vessel has been permanently measured by two sets of GPS receivers (RTK heading receiver). One set has been installed at the bow and one at the stern with 102.5 m between each other. The two receivers have been placed near the centre-line of the vessel, around 6 m above the water level close to the top level of the containers. The GPS measurements (x, y, z and heading) have been stored with a frequency of 1 Hz.

In each lock head two pressure transducers have been installed, one on each side of the lock gate. The transducers have been installed in the sheet pile wall along the south side of the lock, about one meter below the lowest water level. The transducers measure the water pressure (1 Hz) and thereby the water level. Examples of the resulting time series are presented in Section 3.6.1 to 3.6.3.

3.6 Prototype measurement and collected data

The prototype measurements have been performed according to the four tracks of the measurement:

Track 1: Sailing and descending with a draft of 2.6 m
Track 2: Sailing and ascending with a draft of 2.6 m
Track 3: Sailing and descending with a draft of 2.8 m
Track 4: Sailing and ascending with a draft of 2.8 m

During the evening of Friday 31 March and the night of 1 April the traffic on the canal had become quiet and the water level had come to rest. The skipper sailed the tracks with the main engine on slow or dead-slow. The skipper did not experience any specific problem and after the measurements he proceeded his schedule to Nijmegen/Rotterdam.

The lock entry speed was much lower than the safe lock entry speed derived in Section 2.3. The manoeuvres have been characterised as safe, and the vessel did not touch the lock or the lock head unintentionally. The next sections show examples of the registration of the manoeuvring actions of the skipper, the vessel speed and the water level registrations (Aktis,2017).

3.6.1 Data from the main engine ruder and bow thruster

An example of the resulting timeseries of the main engine has been presented in Figure 7.

The graphs show the data from the main engine (Dutch: *hoofdmotor*): the revolutions (Dutch: *Toeren*), the fuel consumption (Dutch: *Brandstofverbruik*) and the load factor (Dutch: *Belastingsgraad*).

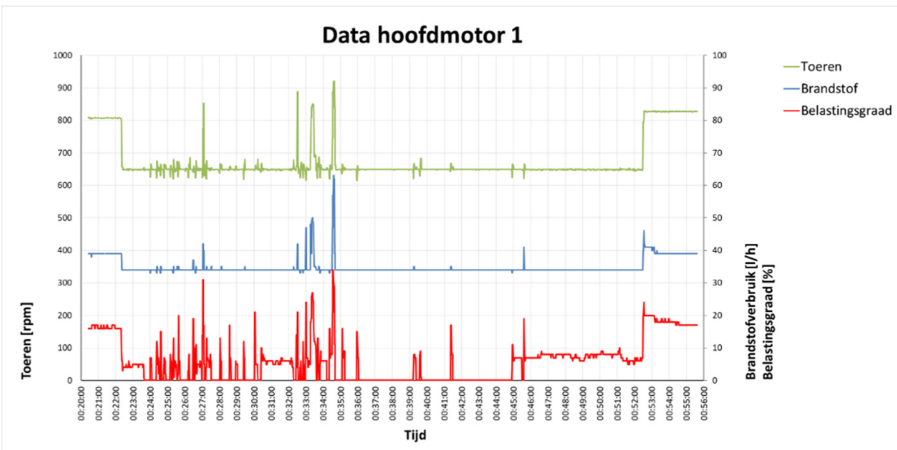

Figure 7: Main engine during sailing and ascending up with a draft of 2.6 m (Track 1)

The vessel entered the lock between 00:30:34 (bow in lock head) and 00:32:57 (stern in lock head) and Figure 7 indicates that during the entry manoeuvre the vessel sailed with the engine on dead-slow. The period in between 00:37:30 and 00:44:20 hours the lock was levelled, which is shown by the load factor of practically zero. The bow left the lock at 00:47:40 and the stern left the lock at 00:52:29. As the stern left the lock the load factor increases.

3.6.2 Data from the GPS: vessel speed at bow and stern (aft)

The timeseries from the GPS have been analysed and processed. The speed of the middle of the vessel was calculated by averaging the speed of the bow and the stern. An example of the resulting timeseries of the computed vessel speed has been presented in Figure 8.

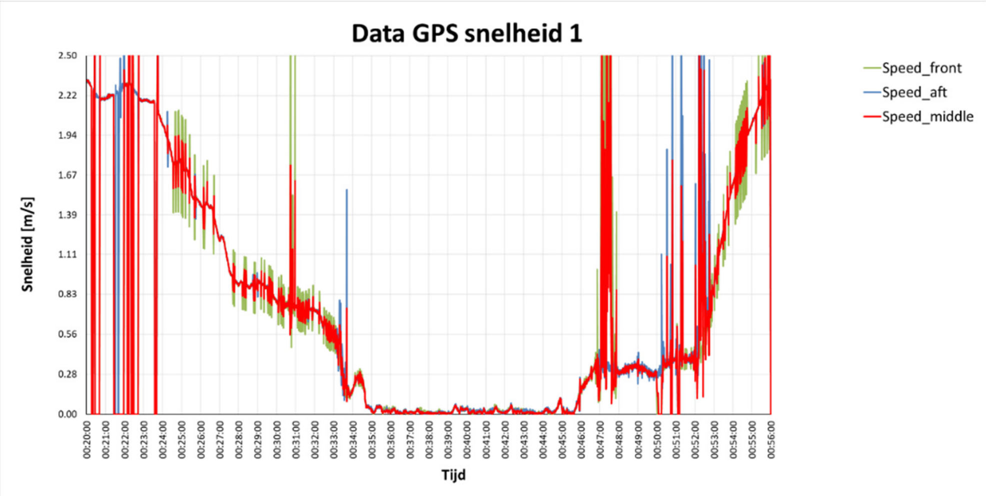

Figure 8: Vessel speed from GPS during sailing and descending with a draft of 2.6 m (Track 1)

The graph shows the vessel speed data (Dutch: *Snelheid*) from the GPS. From 00:30:34 to 00:37:30 and from 00:44:20 to 00:52:29 hours the vessel was in a lock head. These periods correspond to a grassy speed signal as the GPS signal was disturbed by the presence of the lock gates. Fortunately, only one GPS at a time was disturbed. The figure below shows the vessel speed (Dutch: *Snelheid*) and squat as function of the position of the vessels bow and stern (Dutch: respectively: *boeg* and *hek*) during the entering of the lock.

