Bundesanstalt für Wasserbau
Federal Waterways Engineering and Research Institute

Driving Dynamics of Inland Vessels

Vessel Behaviour on European Inland Waterways and Waterway Infrastructure with Special Respect to German Waterways

Driving Dynamics of Inland Vessels

Vessel Behaviour on European Inland Waterways and Waterway Infrastructure with Special Respect to German Waterways

Published in German language by VBW in July 2013
Translation and revision by BAW in July 2016

Publication Data

Published by:
Bundesanstalt für Wasserbau
Federal Waterways Engineering and Research Institute
Kussmaulstrasse 17, 76187 Karlsruhe
Phone: +49 (0) 721 9726-0
Fax: +49 (0) 721 9726-4540
E-mail: info@baw.de
www.baw.de

Cover picture: Einstein, Fotolia

ISBN 978-3-939230-48-9 (Print)
ISBN 978-3-939230-49-6 (Online)

Printed in Germany

About

This publication was prepared in German by members of a working group led by the German expert committees “Inland Waterways and Harbours” (VBW/HTG) and “Inland Vessels" of the German Association for European Inland Navigation and Waterways. It was published in July 2013 and is available on the VBW website www.vbw-ev.de or can be ordered as a hard copy version from "Verein für europäische Binnenschiffahrt und Wasserstraßen e.V.", Haus Rhein, Dammstrasse 15-17, 47119 Duisburg, Germany.

The present English version was translated from the German text by order of BAW by Teamword, Heidelberg. The technical review with some restatements for better understanding and additions were performed mainly by members of BAW, especially Bernhard Söhngen (text), Kristiina Leismann (figures) and Gerlinde Krause (coordination).

The English version can be downloaded from the VBW (www.vbw-ev.de), BAW (www.baw.de) and German PIANC Section (wwwe.pianc.de) websites. Contact BAW ("Bundesanstalt für Wasserbau", Kussmaulstrasse 17, 76187 Karlsruhe, Germany) for a hard copy.

Members of the German VBW Working Group:

Michael Heinz, Generaldirektion Wasserstraßen und Schifffahrt, Bonn (Chairman)
Bernhard Söhngen, Bundesanstalt für Wasserbau, Karlsruhe
Svetlana Doychev, Bundesanstalt für Wasserbau, Karlsruhe
Helmut Broß, Entwicklungszentrum für Schiffstechnik und Transportsysteme e.V. (DST), Duisburg
Hans-Gerd Heidenstecker, Heidenstecker Schifffahrt, Köln-Wesseling
Andreas Hüsig, Generaldirektion Wasserstraßen und Schifffahrt, Bonn
Christian Meyer-Mölleringhof, Generaldirektion Wasserstraßen und Schifffahrt, Bonn
Marcel Lohbeck, VBW, Duisburg

Contents

1 Introduction

For decades the volume of goods traffic in Germany and Europe has been rising steadily and sometimes rapidly, with forecasts predicting further growth. Marine transport has increased significantly, due to the continuing internationalisation of trade and production, and consequently more cargo is transported via means such as road, rail and waterways. It has been evident for many years that road haulage and rail transport can hardly cope with the growing transport volume. At the same time, competition amongst the transport modes is ever increasing, as is cost pressure. There are various factors determining whether transport by ship has advantages over road haulage or rail transport and each mode has its specific strengths.

Inland waterway transport is mainly used for longer distances and larger transport volumes where its economic efficiency is better in comparison to road or rail. The lower cost per ton of cargo transported and distance unit is not the only advantage of transport by inland waterways. It is also more environmentally friendly, causing fewer emissions (in terms of noise and carbon dioxide) and boasting the lowest primary fuel consumption of all of the above-mentioned modes of transport. Moreover, the energy performance of an inland navigation vessel is often underestimated: if, in addition to the energy consumption required for its mere use as a transportation vessel, the so-called “grey energy” is taken into account, meaning the total energy consumed throughout the vessel’s life cycle from manufacturing through maintenance to disposal, inland navigation vessels are even more cost-efficient than the other two means of transport. Seen from the politico-economic perspective, emphasis must also be placed on the external costs (climate gases, air pollutants, accidents and noise) of traffic on inland waterways which are lowest in comparison with rail and road traffic.

The average ship tonnage is increasing at a rate of 1 to 1.5 % per year. This increase is primarily due to competition amongst the transport modes. Public investments in the extension of the waterways are consequently required to improve the availability of high-capacity waterways and enable uninterrupted traffic of large vessels on the major transport routes.

The existing waterways must ensure safe and economic shipping operations for the European fleet of inland vessels, including larger vessels. While recent extensions of waterways have mostly focused on the ship sizes expected for the future, the navigability of a large number of existing inland waterways is subject to limitations. Narrow curve radii or inadequately designed lock approaches or lock canals require increasing nautical skills of the shipmasters and better vessel equipment to cope with the restrictions regarding the ease of navigation.

The objective of this brochure is to look at the different existing waterway situations and cross-sections, showing the sailing and manoeuvring behaviour currently adopted by inland vessels and the resulting loads on the channel bed and banks. The brochure describes the broad range of infrastructures to be found in the Western European network of waterways with special respect to German waterways, ranging from shipping canals to free-flowing and impounded rivers with their special flow and discharge characteristics affecting the dynamics of ships navigating inland waterways.

This brochure’s target readers are:

Shipmasters and shipping company representatives
Staff in waterways administrations
Political representatives
Associations focusing on environmental or economic issues
Research and development institutions

2 Inland navigation vessels and navigation

2.1 Vessels and fleet structure

2.1.1 Ship dimensions and load draughts

The dimensions of inland navigation vessels such as length, beam and draught are limited by the available cross-sections of the main waterways. In central Europe, these are in particular the River Rhine with its impounded tributaries and the network of canals in Western Germany. Since the share of freight transport on the stretches of the Rhine is high and the shipping channel depths and widths are favourable, a Rhine fleet in its own right has developed over time in addition to the vessels working other rivers and canals in the entire network of waterways. The special Rhine fleet consists of individual vessels exceeding 11.45 m in width as well as large push-tow units (pushed convoys) that are not found on the adjoining waterways. The dimensions of European inland navigation vessels, however, mainly depend on the dimensions permitted for craft and units navigating the inland waterways adjoining the Rhine.

The designations chosen for older European vessel types generally refer to the rivers and canals for which they were built. The vessel types Peniche (Theodor Bayer), Gustav Königs (Dortmund-Ems Canal barge) and Johann Welker (Europe Ship), which are still in use today, were designed for shipping in the canals and locks existing or under construction at the time when these ships were built. However, ship owners were permanently under economic pressure and forced to reduce the specific costs of transportation (per ton transported), in particular those related to staff and fuel consumption. As a result, the lengths, widths and draughts of ships increased as well as their drive power.

Even though the increase in ship size leads to less efficient cross-section ratios combined with a reduction in maximum ship speed, the new, more modern vessels generally have improved manoeuvrability, which allows the reduction of both the vessel speed and the safety distances. Modern large motor vessels (GMS) are therefore able to navigate in restricted waterways such as the network of canals in North-Western Germany and the Main-Danube Canal, which were originally designed for the Europe ship. Today, typical locks for inland navigation in European canals are around 12 m wide and around 110 to 200 m long. These dimensions currently limit the maximum beam of a vessel to around 11.4 m, the length of a barge to around 76 m and the length of a motor vessel to 110 m (GMS). Taking the typical water depths and corresponding draughts into account, the load carrying capacity of a single vessel sailing in the canal network is nowadays limited to approximately 1,500 DWT (deadweight tons) for Europe ships (ES), approximately 2,200 DWT for large motor vessels and up to 4,000 DWT for pushed convoys (SV).

The increasing importance of container transport in Europe has resulted in an adaptation of vessel dimensions in large rivers such as the Rhine and the Danube. For instance, the largest ships navigating the Rhine as well as stretches of the Danube and the Dutch and Belgium networks of waterways are up to 23 m wide and about 135 m long. Push-tow units consisting, for example, of a pusher and up to six barges have dimensions of 23 x 270 m or 34 x 190 m. The average navigation channel depth of the largest rivers in Europe allows draughts ranging from 3 to 4 m. The maximum draught presently permitted in many European canals is 2.8 m.

Given the global increase in transport demand, the competition amongst the various transport modes and the rising fuel costs, it is likely that the size of the inland navigation vessels navigating the main waterways will continue to increase while traditional vessel types of smaller dimensions will be crowded out and take to side waterways. To date it is uncertain whether the climate change will have a significant impact on the fleet, for example by leading to the reintroduction of more smaller-sized vessels that are also able to navigate at extremely low water levels, because the data so far obtained on changes in flows, in particular in the Rhine area, is not reliable. At any rate it is to be expected that the available depths and widths of navigation channels, especially in free-flowing waterways, cannot be completely adapted to the increasing ship dimensions because of hydraulic and politico-economic reasons. Fairway widths might even be restricted in order to obtain greater depths at bottlenecks (Söhngen et al., 2010). It is likely, therefore, that shipbuilding technology will overcome these problems by further improving the manoeuvrability of vessels, possibly even using modern track control sys-

Large motor vessel	NL	B	D	Other	Total	Year of construction between 2000 and 2009
Up to 1,000 DWT	1,799	706	430	200	3,135	32
1,001 to 1,500 DWT	691	250	423	293	1657	24
1,501 to 2,000 DWT	298	74	110	65	547	71
2,001 to 2,500 DWT	148	56	55	8	267	41
2,501 to 3,000 DWT	162	46	44	3	255	91
> 3,000 DWT	266	62	9	3	340	275
Total	3,364	1,194	1,071	572	6,201	534
Motor tank vessels	**NL**	**B**	**D**	**Other**	**Total**	**Year of construction between 2000 and 2009**
Up to 1,000 DWT	378	113	125	23	639	22
1,001 to 1,500 DWT	113	52	162	24	351	23
1,501 to 2,000 DWT	102	19	73	21	215	60
2,001 to 2,500 DWT	82	22	58	15	177	38
2,501 to 3,000 DWT	79	21	32	23	155	80
> 3,000 DWT	131	33	14	15	193	141
Total	885	260	464	121	1,730	364

Table 2.1.1-1: European fleet (number of vessels) of inland navigation vessels (Rhine states, Belgium, Luxemburg) according to deadweight classes and countries of origin (as at October 2009)

Vessel size class [DWT]	MLK (Hannover)	DEK (Münster)	WDK (Datteln/Friedrichsfeld)	Rhein-Herne-Kanal, Duisburg	MDK
E 0 - 400	1.2	0.5	0.3	0.3	0.1
E 401 - 650	3.5	4.2	3.3	0.7	1.5
E 651 - 900	14.9	12.7	10.3	6.4	4.8
E 901 - 1,000	9.5	6.1	3.4	2.5	1.7
E 1,001 - 1,500	32.2	45.4	37.7	38.5	24.7
E 1,501 - 2,000	10.0	11.0	19.9	29.5	24.9
E 2,001 - 2,500	9.2	6.4	8.6	8.4	16.5
E 2,501 - 3,000	9.5	7.1	7.5	7.2	14.6
E > 3,000	2.7	2.0	6.0	2.4	1.7
SL 0 - 1,500	5.8	3.7	2.1	4.1	8.3
SL 1,501 - 2,000	0.2	0.1	0.2	0.0	0.2
SL > 2,000	1.3	0.8	0.7	0.0	0.9
Ø DWT E	1,467.0	1,399.0	1,604.0	1,595.0	1,797.0
Ø DWT E + SL	1,424.0	1,374.0	1,588.0	1,547.0	1,691.0