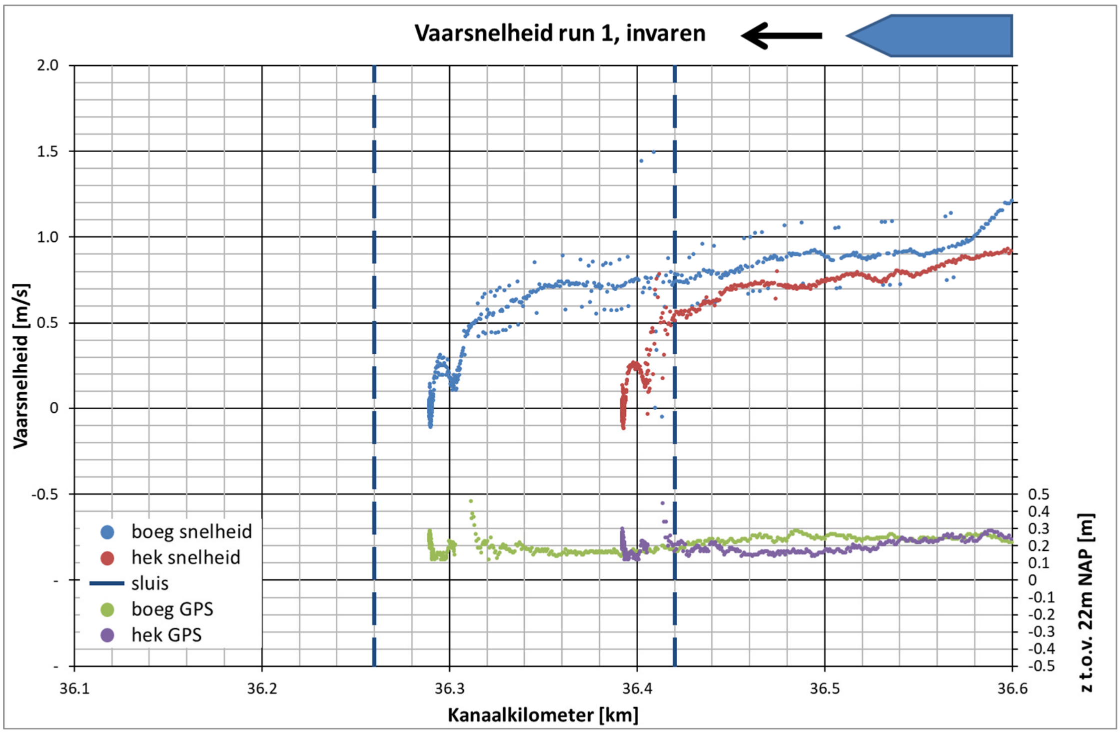

Figure 9: Vessel speed and squat w.r.t. position in the lock with a draft of 2.6 m (Track 1)

3.6.3 Data from the pressure transducers: water level in the canal and in the lock

The timeseries from the pressure transducers have been analysed and processed. An example of the resulting timeseries of the water level has been presented in Figure 10.

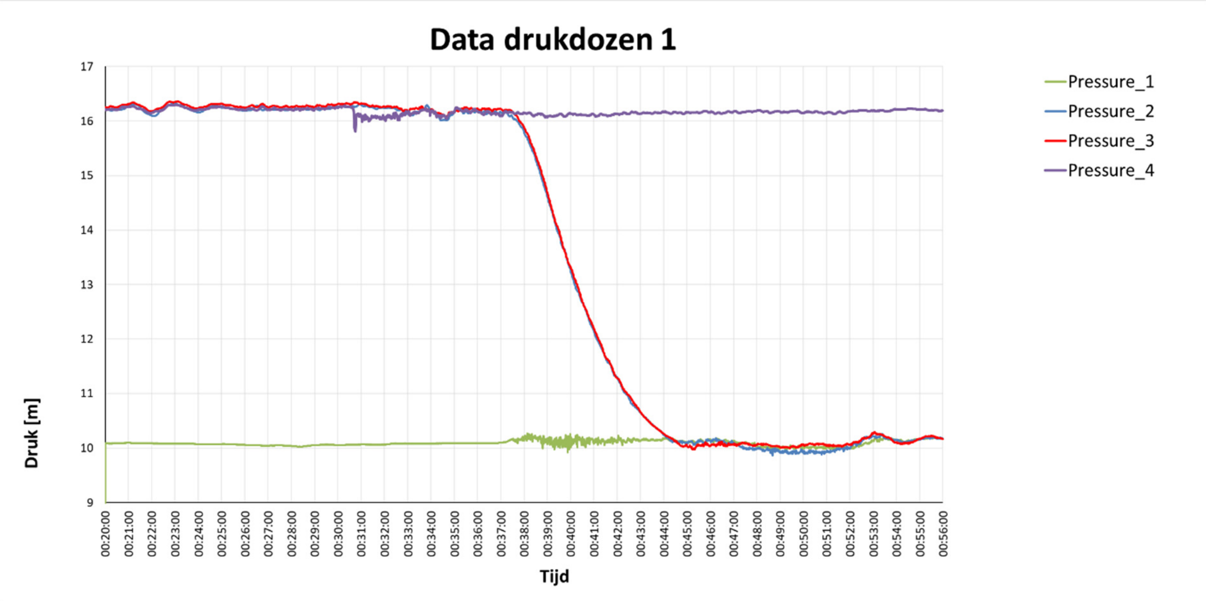

Figure 10: Water level near the lock gates: descending with a draft of 2.6 m (Track 1)

The graphs show the water pressure (Dutch: *Druk*) from the pressure transducers (Dutch: *drukdozen*) as measure for the water level at both sides of the lock gates. From 00:30:34 to 00:52:29 hours the vessel was in the lock. At the start of this period the water level in the upper lock head (Pressure 4) and in the lock chamber (3 and 2) are disturbed by the entering vessel. Subsequently, the lock chamber has been levelled (Pressure 2 and 3). During the departure of the vessel from the lock chamber small water level variations can be seen in the lower lock head (Pressure 2 and 1).

3.7 Input for verification of Schijf's method

The following values have been derived for the four sailing tracks for the understanding of the hydrodynamic process:

- Dimensions of the lock and the water level;
- Use of main engine (propeller) during lock entry and lock departure manoeuvre;
- Sailing speed in the lock during sailing in and during sailing out;
- Maximum squat of bow and stern in lock head;
- Drop in water pressure in the lock head during passing of vessel;
- Duration of lock entering (from bow in lock head to stern in lock head); and
- Duration of lock departure (from bow out of lock head to stern out of lock head).

The verification of the vessel speed with Schijf's method requires the following representative values as input:

1. the lock width and water depth in lock (above the sill); and
2. the beam and draft of the vessel;

and for verification:

3. the average speed of the vessel during entering and departing the lock; and
4. the water level depression and squat of bow and stern passing the lock head.

3.7.1 Vessel speed in the prototype test

The vessel speed in the lock varies slowly (see Figure 9). The average vessel speed has been determined from the duration of the entry or departure manoeuvre and the corresponding sailing distance. The duration has been defined as the time between the bow and the stern reaching the same lock head. The measured average vessel speed for each of the four entry and departure manoeuvres is presented in Table 4.

Sailing			Lock entry		Lock departure		Lock passing time	
Track	Direction	draft of vessel	Duration (102.5m)	average speed	Duration (102.5m)	average speed	from bow in lockhead till stern through lock head	
			[s]	[m/s]	[s]	[m/s]	[s]	[min]
1	down	2.6 m	143	0.717	289	0.355	1315	21.9
2	up		262	0.391	162	0.633	1543	25.7
3	down	2.8 m	178	0.576	392	0.261	1434	23.9
4	up		374	0.274	201	0.510	1721	28.7

Table 4: Average vessel speed during lock entry and departure and lock passing time

The numbers in Table 4 clearly indicate that the 0.2 m extra draft has a significant effect on the duration of the lock entry and departure manoeuvre (25-40% longer).

3.7.2 Water depth and under-keel clearance on the sills during the passing of the vessel

The vertical position of the bow and the stern of the vessel have been measured with the GPS receivers. The main interest was the squat and the remaining under-keel clearance in the lock head above the sill. Unfortunately, the lifted lock gates hinder the GPS signal. Consequently, there are some gaps in the time series of the vertical position of the bow and stern in the lock heads. However, from the GPS signal during the lock approach and in the lock itself, an indication of the squat in the lock head could be derived.

The pressure transducers provide information on the water level depression in the lock head. In addition the actual water levels in the lock heads have been derived from the pressure transducers. During the passing of the vessel the water level fluctuated a few centimetres up to (very short peak of) five decimetres. The largest depressions were measured around the bow during the entry of the bow into the lock head. The representative water level depression and the squat in the lock head during the entry and departure manoeuvres are combined in Table 5.

Sailing		Measurement in lock head					Under keel clearance	
Track	Direction	sill level	water level	draft of vessel	squat from GPS	water level lowering	UKC from GPS	UKC from water level
		NAP+ m	NAP+ m	[m]	[m]	[m]	[m]	[m]
Lock entry manoeuvres:								
1	down	12.25	16.15	2.609	-0.15	-0.45	1.14	0.84
2	up	6.56	10.00		0.05	-0.15	0.88	0.68
3	down	12.25	16.10	2.782	-0.10	-0.40	0.97	0.67
4	up	6.56	10.00		0.05	-0.20	0.71	0.46
Lock departure manoeuvres:								
1	down	6.56	10.05	2.609	-0.20	-0.20	0.68	0.68
2	up	12.25	16.10		-0.15	-0.15	1.09	1.09
3	down	6.56	10.00	2.782	-0.15	-0.20	0.51	0.46
4	up	12.25	16.05		-0.15	-0.10	0.87	0.92

Table 5: Squat, water depth and under keel clearance in the lock heads on the sill

The numbers in Table 5 indicate a significant difference between the UKC estimated from the GPS measurements and the UKC based on the water level from the pressure transducers. The lowest UKC values are found in the lower lock head during the departure manoeuvres. The lock is far from being touched, since the UKC is 0.45 m or more.

4 VERIFICATION OF SCHIJF’S ORIGINAL METHOD

4.1 Computations for verification of Schijf’s method for vessel speed in locks

Schijf’s method as presented in Section 2.2 has been applied to calculate the vessel speed for the water depth and draft conditions that occurred during the measurements. The entering conditions, the measured entering time, the average vessel speed (see Section 3.7.1), and the calculated vessel speed for the measured entering and departure conditions are presented in Table 6.

Verification and Calibration			Track 1		Track 2		Track 3		Track 4	
sailing distance 102.5		m	upper-in	lower-out	lower-in	upper-out	upper-in	lower-out	lower-in	upper-out
Lock Delden	Width	[m]	12.05	12.05	12.05	12.05	12.05	12.05	12.05	12.05
	water depth in lock head	[m]	3.85	3.49	3.49	3.85	3.85	3.49	3.49	3.85
Vessel	Beam	[m]	11.40	11.40	11.40	11.40	11.40	11.40	11.40	11.40
	Draft	[m]	2.609	2.609	2.609	2.609	2.782	2.782	2.782	2.782
Blocking ratio		[%]	64%	71%	71%	64%	68%	75%	75%	68%
	Sailing time (over 102.5 m)	[s]	143	289	262	162	178	392	374	201
	Delden measured vessel speed	[m/s]	0.72	0.35	0.39	0.63	0.58	0.26	0.27	0.51
Schijf's method	v_{op}	[m/s]	0.63	0.44	0.44	0.63	0.52	0.33	0.33	0.52
	Error w.r.t. measurment	[%]	-12.1%	23.3%	11.8%	-0.4%	-10.1%	28.0%	22.1%	1.5%

Table 6: Measured and calculated vessel speed

The measured and calculated sailing speed and the time for sailing in and out of the lock deviate significantly and systematically. The results from Schijf's method indicate that:

- The computed vessel speeds differ up to 28% from the measured vessel speed;
- The vessel speeds computed for the upper lock head are too low;
- The vessel speeds computed for the lower lock head are too high;
- Departing takes more time than entering the same lock head.