Table 2.1.1-2: Regional fleet structures in 2030 (% number of vessels and load carrying capacity in DWT): WDK, RHK, DEK, MLK, MDK

Legend:
E = Self-propelled vessel (single driving or part of a push-tow unit)
SL = Pushed barge (lighter) (part of a push-tow unit)
DWT = Deadweight Tons

Type Vessel size class [DWT]	Lower Rhine (Wesel)	Upper Rhine (Iffezheim)	Moselle	Main upstream of Offenbach	Danube
E 0 - 400	0.4	0.2	0.3	0.1	2.1
E 401 - 650	2.4	0.7	0.3	1.5	1.5
E 651 - 900	5.2	2.2	2.0	4.5	5.6
E 901 - 1,000	2.2	1.3	1.3	1.8	1.0
E 1,001 - 1,500	19.5	16.4	14.6	25.1	17.4
E 1,501 - 2,000	16.0	17.1	18.5	23.1	24.0
E 2,001 - 2,500	14.2	20.2	26.3	18.2	9.2
E 2,501 - 3,000	16.9	28.3	22.8	16.1	8.2
E > 3,000	5.3	6.2	4.7	1.9	1.0
SL 0 - 1,500	2.6	1.6	1.5	6.3	29.0
SL 1,501 - 2,000	0.7	1.3	1.7	0.3	0.2
SL > 2,000	14.6	4.5	6.0	1.1	0.8
Ø DWT E	1,914.0	2,153.0	2,116.0	1,827.0	1,658.0
Ø DWT E + SL	2,008.0	2,150.0	2,127.0	1,748.0	1,307.0

Table 2.1.2-1: Fleet structure in 2030 (% number of vessels and load carrying capacity in DWT): Rhine, Moselle, Main and Danube

Vessel size class [DWT]	ESK	Middle Elbe (Magdeburg)	HOW north of Havel Canal	UHW (Potsdam)	HOW (Spandau)
E 0 - 400	0.2	0.0	0.2	3.1	1.2
E 401 - 650	2.4	8.4	4.2	17.1	4.1
E 651 - 900	10.6	11.3	11.1	15.6	11.6
E 901 - 1,000	9.8	3.5	1.9	6.0	2.1
E 1,001 - 1,500	31.7	20.1	2.5	12.6	2.7
E 1,501 - 2,000	10.4	0.0	5.1	3.6	5.6
E 2,001 - 2,500	10.6	0.0	0.4	1.9	0.8
E 2,501 - 3,000	9.3	0.0	0.4	2.2	0.9
E > 3,000	0.0	0.0	0.0	0.8	0.0
SL 0 - 1,500	15.0	56.7	74.2	36.6	70.8
SL 1,501 - 2,000	0.0	0.0	0.0	0.0	0.0
SL > 2,000	0.0	0.0	0.0	0.5	0.2
Ø DWT E	1,466.0	944.0	1,025.0	933.0	1,056.0
Ø DWT E + SL	1,308.0	643.0	571.0	790.0	604.0

Table 2.1.2-2: Fleet structure in 2030 (% number of vessels and load carrying capacity in DWT): Elbe Lateral Canal, Elbe and the Berlin waterways

Legend:
E = Self-propelled vessel (single driving or part of a push-tow unit)
SL = Pushed barge (lighter) (part of a push-tow unit)
DWT = Deadweight Tons

tems (autopilots) to make the best possible use of the prevailing conditions in existing navigational channels. With fuel costs rising, the trend towards more energy efficient navigation will continue, so that vessels will probably sail at lower speeds and reduced fuel consumption levels. While this evolution will probably only affect ship dimensions to a minor degree, it will have a significant impact on the design of propulsion and steering units.

Changes must also be expected in the number of recreational craft and their size, among other things due to the higher expectations of leisure craft users. Hence, the number of passenger ships in German waterways will probably increase, too. In view of this development it may become necessary to introduce restrictions regarding the size and engine power of leisure craft because of the resulting higher impacts on the bottom and banks of our waterways.

2.1.2 Fleet structure and evolution

The existing infrastructure and the need to operate profitable vessel units which prevails in the logistics market have an impact on the current fleet structure. Since the waterway infrastructure in Western Europe is heterogeneous, there are significant differences between the fleets in terms of size and composition. In some areas, the fairway widths and depths only admit ship sizes in the range from 700 to 1,000 DWT.

However, if the fairway cross-sections in free-flowing rivers such as the Rhine or in canals and impounded rivers are sufficiently wide, it is possible to navigate vessels with 1,200 to 3,000 DWT.

Whenever extension or new development measures are carried out on continuous reaches in the network of waterways in order to enable the navigation of large modern ships, a fleet of larger vessels is created as a precondition of more profitable transport business. In addition to this trend towards bigger vessels, spurred by the development of the network infrastructure, it is also the ongoing replacement of old ships with new vessels which brings the fleet up to modern standards and which in the past has increased the pressure for a further extension of the waterways. Based on the trend observed in the last few decades, the average size of inland navigation vessels (in terms of DWT) can be expected to increase by 1 to 1.5 % per year. As in the past, this development will result from the replacement of smaller older vessels with larger newer craft as well as from ship modifications (increased ship length and in some cases also width). For a better assessment of this trend and to obtain more reliable data for waterway planning, the former BMVBS (today the Federal Ministry of Transport and Digital Infrastructure, BMVI) commissioned forecasts of regional fleet structures in 2010.

Transport by ship on the different reaches of the network of waterways is profitable and attractive due to the larger ship dimensions.

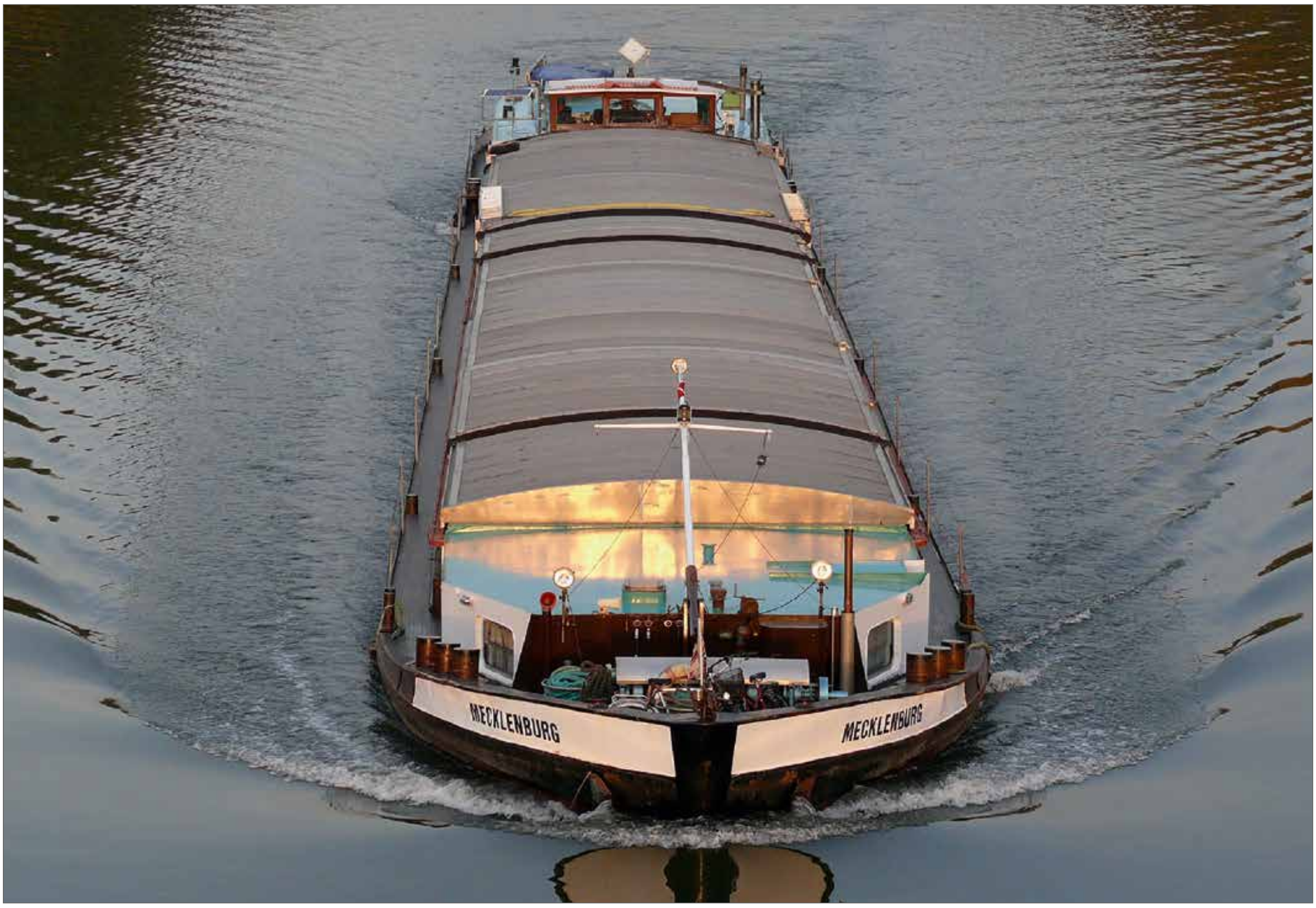
Besides the typical inland navigation vessels listed in Chapter 2, extra-long large motor vessels (max. 135 m long vessel - üGMS) in particular have become increasingly present in the market over the past 15 years. In addition to this vessel type which has a length of 135 m and a beam of 11.45 m and which is often the product of an extension to a GMS, a new type is meanwhile seen on the Rhine more and more frequently (currently more than 100 craft): the so-called “Jowi class” with a length of 135 m and a beam ranging from 13 to 17 m (individual ships are even larger). With more than 3,000 tons transported these ships fall under the category “Self-propelled vessel > 3,000 DWT” in the table referred to here. There are regional differences regarding the deadweight of the ships; however, the operating costs (including crew and fuel) remain almost unchanged when the deadweight increases, i.e. the transport of cargo is generally more profitable with larger vessels if the degree of capacity utilisation is good.

This trend towards larger vessels is not only observed on extended waterways but also on other waterway types. Larger ship dimensions and load draughts on the present waterways also mean that greater nautical and technical demands are placed on the ship and crew alike. The following recommendations for different navigation zones and situations are intended to provide guidance for easy and safe navigation on Germany’s inland waterways.

2.1.3 Inland navigation vessel types and pushed convoys

The following section describes the typical vessels and convoys in the European fleet of inland navigation vessels. Besides providing information on dimensions and on propulsion and steering devices it shows typical values for the achievable ship speed at maximum engine power when sailing in shallow water conditions, i.e. in a navigation channel which is not laterally confined. The typical or reference values indicate the speed relative to the water body, meaning that when the vessel is sailing upstream the values indicated must be reduced by the approximate value of the flow velocity, while for downstream navigation they must be increased to obtain the values over ground. Whereas at large water depths the usable engine power is equal to the installed engine power, smaller water depths only allow the use of reduced engine power. It is for these reasons and also due to hydraulic factors, especially in the critical ship speed range, that the ship speeds indicated below have to be reduced if the water is shallower. As a rule each vessel is unique, frequently undergoing conversions during its life cycle. Some vessels may therefore not be in conformity with the vessel types specified below.

Inland navigation vessel, Peniche class [photo: Juan, Remi]



Motor vessel, Gustav Königs – Class III (with dry cargo) [photo: Liebthal, pixelio.de]

Peniche – Class I according to the classification of inland waterways

Operation range: Rhine, German network of canals, waterways in France, Belgium and the Netherlands

Length	m	37.5 - 38.5	
Beam	m	4.8 - 5.0	
Draught	m	1.8 - 2.5	
Deadweight	t	250 - 365	
Water depth	m	3.0	5.0
Speed	km/h	10	12

Propulsion and steering:
Single screw with 1.0 to 1.1 m diameter and 1 rudder blade, installed engine power approximately 200 kW

Gustav Königs – Class III

Operation range: Rhine, Weser, and Elbe rivers, German network of canals, eastern network of canals, waterways in Belgium and the Netherlands

Length	m	67.0 - 85.0	
Beam	m	8.2	
Draught	m	2.1 - 2.8	
Deadweight	t	749 - 1,300	
Water depth	m	3.0	5.0
Speed	km/h	14	16

Propulsion and steering:
Single screw with 1.2 to 1.5 m diameter and 1 or 2 rudder blades, installed engine power approx. 580 kW

Container vessel with 60 - 90 TEU [photo: Jan v. Bröckel, pixelio.de]

Inland navigation vessel, Johann Welker class with dry cargo [photo: Jan v. Bröckel, pixelio.de]

Motor tank vessel [photo: Jaegers shipping company]

Johann Welker – Class IV

Operation range: Rhine, Danube, Weser, and Elbe rivers, German network of canals, waterways in Belgium and the Netherlands

Length	m	80.0 - 105.0	
Beam	m	9.5	
Draught	m	2.5 - 3.0	
Deadweight	t	1,295 - 2,000	
Water depth	m	3.0	5.0
Speed	km/h	15	18

Propulsion and steering:
One or two ducted propeller(s) with 1.3 to 1.6 m diameter and 1 or 2 rudder blades per propeller; bow thruster. Installed engine power of the main propulsion unit approx. 750 kW

Tanker – Class IV [photo: Bernd Sterzl, Fotolia]

Container vessel with 180 - 216 TEU
[photo: Irina Fischer, Fotolia]

Large motor vessel (with dry cargo) [BDB e. V.]

GMS (large motor vessel) – Class Va

Operation range: Rhine and Danube rivers, North German network of canals, waterways in the Netherlands and Belgium

Length	m	85.0 - 110.0	
Beam	m	10.4 - 11.45	
Draught	m	2.7 - 3.2	
Deadweight	t	1,660 - 2,900	
Water depth	m	3.0	5.0
Speed	km/h	15	18

Propulsion and steering:
One or two ducted propeller(s) with 1.6 to 1.8 m diameter and 1 or 2 rudder blades per propeller; bow thruster. Installed engine power of the main propulsion unit up to approx. 2,000 kW

135 m long tanker [photo: Jaegers shipping company]

Rhine and Danube ships – Class Vb (length-extended GMS / üGMS)

Operation range: Rhine and Danube rivers, some canals in North-West Germany, waterways in Belgium and the Netherlands

Length	m	110.0 - 135.0	
Beam	m	11.45	
Draught	m	2.8 - 3.7	
Deadweight	t	2,720 - 3,500	
Water depth	m	3.0	5.0
Speed	km/h	15	18

Propulsion and steering:
Two ducted propellers with 1.6 to 1.8 m diameter and 2 rudder blades per propeller; 2 bow thrusters. Installed engine power of the main propulsion unit approx. 2,000 kW

Canal-going extra-long large motor vessel
[photo: Klaas Hartz, pixelio.de]

Extended motor vessel (üGMS) with wide beam
[photo: BDB e. V.]

Rhine ships Jowi class – Class Vb (length- and beam-extended GMS)

Operation range: Rhine

Length	m	110.0 - 135.0	
Beam	m	13.0 - 17.5	
Draught	m	2.8 - 4.0	
Deadweight	t	2,590 - 8,400	
Water depth	m	3.0	5.0
Speed	km/h	14	16

Propulsion and steering:
Two or three ducted propellers with 1.6 to 1.8 m diameter and 1 or 2 rudder blades per propeller; 2 bow thrusters. Installed engine power of the main propulsion unit approx. 3,000 kW

Class Vb: Push-tow unit – breasted-up formation
[photo: DTG eG]

Push-tow unit (convoy), motor vessel pushing one barge – Class Vb

Operation range: Rhine and Danube rivers, network of canals in North-West Germany, waterways in Belgium, the Netherlands, etc.

Length	m	185.0 - 190.0	
Beam	m	11.45	
Draught	m	2.8 - 3.7	
Deadweight	t	3,740 - 5,200	
Water depth	m	3.0	5.0
Speed	km/h	13	16

Propulsion and steering:
Two ducted propellers with 1.6 to 1.8 m diameter and 2 rudder blades per propeller; 2 bow thrusters. Installed engine power of the main propulsion unit approx. 2,000 kW.

Breasted-up formation [photo: DTG eG]

Push-tow unit, motor vessel with three barges – Class VIa

Operation range: Rhine

Length	m	185.0	
Beam	m	22.9	
Draught	m	2.8 - 3.7	
Deadweight	t	7,920 - 10,500	
Water depth	m	3.0	5.0
Speed	km/h	12	14

Propulsion and steering:
Two or three ducted propellers with 1.6 to 1.8 m diameter and 1 or 2 rudder blades per propeller; 2 bow thrusters; installed engine power of the main propulsion unit approx. 2,800 kW.

Pushed convoy – four barges [photo: Rhenus PartnerShip GmbH]

Push-tow unit, pusher with four barges – Class VIb

Operation range: Rhine, Danube, and Schelde rivers

Length	m	185.0 - 195.0	
Beam	m	22.9	
Draught	m	2.8 - 4.0	
Deadweight	t	7,650 - 11,000	
Water depth	m	3.0	5.0
Speed	km/h	12	14

Propulsion and steering:
Two ducted propellers with 1.6 to 1.8 m diameter and 2 rudder blades per propeller; 1 or 2 bow thrusters or a flanking rudder; installed engine power of the main propulsion unit approx. 3,400 kW.

Pushed convoy [photo: Imperial Shipping Holding GmbH]

Push-tow unit, push boat with six barges – Class VIc

Operation range: Rhine and Danube rivers

Length	m	270.0	
Beam	m	22.8	
Draught	m	2.8 - 4.0	
Deadweight	t	11,500 - 17,000	
Water depth	m	3.0	5.0
Speed	km/h	11	13

Propulsion and steering:
Two or three ducted propellers with 1.8 to 2.0 m diameter and 2 rudder blades per propeller; 1 or 2 bow thrusters or a flanking rudder; installed engine power of the main propulsion unit approx. 4,500 kW.

Tug [photo: Gerd Frick, MarineTraffic.com]

Tug – Class I

Operation range: Schelde, Rhine, Danube, Weser and Elbe rivers

Length	m	20.0 - 25.0	
Beam	m	7.0-9.0	
Draught	m	1.3 - 2.5	
Water depth	m	3.0	5.0
Speed	km/h	13	14

Propulsion and steering:
Two ducted propellers with 1.6 to 1.8 m diameter and 2 rudder blades per propeller, 1 bow thruster; installed engine power of the main propulsion unit approx. 10,00 kW.

Class VIb: River cruise ship [photo: Ralf Gosch, Fotolia]

River cruise ship – Class VIb

Operation range: Rhine, Danube, Weser, and Elbe rivers, waterways in the Netherlands and Western Germany

Length	m	80.0 - 135.0	
Beam	m	11.4 - 22.9	
Draught	m	1.0 - 1.8	
Water depth	m	3.0	5.0
Speed	km/h	15	18

Propulsion and steering:
Two or three ducted propellers with 1.6 to 1.8 m diameter and 1 or 2 rudder blades per propeller; 2 bow thrusters; installed engine power of the main propulsion units approx. 1,200 kW.

Class VIb: Passenger boat [photo: BDB e. V.]

Passenger boat – Class VIb (for day trips and events)

Operation range: Rhine

Length	m	80.0 - 135.0	
Beam	m	Max. 22.9	
Draught	m	2.0	
Water depth	m	3.0	5.0
Speed	km/h	16	19

Propulsion and steering:
Two or three ducted propellers with 1.6 to 1.8 m diameter and 1 or 2 rudder blades per propeller; 1 bow thruster; installed engine power of the main propulsion unit approx. 1,400 kW.

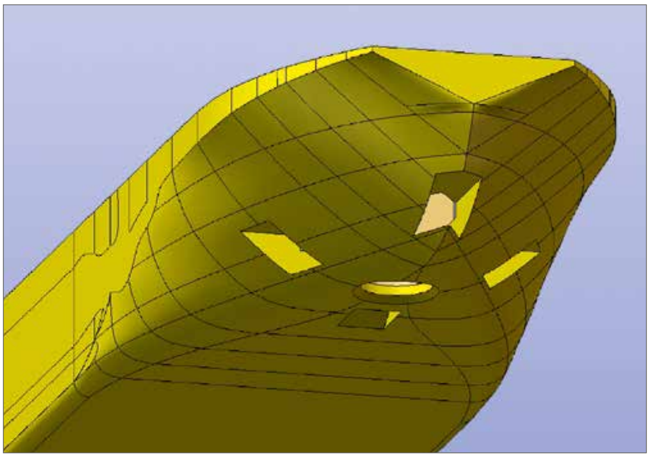


Fig. 2.2-1: Bow with V-shaped frame and transverse thruster [DST]

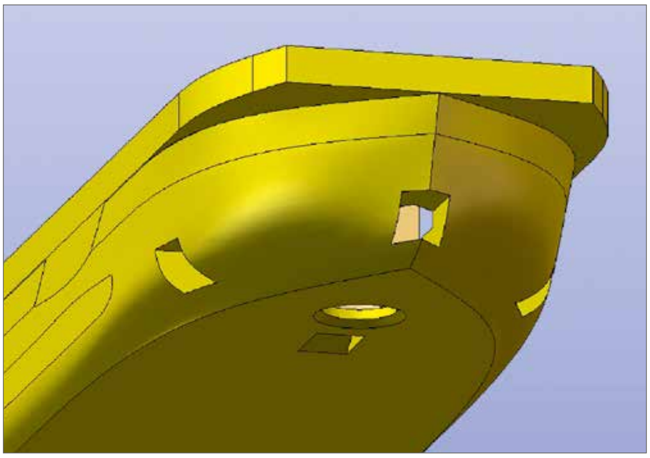


Fig. 2.2-2: Bow with U-shaped frame and transverse thruster [DST]