The above findings indicate that the agreement between the measured and the calculated vessel speeds can be improved by the adaption of Schijf's method for the systematic deviations.

5 CALIBRATION OF SCHIJF'S METHOD

5.1 Schijf's method for vessel speed in locks

An explanation for the systematic deviation between the measured and the calculated vessel speeds are the hydraulic processes in the lock which are not accounted for in Schijf's method:

- The effect of the dead-end waterway, resulting in increased water level in the lock in front of the bow;
- Hydraulic resistance between vessel hull and lock chamber that results in a water level inclination along the vessel.

The above mentioned two effects have been added to Schijf's original method by a correction of the water depth in the lock head. The corrections are elaborated in the next section.

5.1.1 Adaption for dead end lock

A vessel entering a lock with speed below the limiting speed increases the water level in the dead of the lock. The water level in the return flow in the lock is lower than in the dead end of the lock. This operational water level depression (z_{op}) in the return flow can be computed with Schijf's method. In the adaptation of Schijf's method it is assumed that the water level in the return flow of the vessel is equal to the water level in the outer harbour. This implies that the water level at the bow in the dead-end of the lock is z_{op} higher than in the return flow around the vessel and thus z_{op} higher than in the canal.

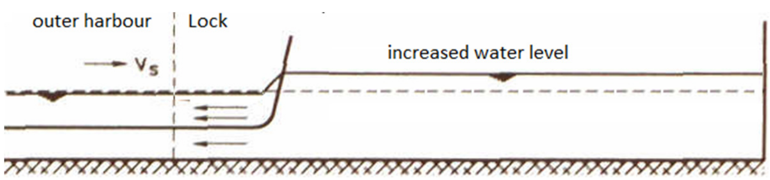

Figure 11: Water level during lock entry

At the beginning of the lock entry manoeuvre when the bow just enters, the vessel is hardly affected by the higher water level in the lock. However close to the end of the entry manoeuvre the vessel is lifted z_{op} above the still water level assumed in the calculation. It is assumed that on average a vessel entering a lock is lifted 50% of the calculated z_{op} above the still water level in the canal.

The flow around a vessel departing from a lock is similar to sailing in a canal, with a water level around bow and stern equal to the still water level. As such the effect of a dead end-lock is not present during a lock departure manoeuvre.

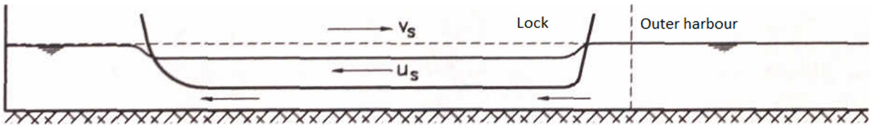

Figure 12: Water level during lock departure

The following adaption ΔD_1 is made for the dead-end effect:

$$\Delta D_1 = C_1 \cdot z_{op} \tag{6}$$

With:

z_{op} = Operational water level depression around the vessel in the lock [m],
C_1 = Factor based on the manoeuvre: $C_1 = 0.5$ for lock entry; $C_1 = 0$ for lock departure [-].

5.1.2 Adaption for hydraulic resistance in return flow around the vessel

In the situation with a high blockage ratio the clearance between the vessel and the lock is very small, while at the same time the return flow velocity is extremely high. This combination results in a significant hydraulic resistance and therefore a water level slope in the return flow. lock that affects the water depth in the lock. Therefore, it has been proposed to adapt the hydraulic resistance in the computation. The water level slope i [m/m] in the return flow can be calculated following Chézy:

$$i = \frac{v^2}{C^2 * R} \tag{7}$$

With:

v = Return flow around the vessel [m/s]
R = Hydraulic radius of the wet area between the vessel and the lock wall [m]:

$$R = (D_{lock} \cdot W_{lock} - T \cdot B)/(2 \cdot D_{lock} + W_{lock} + 2 \cdot T + B) \tag{8}$$

C = Coefficient of Chézy [$m^{1/2}/s$]:

$$C = 18 * \log(\frac{12 * R}{k_N}), \tag{9}$$

With:

$k_N = 0{,}001$ (Nikuradse roughness representative for surface of vessel and lock)

De Nikuradse roughness ($k_N = 0{,}001$) has been selected to be representative for the steel and concrete surface of the vessel and Lock Delden.

When sailing through the lower head the water level slope is present over the whole length of the vessel. Sailing through the upper head of the lock the water level slope is only applicable in the shallow part in the lock head. The length of the lock head in Lock Delden is estimated at some 20% of the length of the vessel. It is proposed to adapt the water depth in the computation of the vessel speed with the water level slope over the length of the vessel (lower head) or the length of the lock head (upper head). The coefficient ${C_B}^2$ has been added to account for the amidships cross-section being present over part of the vessel length. This results in the following adaption ΔD_2 for the slope of the water level in the return flow:

$$\Delta D_2 = C_2 \cdot -i \cdot L \cdot {C_B}^2 \tag{10}$$

With:

C_2 = Factor depends on the lock head: $C_2 = 1.0$ lower; $C_2 = 0.2$ upper lock head [-].
L = Length of vessel [m]
C_B = Block coefficient of vessel: $C_B = 0.9$ for tested vessel [-]

5.1.3 Combining the adaptations

The corrected water depth in the lock due to the proposed adaptions are combined in:

$$D_{lock,adapted} = D_{lock} + C_1 \cdot z_{op} + C_2 \cdot -i \cdot L \cdot {C_B}^2 \tag{11}$$

The proposed values for C_1 and C_2 are summarized in Table 7:

Sailing direction	Lock head	Dead-end ahead of the bow	Water level slope in return flow
Lock entry	Lower	$C_1 = 0.5$	$C_2 = 1.0$
Lock entry	Upper	$C_1 = 0.5$	$C_2 = 0.2$
Lock departure	Lower	$C_1 = 0.0$	$C_2 = 1.0$
Lock departure	Upper	$C_1 = 0.0$	$C_2 = 0.2$

Table 7: Proposed coefficients in adaptation of Schijf's method

The above proposed adaptions have been added in Schijf's method via an iterative calculation process. In the first iteration the vessel speed, water level depression and return flow are calculated with the original method. The water level depression and return flow are then applied to calculate the adaption to the water depth in the lock. In the subsequent steps the water level adopted from the previous computational step is used as input for Schijf's method.