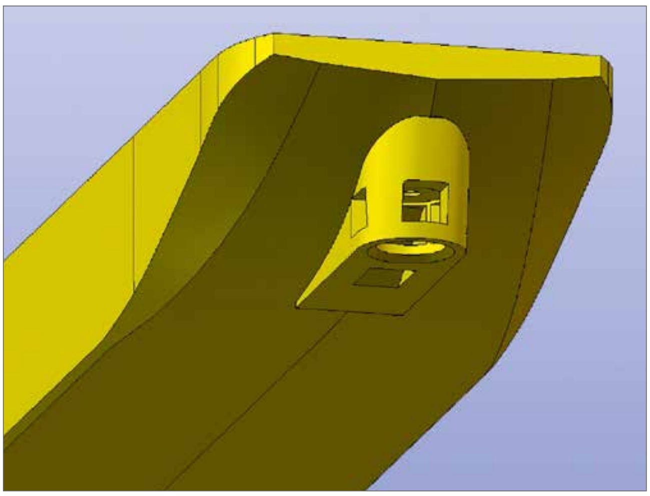


Fig. 2.2-3: Wedge-shaped bow with bow thruster [DST]

2.2 Vessel hull form and construction

Although the waterway infrastructure has been significantly improved by hydraulic engineering works, the different zones of operation are characterised by differing requirements regarding the vessel hull form as well as the propulsion and manoeuvring systems. Sailing in a canal, for instance, requires only little propelling power but high manoeuvrability. On the other hand, a ship travelling on the Rhine needs an optimised hull form, a relatively high propelling power and appropriate manoeuvrability. Moreover, its deadweight tonnage must be high.

There is no vessel shape that meets all of these requirements, which is why a vessel's hull form is designed to fit the respective zone of operation in which the ship is most likely to navigate most often. When sailing in other operation areas, the vessel's hydrodynamic properties and profitability of operation will be affected.

This is the fundamental basis on which decisions have to be made regarding the:

- Shape of the bow,
- Shape of the aft-ship,
- Moulded depth,
- Type of the propulsion system,
- Number of propulsion devices or number of propellers,
- Type of manoeuvring system (single-, twin- or triple-blade rudder) and
- Transverse thrusters (bow thruster, stern thruster, bow rudder).

Bow shape and bow thruster

On ships navigating in rivers with higher flow velocities, V-shaped frames are frequently used for the bow. Figure 2.2-1 shows this bow shape combined with a transverse thruster.

In contrast to V-shaped bow frames, U-shaped frames lead to a higher displacement and consequently a higher deadweight tonnage if the stern shape and the main dimensions are the same. If ship dimensions and ship speed are identical, a ship with a U-shaped frame tends to need a somewhat

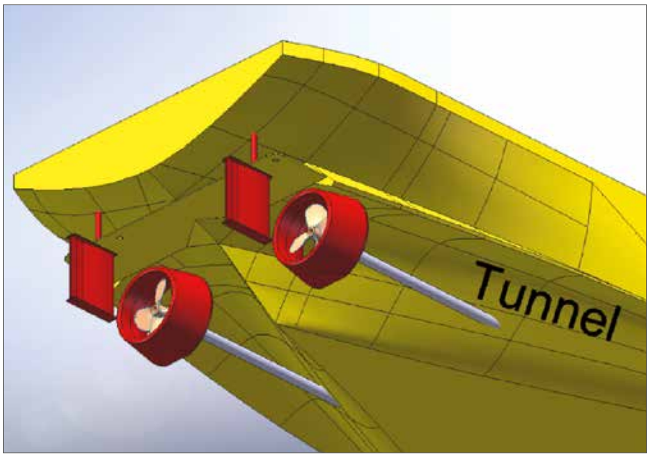


Fig. 2.2-4: Aft-ship with tunnel and two screws [DST]

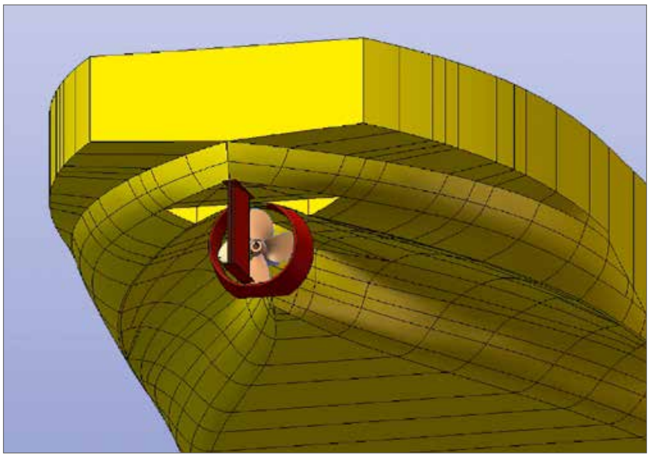


Fig. 2.2-5: Single-propeller system with single-blade rudder system [DST]

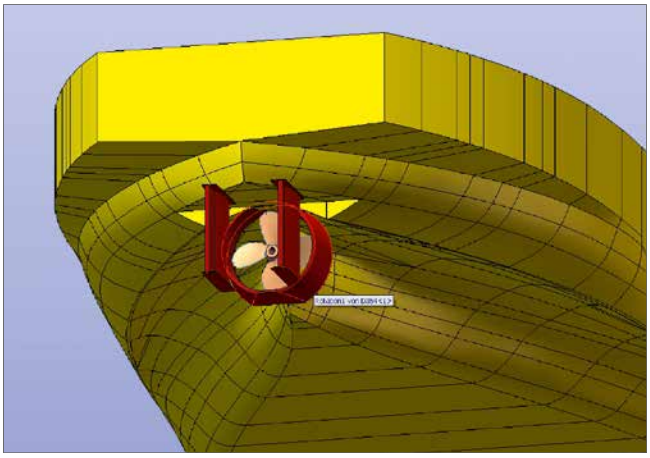


Fig. 2.2-6: Single-propeller system with twin-blade rudder system [DST]

higher drive power than a ship with a V-shaped frame. Hence, when choosing the bow shape, a crucial factor is whether the priority is to minimise fuel consumption or to maximise deadweight tonnage. Figure 2.2-2 shows a bow with a U-shaped frame and transverse thruster.

Figure 2.2-3 shows a wedge-shaped bow fitted with a bow thruster in an attached gondola. The wedge-shaped bow is mainly used for pushed barges. This relatively simply construction will sometimes also be used for motor vessels with the aim of reducing construction costs. The displacement is higher with a wedge-shaped bow than with V- or U-shaped frames, but more drive power is needed to achieve the same ship speed. The bow thruster depicted in Fig. 2.2-3 is a four-channel system which provides thrust through 360 degrees.

Aft-ship shape, number of propellers and steering systems

The construction of the stern of an inland navigation vessel typically is dominated by one or several so-called tunnels (see Fig. 2.2-4) which are located above the propeller(s). The function of these tunnels is to ensure that the propulsion process is not disturbed by the inclusion of air into the afflux to the propeller, coming from the water surface when the vessel is only partly laden or sailing without cargo. If there is significant air ingress into the propulsion system, the propeller thrust is reduced or in some cases even entirely interrupted. Without the use of tunnels, the propeller would have to be designed with a smaller diameter and lower propulsion efficiency. Another option would be to increase the draught by using ballast water.

Today, all new inland navigation vessels have ducted propellers with a nozzle. Propellers without nozzles can only transmit limited thrust loads with acceptable efficiency. A ducted propeller with nozzle, on the other hand, enables higher thrust loads to be transmitted at better efficiencies. In the following only stern types designed for ducted propellers are considered.

Most inland vessels use a single or twin-propeller system. Compared to the twin propeller system, a single propeller unit (see Figs. 2.2-5 and 2.2-6) allows a more streamlined underwater body and thus needs less drive power to reach

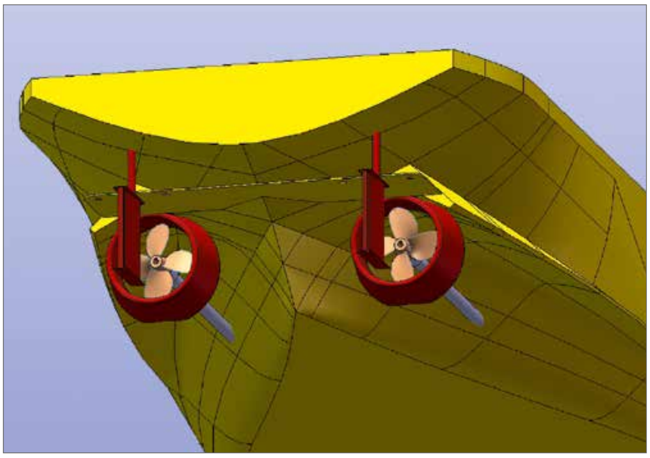


Fig. 2.2-7: Twin-propeller system with single-blade rudder system [DST]

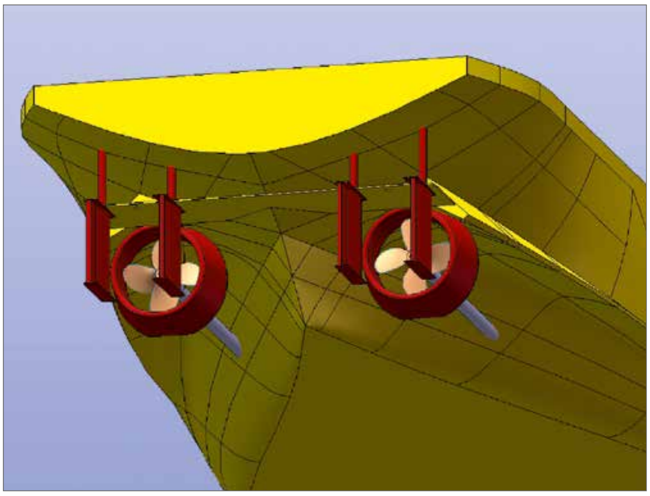


Fig. 2.2-8: Twin-propeller system with twin-blade rudder system [DST]

the same speed. Assuming the same fore body shape, the displacement and consequently the deadweight tonnage of a ship with a single-propeller system are lower than that of a vessel with twin-propellers. Single-blade and twin-blade rudders are used in both systems. The hydrodynamic properties of the single-blade rudder are better when the vessel is in forward motion because less drive power is generally required for the same speed. However, the twin-blade rudder fulfils higher manoeuvring requirements.

If the thrust loads are very high, twin-propeller systems are used (see Figs. 2.2-7 and 2.2-8). Twin-propeller systems can also be used in push boats for units with one, two or more barges. Moreover, the twin-propeller drive recommends itself in navigation zones with low water levels and/or low fairway depths where vessels cannot be laden with the maximum draught, but only with partial loads, and the propeller diameters must be relatively small. To ensure that there is nevertheless sufficient thrust for a vessel carrying maximum load, two propellers are used.

A triple-propeller system is rarely used on inland navigation vessels with the exception of pushers. It is found in some vessels with a beam exceeding 15 m. Pushers with a beam of more than 12 m and high thrust load are fitted with either three or four propellers. Which of the two systems is chosen is based on the same reasons as the choice between single- and twin-propellers.

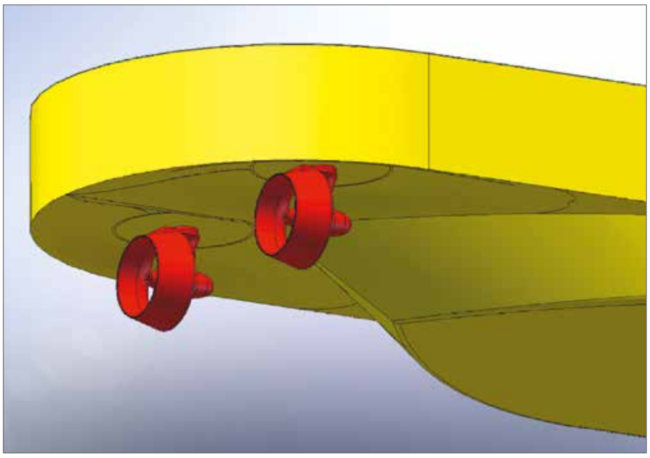


Fig. 2.2-9: Rudder propeller [DST]

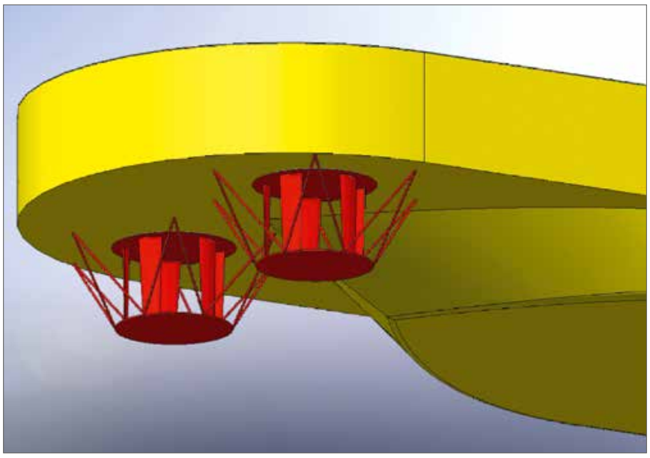


Fig. 2.2-10: Vane-screw propeller [DST]

Selection of the propulsion and manoeuvring systems

As a rule, large pushers and motor vessels have a main drive using propellers and a separate manoeuvring or steering system. Small pushers used for short distances or harbour operations, tugs and passenger ships are sometimes equipped with a drive having an integrated steering system, hence their high manoeuvrability. The rudder propellers used (see Fig.2.2-9) can be turned horizontally by 360° and all of the thrust produced by the system can be used to generate transversal force. The rudder propellers can be either with or without nozzles. Their number depends on the thrust and manoeuvrability required for the respective type of operation. Vane-screw propellers are mainly used for passenger ships and for port service or harbour tugs (Fig. 2.2-10). The propeller can provide 360° directional control by adjusting the blade angle.

2.3 Propulsion and steering devices

2.3.1 Ship propellers

To accelerate a vessel from rest a certain force is required. This force is the thrust which is generated primarily by the ship's main drive, the propeller (or screw). The propeller is acting as a pump which produces an accelerated water jet in a particular direction. The thrust is the reaction force against the water jet and directed in the opposite direction of the jet.

The magnitude of the thrust force depends on two factors: the volume of water which is accelerated by the propeller within a specific time and the difference between the flow velocity upstream and downstream of the propeller.

Propellers are often distinguished according to their profile. The profile is created in systematic test series in which geometric parameters are systematically varied. The most commonly used free turning propeller (without a nozzle) is the Wageningen propeller in the so-called B series. Kaplan and skew propellers are the most important ducted propellers that have proven their superiority for inland navigation with its high degrees of thrust load. However, new profiles for propellers and nozzles continue to be developed with the aim of increasing efficiency, reducing the noise and the energy consumption of propulsion devices.

In the following a distinction is made between the different propeller types according to their basic design characteristics. Water jet propulsion is mentioned as an alternative drive system.

Fixed pitch propeller

The fixed pitch propeller is the type most commonly used in inland waterway transport (Figures 2.3.1-1 and 2.3.1-2). The drive power of one propeller is between 200 and 10,00 kW depending on its diameter and turning speed. Multi-propeller drive systems are used as a rule to increase drive power.

Fig. 2.3.1-1.: Propeller without nozzle [DST]

Fig. 2.3.1-2: Propeller with nozzle [DST]

The thrust direction is changed either via a reversible engine or with a reversing gear. The thrust and thus the speed can be increased by augmenting the number of propeller revolutions.

Generally, if the propeller diameter is increased whereas the drive power remains unchanged, the input energy (fuel) is used more efficiently. However, for practical reasons the propeller diameter can only be increased up to a specific limit on inland navigation vessels because of their shallow draught. To avoid ingress of air, the diameter generally must not be much larger than the ship's draught and to avoid contact with the waterway bed, the propeller must not project beyond the ship's bottom.

To increase the propeller diameter as much as possible, a tunnel is installed on most inland navigation vessels to enable a propeller design with a diameter larger than the minimum draught. But, as has been mentioned above, this increase is limited to avoid ingress of air into the tunnel since this will significantly reduce the thrust effect. If the propeller diameter is too large, the risk of air ingress and the resulting loss of drive power are especially high for a vessel without cargo undertaking a stopping manoeuvre. As mentioned earlier, it is possible to mitigate this risk by loading ballast water in order to increase the draught.

A fixed pitch propeller is installed either as a free turning wheel or as a propeller inside a nozzle. The latter is chosen especially for propulsion units of slowly sailing vessels with high requirements regarding thrust, such as tugs, pushers and pushed convoys, but also self-propelled vessels which require a high level of thrust force. In comparison to free wheels, the effective thrust, that means both the thrust of the propeller blades and of the nozzle, is about 20 % greater. However, due to air intrusion problems the required propeller immersion is greater with a ducted propeller than with a free turning propeller. Since ship speeds are generally lower in inland waterways than at sea and moreover the approach flow conditions are negatively affected by shallow water, ducted propellers have become the norm. Free turning wheels are mostly found in recreational boats, due, amongst other things, to their greater resilience regarding contact with the bed and because a nozzle would not offer any hydro-mechanical advantages for ships sailing at high speeds.

Hydraulic propeller efficiency rates, i.e. the relation of usable thrust power to the engine power at the propeller shaft, can reach up to 60 % at the design point. However, inland vessels operate seldom at the design point. The ship may sometimes be part of a pushed convoy. It may be navigating at different speeds, especially speeds lower than the design point, or in large or small water depths. It may be sailing without cargo or fully laden and it may be navigating in a canal or in shallow water, upstream or downstream. Hence, there often is a considerable difference between the operating point and the design point, and the efficiency rate is frequently only about 0.4.

Moreover, the rigid coupling of the propellers to the propulsion engine (with or without a gear) means that the engine often has to be operated at speeds which are not optimal, e.g. too low. As a result, the ship's engine operates often far away from the design point. Thus, the engine efficiency is reduced and the specific fuel consumption is increased compared to the design point. It follows from this that the propellers and the engine must be perceived as one unit. The disadvantages mentioned above can be offset by using diesel electronic drives, multi-propeller systems or variable tunnel geometries. In view of the cost of such investments it is difficult to foresee whether such solutions will be viable in practice.

Variable pitch propeller

The variable pitch propeller (Fig. 2.3.1-3) works in the same way as the fixed pitch propeller, except that the pitch of the blades can be varied continuously. This means that e.g. a constant engine and/or shaft speed can be maintained while changing the thrust, also during stopping manoeuvres. This helps to increase the engine efficiency by sailing with an optimal rotational speed. But also the hydraulic efficiency can be improved compared to a fixed propeller if the pitch is always properly adapted to the different operating conditions. In all cases when the ship speed is not at the design point, a variable pitch propeller has better efficiency than a fixed propeller.

However, the hydraulic efficiency of a variable pitch propeller is not far away from that of a fixed propeller, even in the case of optimal pitch adaption, and equals that of a fixed pitch propeller at the design point only because the geometry of the blades is sometimes less favourable. Variable pitch propellers are therefore mainly employed in deep water conditions, i.e. in maritime navigation.

The variable pitch propeller has not become established as a standard in inland navigation. This is probably due to the construction costs, which are considerable in comparison to a fixed pitch propeller. Moreover, the maintenance costs are relatively high when sailing in shallow water and close to the banks (touching the ground) as well as in the event of ice drift or, for that matter, damage from debris at flood levels.

Fig. 2.3.1-3: Variable pitch propeller [SCHOTTEL]

Rudder propeller

The rudder propeller is a so-called Z drive (Fig. 2.3.1-4). It is possible to turn the propeller by 360°, i.e. over the entire horizontal plane. The rudder propeller, also referred to as a Schottel rudder propeller (SRP) after the manufacturer who first invented it, thus simultaneously serves as the main rudder. It is mainly used in craft with particularly high manoeuvrability requirements.

Fig. 2.3.1-4: Rudder propeller [SCHOTTEL]

Cycloidal propeller

This propeller which is also known as a Voith-Schneider propeller (Fig. 2.3.1-5) after the engineer and manufacturer features an array of vertical blades mounted on a rotating circular disc. The pitch of the blades is controlled by an eccentric gear. The thrust is not adjusted by changing the number of revolutions but by altering the eccentricity (pitch) of the propeller. With a cycloidal propeller, the thrust direction can be varied by 360° over the horizontal plane. It is the preferred choice for craft with a constant draught that require high manoeuvrability, e.g. passenger ships or harbour tugs (so-called water tractors). It is also typically used as a bow thruster in pushed convoys.