5.2 Computations for calibration of Schijf's method adapted for vessels in locks

The calculations with the adaptation of Schijf's method have been executed for the conditions that occurred during the measurements. The main results are presented in Table 8 together with the measured vessel speed and the results from Schijf's original method.

Verification and Calibration			Track 1		Track 2		Track 3		Track 4	
sailing distance 102.5		m	upper-in	lower-out	lower-in	upper-out	upper-in	lower-out	lower-in	upper-out
Lock Delden	Width	[m]	12.05	12.05	12.05	12.05	12.05	12.05	12.05	12.05
	water depth in lock head	[m]	3.85	3.49	3.49	3.85	3.85	3.49	3.49	3.85
Vessel	Beam	[m]	11.40	11.40	11.40	11.40	11.40	11.40	11.40	11.40
	Draft	[m]	2.609	2.609	2.609	2.609	2.782	2.782	2.782	2.782
Blocking ratio		[%]	64%	71%	71%	64%	68%	75%	75%	68%
	Sailing time (over 102.5 m)	[s]	143	289	262	162	178	392	374	201
	Delden measured vessel speed	[m/s]	0.72	0.35	0.39	0.63	0.58	0.26	0.27	0.51
Schijf's method	v_{op}	[m/s]	0.63	0.44	0.44	0.63	0.52	0.33	0.33	0.52
	Error w.r.t. measurment	[%]	-12.1%	23.3%	11.8%	-0.4%	-10.1%	28.0%	22.1%	1.5%
Schijf+Adaption	v_{op}	[m/s]	0.68	0.36	0.40	0.62	0.56	0.25	0.28	0.50
	Error w.r.t. measurment	[%]	-5.2%	1.9%	3.4%	-2.3%	-3.2%	-4.7%	3.0%	-1.0%

Table 8: Measured and calculated vessel speed without with adapted method

The computed values are plotted w.r.t. the measured values in Figure 13.The error in the computed values w.r.t. the measurements are in most cases significantly smaller for the adapted method.

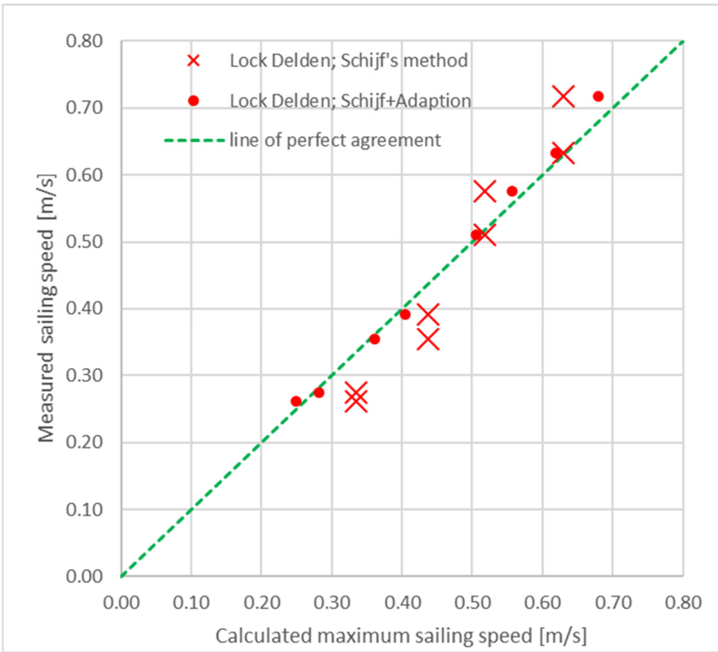

Figure 13: Measured and calculated vessel speed without and with adapted method

5.3 Conclusions on the verification with data from prototype measurements

Concerning the proposed adaption of Schijf's method for the calculation of the vessel speed in locks the following conclusions were drawn.

- With the proposed adaption of Schijf's method the differences between the measured and calculates lock entry and departure speed is 5% or less.
- The difference between the computed and measured velocities reduced from a maximum of 28% for Schijf's original method to 5% or less with the adapted method.
- The validation covered blockage ratios between 64% and 75% ($0.64 < k < 0.75$).

The conclusions on the adaptation of Schijf's method are based on 8 prototype measurements from Lock Delden. In the next section prototype measurements from other locks and from a ship lift are added to the data set for validation of the adaptation of Schijf's method.

6 COMPARISONS WITH DATA FROM SAMBRE LOCKS AND LÜNEBURG LIFT

6.1 Prototype measurements on the Sambre

Prototype tests with a similar setup as for Lock Delden have been executed on the Sambre River in Belgium. The Sambre River is a meandering river in the southern part of Belgium. The river is part of the waterway connection between the Scheldt and the Meuse rivers. As part of the project Seine – Escaut Est (SEE) the navigation route will be increased from CEMT Class IV to CEMT Class Va vessels with a length of 110 m. In addition to several manoeuvring simulation studies, the Service Public de Wallonie (SPW) performed a prototype test to measure the behaviour of a large vessel navigating in the narrow and curved Sambre river (Bousmar e.a.,2013).

The SPW has reported the prototype measurements on the Sambre in a measurement report (SPW,2010). The measurements on the Sambre have been executed on 11 December 2009 with a loaded Class Va vessel with length: 105 m, beam: 10.5 m and draft: 2.6 m. The test covered sailing over 38 km of the Sambre river (from Pont-de-Loup up to Namur), including the passage of 5 navigations locks. The horizontal dimensions of the lock are $L_{lock} \geq 112$ m and $W_{lock} = 12.5$ m which complies with CEMT Class Va. During the passing of the locks the minimum water depth in the locks was $D_{lock} \geq 3.45$ m. The blockage ratio of the vessel was high ($0.46 < k < 0.63$) but not extremely high ($k > 0.75$) that special measures are required for locking the vessel (PIANC,2015).