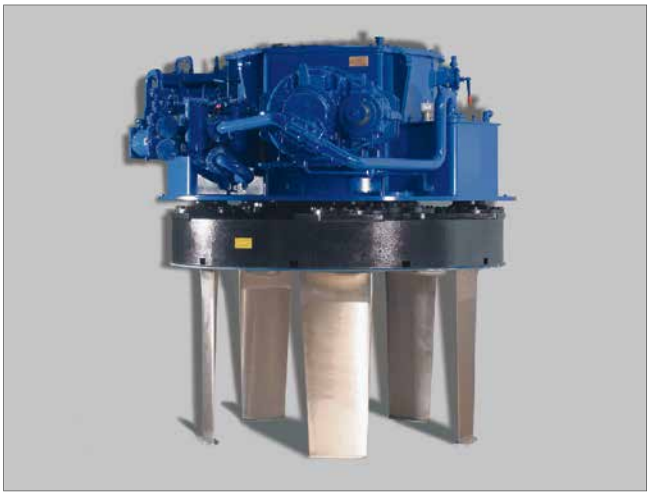


Fig. 2.3.1-5: Cycloidal propeller [Voith AG, Heidenheim]

Pod-drives

The propeller is mounted on a gondola (also referred to as pod drive) with an electric motor that actuates the propeller. The complete drive system is housed in a streamlined gondola (the pod) mounted to the bottom of the ship. As a rule,

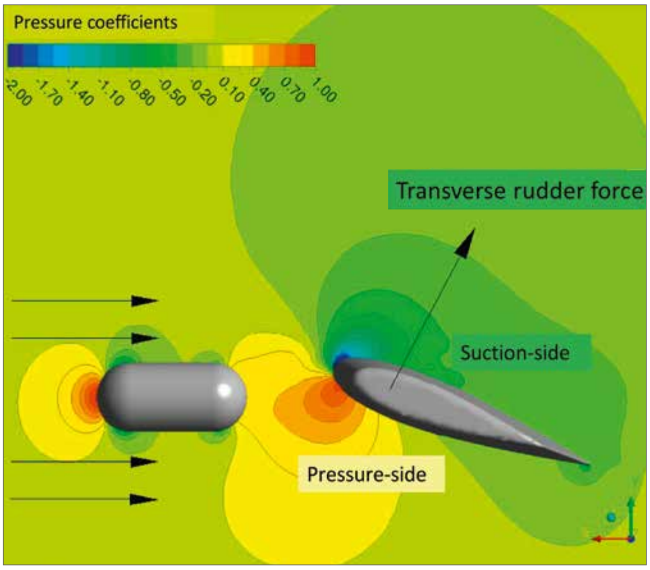


Fig. 2.3.2-1: Rudder action [DST]

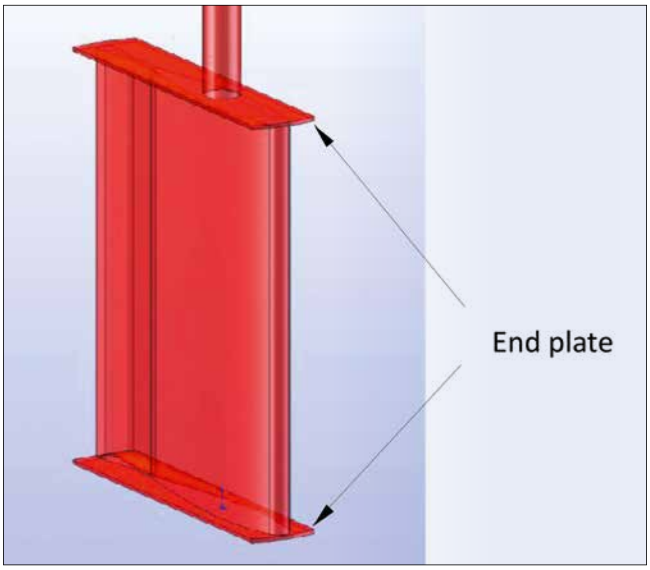


Fig. 2.3.2-2: Rudder blade with end plates [DST]

these propellers combine driving and steering functions, i.e. the thrust can be directed by rotating the pod system (Azi-Pod = Azimuthing Electric Propulsion Drive), in the same way as with a rudder propeller (azimuthing propeller). The vessel can thus change course without needing a conventional rudder. Pod drives use one or two propellers which can be co- or counter-rotating. The use of "podded drives" on inland navigation vessels as an alternative to a combination of propellers and rudders has already been discussed in various research and demonstration projects. In particular, pod drives are increasingly used in passenger ships.

Water-jet propulsion

Water-jet propulsion (also referred to as pump jet, hydro-jet or jet propulsion) offers an alternative to propeller drives. High-speed, lightweight petrol or diesel engines or gas turbines drive an impeller (enclosed propeller), which sucks in water underneath the hull and pumps it out at the stern via movable nozzles. Compared to conventional propeller drives, water-jet propulsion offers many advantages in shallow water, for example the fact that no rudder or rudder drive is needed. The great drawback, however, is that the propulsion performance is significantly lower than if propellers were used; the power requirement consequently is 20 to 40 % higher. At present, water-jet propulsion is primarily used for high-speed ferries, special ships and rescue units.

2.3.2 Stern rudders

The main rudders are located behind the propulsion units and create a high transverse force due to a higher speed of approach which results from the propellers' slipstream. The flow around the rudder creates the rudder action and/or the transverse rudder force. If the rudder is held at zero (neutral position), there is an almost symmetric flow around the rudder and the transverse forces in port direction and starboard direction approximately cancel each other out. Figure 2.3.2-1 illustrates the flow field, the pressure distribution and the forces acting on a typical rudder.

If the rudder is turned (Fig. 2.3.2-1 shows a rudder angle to portside) pressure is created on its inner side, while an even greater suction effect is produced on its outer side. Therefore the afterbody of the craft moves to starboard and the fore body to port. The transverse rudder forces increase generally from the neutral position with increasing rudder angles, but only up to approximately 35° if a single rudder is used and up to 45° if twin rudders are used. The longitudinal rudder forces towing on the rudder in the backward direction also increase which, in turn, causes the ship resistance to increase. Greater rudder angles mainly result in pressure

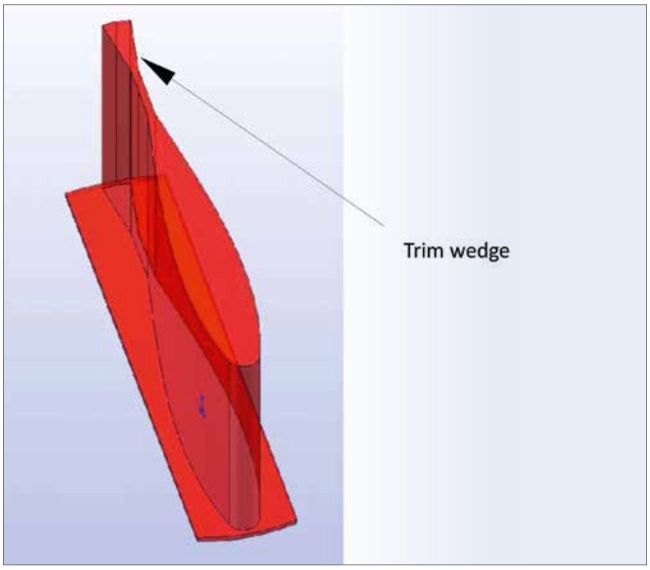


Fig. 2.3.2-3: Rudder profiles with trim wedges [DST]

forces, but not suction forces, acting on the rudder since the flow on the suction side separates from the rudder blade. Thus, the crosswise rudder forces decrease and the drag forces increase with higher rudder angles. Hence, whenever a change of rudder angle occurs, the speed of the sailing ship decreases, and the greater the angle of the rudder, the greater the reduction of speed. Hence, when in forward motion, greater rudder angles should be avoided.

It is possible to increase the rudder forces by reducing the pressure compensation between the suction and pressure sides. To this end, so-called end plates can be mounted to the rudder's top and bottom edges (see Fig. 2.3.2-2).

Trim wedges at the aft end of the rudder cause the pressure centre to shift aft and the transverse rudder force to increase. However, this also leads to an increase of the rudder's inherent resistance (see Fig. 2.3.2-3).

Single-blade rudders

As a rule, single-blade rudders (Fig. 2.3.2-4) have the lowest inherent resistance. They are located in line of the propeller axis, thus reducing the losses due to swirl in the propeller wash. When the propeller is not rotating, a single-blade rudder has only little effect because the approach flow is disturbed and there is no propeller wash.

Flap rudders

Flap rudders (Fig. 2.3.2-5) are special single-blade rudders generating greater transverse rudder forces at relatively small rudder angles. This type of rudder has an articulated flap mounted to the aft edge of the main rudder blade. Since the flap angle is greater than the angle of the main rudder blade which is connected ahead of the flap, the transverse force produced by a flap rudder generates an additional rudder force. The rudder angle/flap angle ratio is fixed.

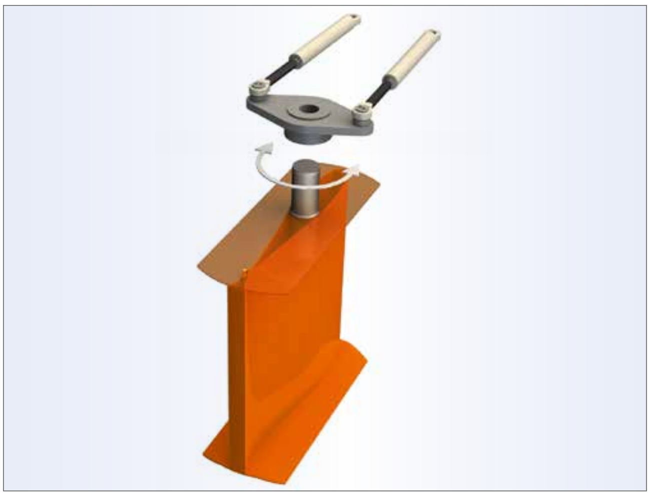


Fig. 2.3.2-4: Single-blade rudder [DST]

Fig. 2.3.2-5: Flap rudder [DST]

Fig. 2.3.2-6: Twin-blade rudders [DST]

Fig. 2.3.2-7: Triple-blade rudder, Hitzler system [DST]

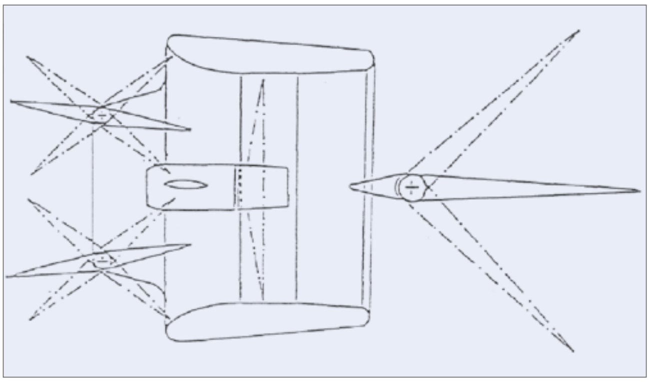


Fig. 2.3.2-8: Flanking rudder (left), location in front of the nozzle [VBW]

Twin-blade rudders

Normally the inherent resistance of twin-blade rudders is greater than that of single-blade rudders. They are used if there is not enough room in the afterbody to provide the required blade area of a single rudder. Twin-blade rudders (Fig. 2.3.2-6) offer better steering properties at low ship speeds when the propellers are not rotating, for example when entering locks. Moreover, greater rudder angles are possible before the rudder stalls. There are two factors contributing to rudder action here: the hydrofoil effect which is dominant in single-blade rudders and the deflection of the propeller jet generating corresponding transverse forces. Hence, the possible transverse rudder forces are often greater by a factor of more than two than the transverse forces of a single-blade rudder.