The vessel was equipped with various instruments to register the manoeuvring action of the skipper and measure the position of the vessel. The water level depression in the Sambre was measured at various locations in the river during the passing of the vessel, but not in the lock. The type of prototype measurements and the recorded data correspond well with the prototype measurements for Lock Delden. This makes it possible to add the measurements from the Sambre to the present data set for the verification of the proposed adaption to Schijf's method.

6.2 Measurement and verification for the five Sambre locks

The measurements in the Sambre relate to sailing downstream. During the measurements the vessel the entered the lock through the upper head and the departure through the lower head. The vessel passed 5 unique locks with slightly different water depths in the lock heads. In the Sambre Locks E14 Auvelais and E17 Salzinnes the sills of the mitre gates are locally higher than the lock floor. These sills have hardly impact on the return flow, however, the higher level increase the risk of grounding the vessel at the sill at a higher sailing speed.

The measurements in the locks in the Sambre comprised the positions of bow and stern of the vessel, and the manoeuvring actions, but not the water levels in the lock heads. The position of the vessel was measured with three GPS antennas located at the bow, the stern and the centre point of the vessel that registered the position (X, Y and Z) of the vessel. The manoeuvring actions of the skipper have been registered by video cameras.

All signals have been verified and stored with a frequency of 1 Hz. Because the locks in the Sambre have horizontal moving (transversal) gates or mitre gates, the GPS measurements have not been interrupted by lifted lock gates (as was the case with the lifting gates in Delden). Additionally, the central GPS data enabled series reconstructions when missing data.

6.3 Verification calculations

The values from the prototype measurement have been collected for calculations. These data are presented in Table 9 together with the results of the calculations with Schijf's method.

Verification and Calibration		E13 Roselies		E14 Auvelais		E15 Mornimont		E16 Floriffoux		E17 Salzinnes	
sailing distance 93.6 m		upper-in	lower-out	upper-in	lower-out	upper-in	lower-out	upper-in	lower-out	upper-in	lower-out
Sambre Locks Length	[m]	112		136		112		112		136	
Width	[m]	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
water depth in lock head	[m]	3.84	3.95	4.16	3.45	4.70	4.39	3.92	4.64	4.45	3.85
Vessel Beam	[m]	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50
Draft	[m]	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60
Blocking ratio	[-]	0.57	0.55	0.53	0.63	0.46	0.50	0.56	0.47	0.49	0.57
Sailing time (over 93.6 m)	[s]	151	161	107	165	115	127	99	95	102	130
Measured vessel speed	[m/s]	0.62	0.58	0.87	0.57	0.81	0.74	0.95	0.99	0.92	0.72
Schijf's method V_{op}	[m/s]	0.84	0.90	1.02	0.62	1.32	1.15	0.89	1.29	1.18	0.85
Error w.r.t. measurment	[%]	36%	55%	17%	9%	62%	56%	-6%	31%	29%	18%
Schijf+Adaption V_{op}	[m/s]	0.91	0.86	1.10	0.56	1.42	1.12	0.96	1.26	1.27	0.80
Error w.r.t. measurment	[%]	46%	48%	26%	-1%	74%	51%	1%	28%	39%	11%

Table 9: Verification calculations of vessel speed for Sambre locks

The sailing speeds from Table 9 have been presented in Figure 14 (dark blue markers) together with the vessel speeds from Lock Delden (red markers). Figure 14 presents also some data from the Lüneburg ship lift (Light blue markers), which are further discussed in Section 6.4.

At first glance the data points in Figure 14 could give the impression that the measured and calculated vessel speeds for the Sambre locks are much less in agreement than for Lock Delden. Figure 14 indicates that the calculated vessel speeds in the Sambre locks are generally much higher than in Lock Delden. This corresponds to the fact that the blockage ratio in the Sambre locks ($0.46 < k < 0.63$) was in general lower than in Lock Delden ($0.64 < k < 0.75$), see also Figure 16.

The data points in Figure 14 indicate that the agreement is good in the lock heads where the (calculated) vessel speed is less than approximately 0.8 m/s (approximately 3 km/hr).

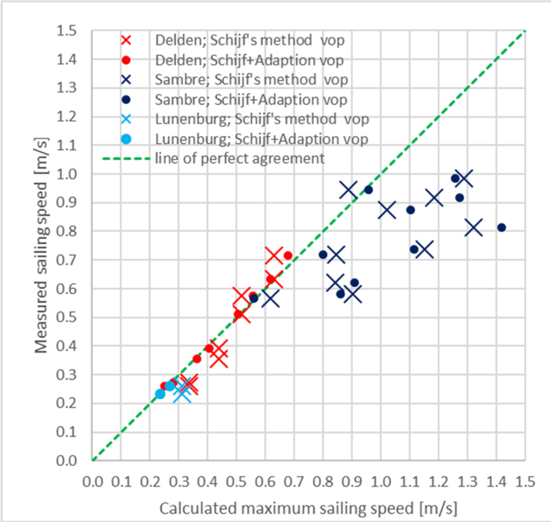

Figure 14: Measured and calculated vessel speed without and with adapted method

Figure 14 indicates that the calculated vessel speed forms an upper boundary for the vessel speed. The skipper intentionally sailed with a maximum speed of about 0.8 m/s (3 km/hr) even if that is much slower than physically possible.

Figure 15 presents the use of the main propeller during the entry manoeuvres in lock E13 and E15. The vertical lines mark the time that the bow and the stern enter the lock heads. The graphs indicate that in these Sambre locks the main engine was used only part-time during the entry manoeuvre (whereas in Lock Delden the main engine has been used throughout almost the entire entry manoeuvre, see Figure 7 for an example).