Multi-blade rudders

In the past, triple- or multi-blade rudders like the "Hitzler rudder" and the "Schilling rudder" were used, and these so-called high-performance rudders were to improve the manoeuvrability at slow speed of ships with simple flat plate rudders and low drive power. Given the drawbacks of multi-blades rudders, such as their sensitivity to external influences in particular at low water, the often long repair times associated with higher costs as well as the generally higher inherent resistance compared to single- and twin-blade rudders, the trend towards more multi-blade rudder installations did not continue. Today, these systems are only found on the older vessel types (see Fig. 2.3.2-7).

Flanking rudders

Flanking rudders are positioned forward of the propeller, in addition to the main rudder. They are exclusively used in push boats which require excellent manoeuvrability also when driving backwards (coupling manoeuvre, bow downstream; Fig. 2.3.2-8).

When the ship is making headway, flanking rudders can reduce the thrust because they disturb the free flow of water to the propeller. As a result, in more recent designs one or two transverse thrusters in the fore part have been installed

Fig. 2.3.2-9: Push boat (SB), double transverse thruster [DST]

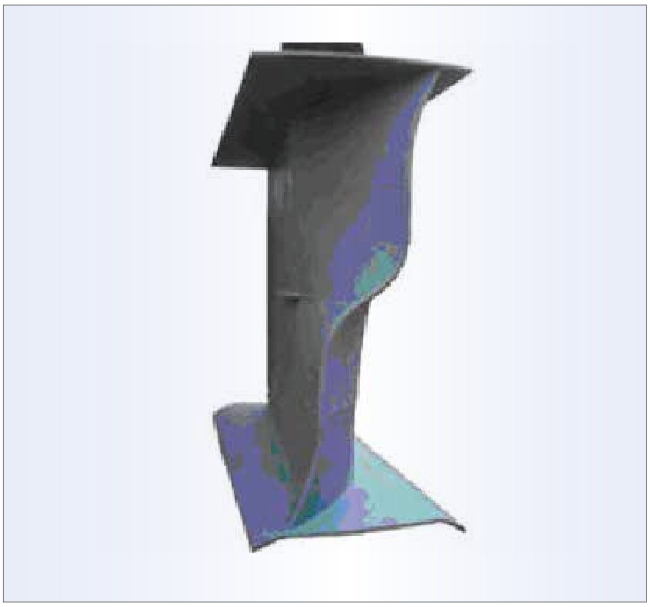


Fig. 2.3.2-10: Propeller-rudder system [source: Van der Velden]

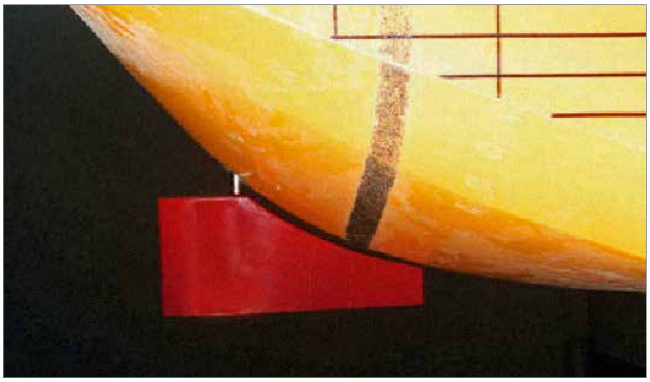


Fig. 2.3.3-1: Passive bow rudder at the pontoon bow of a pushed barge [DST]

instead of flanking rudders. Figure 2.3.2-9 shows a transverse thruster located at the bow of a push boat which has not yet its final operating draught.

Propeller-rudder systems

The so-called propeller-rudder systems are an innovation in rudder technology. They were developed by inland vessel experts working closely together and have already proven their worth on many ships. Propeller-rudder systems feature a special twisted rudder profile with end plates (Fig. 2.3.2-10). It reduces the swirl of the propeller jet stream and thus increases the efficiency of the propeller (greater thrust due to utilisation of the swirl).

2.3.3 Bow rudders

With the size of transport vessels ever increasing, the manoeuvrability requirements of a standing or traveling ship also become more challenging. The requirements are “course keeping” and “course changing”. By complementing the aft manoeuvring systems with steering elements in the bow, manoeuvring operations are facilitated for large vessels in particular, which also contributes to improving navigation safety. Depending on their operation areas, ships are equipped with either active or passive bow rudders.

Passive bow rudders

Passive bow rudders have one or two blades. In most cases rudder angles of up to 45° are possible. The transverse rudder force is exclusively caused by the approach flow against the blades (which equals the vessel speed relative to water and is not increased by the propeller jet stream as in the case of stern rudders), i.e. while the ship is moving (hydrofoil effect). Passive bow rudders are mainly used in pushed convoys. They reduce the swept area width required by ships when navigating bends and provide support during cross wind. This is especially the case with unloaded or container vessels that sail at greater speeds where bow thrusters lose efficiency. At slow ship speed, however, for example during manoeuvres (docking and casting off, passing locks, moving backwards), passive bow rudders are almost ineffective (see Fig. 2.3.3-1).

Fig. 2.3.3-2: Bow thruster with propeller in vertical position. Top left: design with a steering grid that can rotate by 360° [Van Tiem, Druiten, Netherlands]

Active bow rudders (bow thrusters)

Active bow rudders (also transverse thrusters or bow thrusters) are propulsion devices installed in the bow of a vessel. Most bow thruster designs involve a tunnel and an impeller. In contrast to a passive bow rudder, the effect of an active bow rudder decreases with increasing ship speed relative to the water. It has its maximum effect when the ship's speed through the water is nil. Amongst other things the decrease in effect is due to the formation of a low pressure zone behind the bow thruster jet which is due to separation of the approach flow (equals vessel speed through the water). Moreover, the inflow to the impeller is disturbed at the inlet.

Active bow rudders can be distinguished according to the position of the propeller. In most cases a propeller mounted in a horizontal position is fully immersed even when the vessel is without cargo, consequently no air can be sucked in.

If the propeller is mounted in a vertical position, only its lower part is immersed when the vessel is without cargo. To obtain the maximum possible thrust it is therefore necessary to load ballast into the fore body or to de-aerate that part of the bow thruster tunnels that is above the water line with a vacuum pump before operating the thruster (see Fig. 2.3.3-2).

2.4 Coupling system

Different types of coupling technology are used to form pushed convoys consisting of a pusher or a pushing motor vessel and one or several pushed barges. As a rule, the ships are fitted with towing winches for coupling with towing cables.

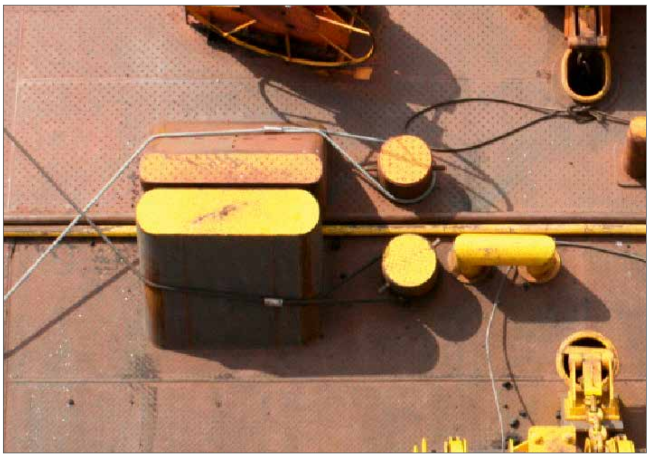


Fig. 2.4-1: Portside coupling system [DST]

Fig. 2.4-2: Side view of a coupling system [DST]

Fig.: 2.4-3 Guide rail [DST]

The towing cables and the coupling system must be designed in such a way that longitudinal and transverse forces as well as any differences between the ships' draughts caused by the deformation of the water surface (encounters, overtaking, waves, etc.) are reliably absorbed and the vessels are coupled as a rigid convoy. For this purpose the cables are aligned both perpendicular and parallel to the ship's motion (see figure). Their breaking force is about 600 kN. Figure 2.4-1 shows the port side of a coupling unit. Figure 2.4-2 provides a side view of the coupling.

There is another type of coupling system where forces are transmitted via an electro-hydraulic mechanism. It is used to form convoys with a motor vessel and a pushed barge. One or two vertical guide rails are installed on the barge (Figure 2.4-3) and the pushing motor vessel is fitted with one or two hydraulic cylinders with locking bars, which engage with the guides when the vessels are coupled. The locking bars can be turned ninety degrees in the guide rails to achieve an interlock both longitudinally and laterally (see Figure 2.4-4). The connection is made via the hydraulic cylinders (see Figure 2.4-5).

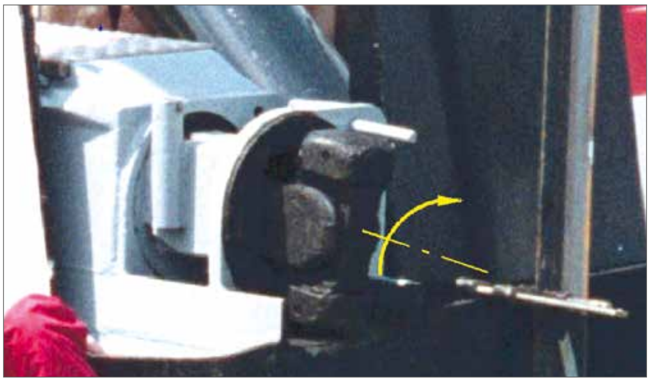


Fig. 2.4-4: Locking bar [DST]

Fig. 2.4-5: Electro-hydraulic coupling [DST]

The electro-hydraulic coupling system can be steered from the helmstand and allows control of the angle between motor ship and barge in front. One hydraulic cylinder is extended while the other secures the coupling position (the two cylinders are interlocked), to compensate the transverse and longitudinal forces. The barge is at an angle to the motor vessel and therefore has the effect of an oversized bow rudder. An articulated coupling enables the pushed convoy to adapt its geometry to the curvature of bends. For this reason, less swept area width is required in bends for a convoy with an articulated coupling than for convoys with rigid couplings. The necessary rudder angles are also smaller, which translates into a reduced loss of speed compared to a rigid convoy.

2.5 Information systems, communication and telematics

Apart from the dynamic aspects of the interaction between inland navigation vessels and waterways, up-to-date information and communication regarding waterways and ship traffic are increasingly important. Information on navigation situations and restrictions (blockings, water depths), for example, has proven valuable for many years and is traditionally broadcast by NIF, the nautical radio information service. New information systems have enlarged the scope of information available for inland navigation.