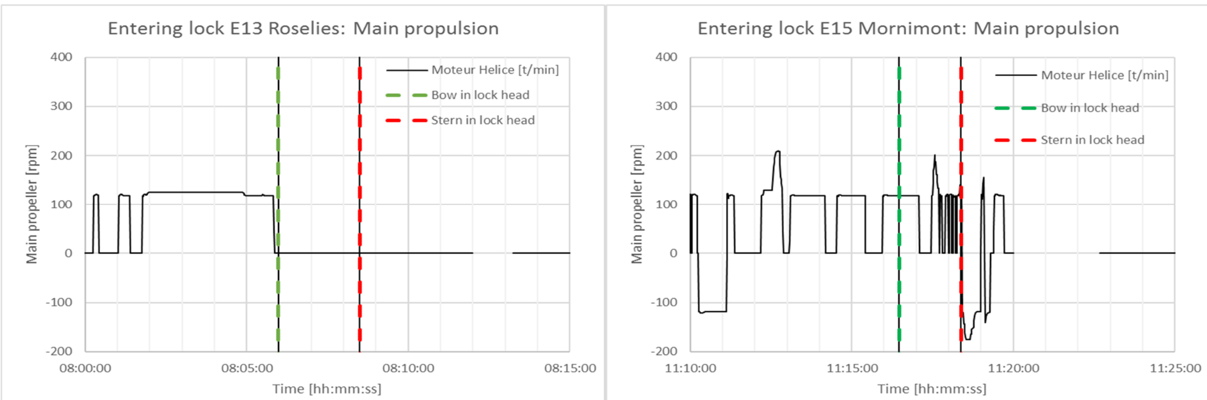

Figure 15: Entry manoeuvre Sambre locks; main propulsion and propeller

In Figure 16 the vessel speeds have been plotted as function of the blockage factor of the vessel in the respective lock heads. This presentation of the data indicates that the measured and calculated vessel speed are in good agreement for the blockage ratio higher than $k > 0.6$ and that for smaller blockage ratios the measured vessel speed is equal or lower than calculated. As such Schijf's method gives an accurate upper boundary for the vessel speed in locks with a low blockage ratio ($k < 0.6$).

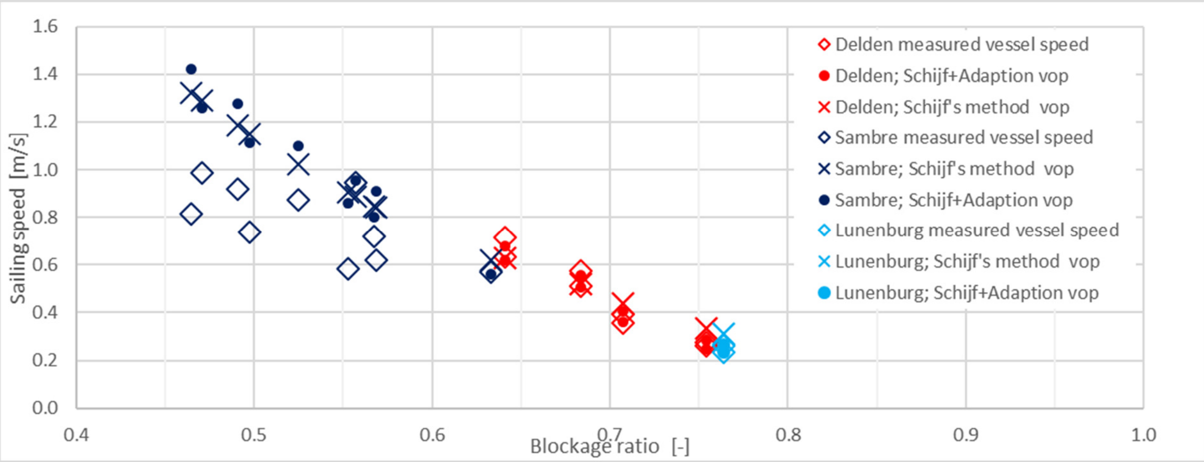

Figure 16: Measured and calculated vessel speed as function of blockage factor

6.4 Prototype measurement from the Lüneburg ship lift

Prototype measurements for the Lüneburg ship lift have been described by Spitzer and Söhngen (2013). The ship lift has dimensions of L=110 m, W=12.25 m and D=3.41 m. A total of 14 measurements were carried out. The measurements comprised the entering of the lift and the departure from the lift. The vessel entered the ship lift with an approach speed that varied from 2 to 8 km/hrs, whereas the blockage ratio was very high ($k > 0.75$), which results in a limiting speed in the ship lift of 0.37 m/s (1.3 km/hrs).

The average vessel speed in the ship lift has been adopted from the graph and presented in Table 10. The results have also been presented in the Figure 14 and Figure 16. Contrary to the Sambre data, the Lüneburg ship lift data show blocking ratio of 76% (($k = 0.76$) that is higher than for Lock Delden.

Verification and Calibration			Lunenburg	
sailing distance 100 m			trough-in	trough-out
Ship lift	Length	[m]	100	100
	Width	[m]	12.25	12.25
	water depth in lift	[m]	3.41	3.41
Vessel	Beam	[m]	11.40	11.40
	Draft	[m]	2.80	2.80
	Blocking ratio	[-]	0.76	0.76
	Sailing time (over 90 m)	[s]	360	402
	Lunenburg measured speed	[m/s]	0.28	0.25
	Lunenburg; Schijfs method v_{op}	[m/s]	0.31	0.31
	Error w.r.t. measurment	[%]	12%	25%
	Lunenburg; Schijf+Adaption v_{op}	[m/s]	0.27	0.24
	Error w.r.t. measurment	[%]	-4%	-5%

Table 10: Measured and calculated vessel speed for the Lüneburg ship lift

Table 10; Figure 14 and Figure 16 show good agreement between the measured and calculated data, and also that the adaptation of Schijf's method significantly reduces the error w.r.t. the measurements.

6.5 Conclusions on the verification with data from Sambre locks and Lüneburg ship lift

From the verification of the adaption of Schijf's method with data from the Sambre locks and the ship lift at Lüneburg the following conclusions can be drawn:

- The data sets from the Sambre locks cover a blockage range ($0.46 < k < 0.63$) that is not covered by the data set from Lock Delden; and the data sets from the Lüneburg ship lift cover a blockage range ($k > 0.75$) that is also not covered by the data set from Lock Delden;
- The three data sets cover together a wide range of blockage ratios $0.46 < k < 0.76$.
- The three data sets indicate that the vessel speed for blockage ration of $k > 0.6$ can be accurately calculated with the proposed adaption of Schijf's method.
- For smaller blockage ratios ($k < 0.6$) the calculated vessel speed forms an upper boundary for the vessel speed.

7 SUMMARY AND CONCLUSIONS

7.1 Situation

The increase of vessel sizes puts pressure on the waterway authorities to allow larger vessels in the existing infrastructure. The Twentekanaal in the Netherlands is in a process of upgrading from CEMT Class IV to Class Va. Therefore, the clearances in the Lock Delden will in future become below the minimum clearances that are recommended in the guidelines (RVW,2017).

The situation of Lock Delden has been investigated in several steps using desk studies backed up with prototype measurements. The conclusions of each step have been used to evaluate the requirements for the next step.

7.2 Initial desk study

The initial study comprises a desk study on the behaviour of a vessel sailing with very small clearance in the confined water of a navigation lock. Schijf's method has been applied for the calculation of the sailing speed and water level depression around the vessel. The desk study resulted in the following conclusion for the Class Va vessel in the existing Lock Delden:

- The beam clearance and the under-keel clearance become less than recommended;
- The minimum blockage ratio increases to 80% where special measures are recommended for a blockage above 75%.
- The maximum operational vessel speed reduces from 0.65 m/s to 0.25 m/s.
- The maximum lock entry time is more than doubled and with a loaded class Va vessel the lock-Cycle time increases with 11 minutes;
- The limiting speed of and the return flow and the water level depression around the Class Va vessel are significantly less than around the Class IV vessel.

The above results of the desk study indicated that:

- Special measures might be necessary to accommodate Class Va vessels in Lock Delden;
- The decrease of the vessel speed and the subsequent increase of the lock-cycle time might have an impact the capacity of the lock.

The above vessel clearances and vessel speed, together with the uncertainty in the application of Schijf's method for the very confined water in a lock situation lead to the decision to perform prototype measurements in Lock Delden.

7.3 Prototype measurement Lock Delden

- Prototype measurements were performed in Lock Delden with a Class Va vessel with draft of 2.6 m and with draft of 2.8 m, in both sailing directions.
- The skipper used the engine to dead-slow and during the lock entry and departure manoeuvres he did not experience any specific problem;
- The vessel speed computed with Schijf's original method appear to differ up to 28% from the measured vessel speed;
- The vessel speed computed for sailing in the upper head is lower than measured;
- The vessel speed computed for sailing in the lower head is higher than measured;
- The lock entry manoeuvre takes less time than the lock departure manoeuvre.

The above results of the prototype measurements indicate that:

- With the limitation of the use of the engine to dead-slow it appeared to be possible to perform the lock entry and departure safely, even with a blockage of k=0.75;
- The calculations with Schijf's original method resulted in a systematic deviation from the measured vessel speeds. Therefore, Schijf's method should be adapted to counteract these deviations

7.4 Adaptation to Schijf's method

The systematic deviation between the measured and the calculated vessel speed can be explained from hydraulic processes in locks that are not accounted for in Schijf's original method:

- The lock is a dead-end waterway;
- The velocity of the return flow in the narrow clearance between the vessel and the lock is high and the resulting water level slope in the lock becomes significant.

The present paper proposes to adapt Schijf's method on the above two aspects in locks. From the vessel speed computed with the adapted method the following conclusion are drawn:

- The proposed adaption on Schijf's method results in significant smaller differences (5% or less) between the measured and calculates lock entry and departure speed.
- The maximum error has been reduced from 28% to 5% of the measured vessel speed;
- The measurements in Lock Delden cover the blockage ratio: 64% to 75% ($0.64 < k < 0.75$).

The above conclusions are based on eight measurements from Lock Delden.

7.5 Comparison with data from locks in the Sambre river and the Lüneburg ship lift

Measurements in locks in the Sambre comprised ten lock and two ship lift entry or departure manoeuvres. From the calculation of the blockage ratio and vessel speed in the locks the following conclusion can be drawn:

- The blockage ration in the Sambre locks varied between 46% to 63% ($0.46 < k < 0.63$), a range that was not yet covered by the data from Lock Delden;
- For low blockage ratios ($k < 0.6$) the measured vessel speed is lower than computed;
- The manoeuvring actions indicate that the skipper used the main engine in the Sambre locks to dead slow and sparsely. This could explain why the vessel speed is lower than calculated.
- The blockage ration in the Lüneburg ship lift is 76% ($k = 0.76$), just above the range that was not covered by the data from Lock Delden; the adaption on Schijf's method results in similar error as for Lock Delden (5% or less) and a similar reduction compare to Schijf's original method.

7.6 Final conclusion on the proposed adaption of Schijf's method for locks

A simple method has been developed to evaluate the sailing speed and time required for the entering and departing of the lock chamber. The basis of the calculation method is Schijf's well-known method that describes the hydraulics around a vessel sailing at constant speed in a prismatic canal.

For vessel sailing in locks the hydraulics conditions deviate from the assumptions of Schijf's method. Two adaptations have been proposed to account for hydraulic aspects that are not accounted for. The adaptations to Schijf's methods for the calculations of the vessel speed in a lock have been verified for eight measurements in Lock Delden, ten measurements in locks in the Sambre river and two measurements in ship lift Lüneborg. The following final conclusions were drawn:

- The vessel speed in the confined water in locks is significant affected by the dead-end waterway of the lock and the hydraulic resistance (and water level slope) in the return flow. The original version of Schijf's method does not account for these specific hydraulic processes in locks.
- To account for these hydraulic aspects in locks, two adaptations have been proposed to Schijf's original method.
- Calculations with the adaptions show a very good agreement with measurements from situations with high blockage. For the blockage ration of 60% or higher ($k > 0.6$) the error in the calculated vessel speed is less than 5%.
- For blockage ratios of less than 60% ($k < 0.6$), or a calculated vessel speeds of 0.8 m/s (3 km/hr) or higher, the method gives the upper boundary for the vessel speed in the lock.

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