They include the internet portal ELWIS (ELectronic Waterway Information System) and the Electronic Chart of Waterways according to the inland Electronic Chart Display and Information System (ECDIS) standard, including information about water depths. These charts are the basis for all telematic applications relevant for inland navigation. The aim of the above systems is:

- To provide better, faster and updated information on the state of waterways
- To ensure safer ship traffic and better navigation options
- To optimise the loading capacity of the vessels

The www.elwis.de portal provides continuously updated information on inland navigation, in particular:

- Fairway and traffic related messages of Germany (NfS)
- Notices for seafarers (BfS)
- Hydrological information

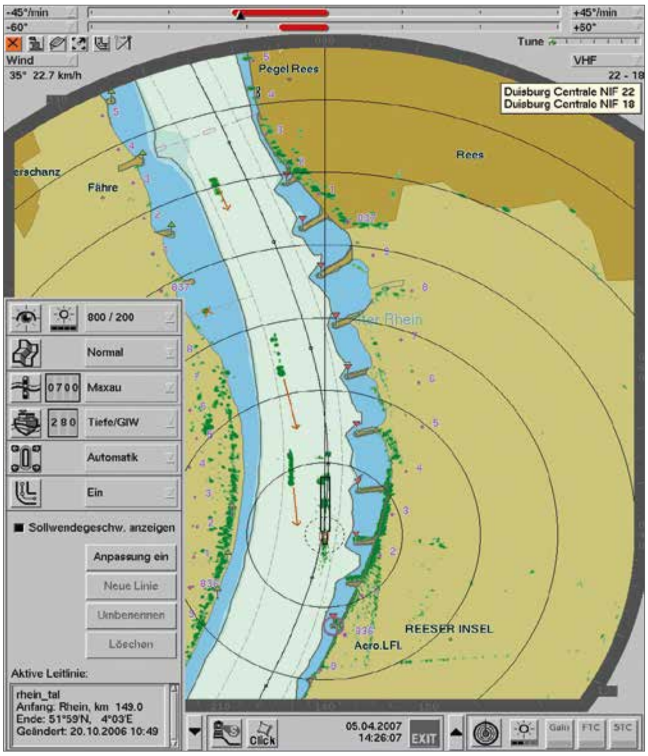


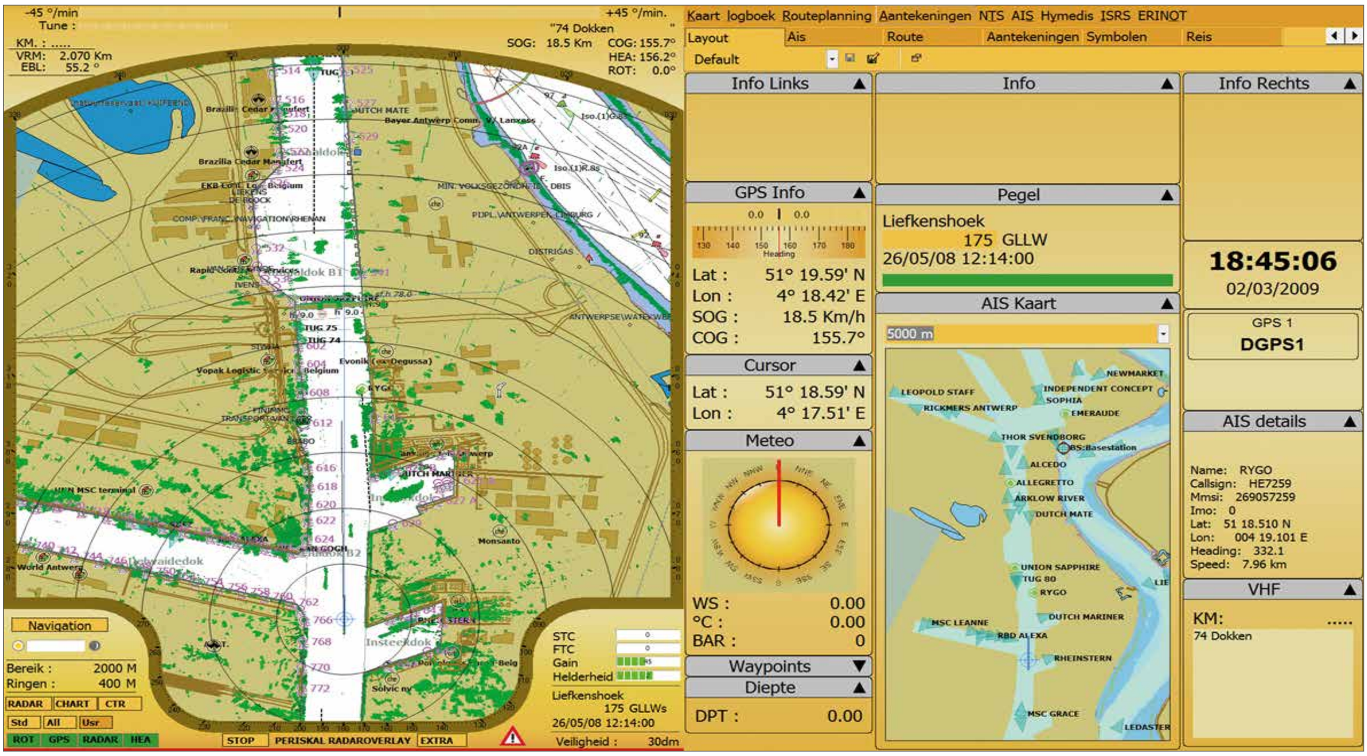
Fig. 2.5-1: Screenshot of Radar Pilot 720° ... [left, photo: innovative navigation GmbH]

- Shipping law / inspection
- Transport-related information
- Data and facts about inland waterways
- Transport statistics
- Recreational navigation
- Addresses and other information

In addition, continuously updated information is provided regarding water levels, temporal blockings of waterways, codes of practice, waterway tolls, etc. It is important for inland navigation and all parties involved in the transport chain, i.e. port operators, transshipment companies, shippers, charterers, forwarding agents, etc. in Germany and in some cases beyond German borders.

Electronic Chart of Waterways and telematic applications

The electronic chart of waterways (Inland ENC (Electronic Navigation Chart) according to the Inland ECDIS Standard provides information about water depths, thus facilitating



… and Periscal Radar Overlay [right, photo: Periskal Group]

navigation on inland waterways and enabling the optimal utilization of cargo capacity. These charts are prepared by the Federal Waterways and Shipping Administration of Germany (WSV). In addition to bank courses, depth information and geo-references the charts also contain attributes (buoys, warning signs, shipping police regulations, etc.).

Future telematics applications in the field of inland navigation will be based on the Inland ECDIS Standard. These applications can be used either in the so-called information mode or in an active mode called navigation mode.

For this purpose a water level calculation model is connected with the system which enables the shipmaster to display the actual depths along the reach considered by using current water levels measured at reference gauges. These data can be retrieved from ELWIS, for example.

Information mode means the use of the Inland ECDIS Standard for information purposes only, i.e. the respective equipment and applications are used without overlaid radar image.

However, it is only in the navigation mode that a significant added value is obtained. Navigation mode means the use of the Inland ECDIS Standard, i.e. of the respective equipment and applications with overlaid radar image when steering the ship. The equipment or applications shall meet the requirements set forth by the Inland ECDIS Standard as well as the provisions applicable to navigation radar equipment and rate of turn indicators. Conformity tests shall be performed.

Examples of equipment and applications for Inland ECDIS in navigation mode are, for instance, RADARpilot 720° and Periskal Radar Overlay. These applications have also been approved as integrated navigation systems.

The main advantages when using the navigation mode are the interlinking and more specifically the presentation of waterway and navigation data: via DGPS the shipmaster can overlay the ship's position with up-to-date pictures regarding the position and orientation of other vessels on the electronic chart of waterways (see Fig. 2.5-1). This information is represented both on the chart itself and on the radar image; additional AIS information can also be shown, if necessary.

Based on bathymetric information stored in the Inland ENCs and actual gauge data, the system can display the actual depths in selected bottlenecks, thus enabling the shipmasters to find out optimal routes.

In addition to optimising the economic efficiency of ship operation this means a marked improvement to the safety and ease of navigation due to additional information on the ship-waterway system.

Besides their use as information/navigation systems for inland navigation vessels and/or as automatic identification systems (with AIS transponder) or radar monitoring systems run by traffic control centres, the above-mentioned systems can also serve as route planning/logistics applications or complement existing systems in the forwarding industry.

2.6 Special transport operations and approvals

The division of labour in Europe and across the globe increasingly requires an optimal organization of transportation from producers to consumers. This mainly concerns large and heavy components, e.g. machine and plant parts, bridges, bridge components, wind power plant segments, all types of cranes, accumulators, components for coal, natural gas and nuclear power stations, entire production plants for chemical factories, refineries and boiler plants with unit weights of up to 1800 tons and dimensions reaching 100 m in length, 25 m in width and 10 m in height, depending on the waterway used.

In all of these cases the vessel or hull type best suited to the cargo dimensions must be selected. A standard large motor vessel or pushed barge is often suited to the purpose. In some cases special ships are needed due to requirements regarding draught or vertical clearance under bridges, approvals required for the waterway and/or regulations issued by the waterway authorities. Hence, the issue of ship dynamics is not a priority, even though it always plays a role in transport planning and cost calculations.

The most common type of special transport on rivers and canals is pontoon hauling. As a rule, ships without a propulsion system are used, i.e. they are moved by push boats and/or

Examples of special transports:

Fig. 2.6-1: Special pontoon with tug and push boat [Heidenstecker]

tugs. For the majority of traditional pontoons, also referred to as deck barges, the length-to-width ratio is different than is the case with inland cargo vessels or pushed barges, meaning they are shorter and wider! Besides providing the stability required (optimum weight distribution) this enlarges the loading area which extends over almost the entire width and length of the pontoon. Moreover, the lower part of the pontoon can be used for water ballast to optimise the trim and manipulate the air draught. The Ro-Ro (Roll-on/Roll-off) pontoon is a special type of pontoon onto or into which a heavy transport object can be rolled by using special trucks (with up to 20 axles). Thus, no loading and unloading for pre- or on-carriage is needed. Furthermore, in certain navigation zones where vertical bridge clearance is not sufficient, additional ballast is useful.

Since specific requirements have to be met in terms of ship dimensions, volume of the goods transported and waterway conditions, special transports often require written approvals by the national waterways and shipping administrations which can be applied for. However, in most cases a report by an officially approved expert documenting the strength and stability of the ship with the specific cargo is a prerequisite for obtaining an approval. Other influences occurring on the transport reach such as wind, high or low water, flow, etc. are taken into account and contained in the approval as conditions. These conditions may stipulate that night navigation is not permitted, or only single-lane traffic is permitted on certain reaches, or they may specify the number of push boats and/or propulsion units to be used, etc. They are based on § 1.21 Rhine Shipping Police Regulations (Rheinschifffahrtspolizeiverordnung) and/or § 1.06 Inland Navigation Regulations (Binnenschifffahrtsstraßen-Ordnung).

With a few exceptions the underwater shape of a pontoon corresponds to a large degree to that of a pushed barge: it is squarer and can therefore move only very slowly against the river's flow direction or needs much power to do so. This negative effect is heightened when the pontoon is laden and has its respective draught. As a result, there is a strong buildup of water at the bow of the pontoon and a strong suction force in the wake behind the stern. Hence, regardless of whether the pontoon is towed or pushed or even both the travelling speeds that can be achieved are low. Nevertheless special transports using inland waterways are often the only alternative available for transporting large and heavy cargo items from and to sea ports or hinterland destinations, also in combination with on-carriage via road and rail.

Fig. 2.6-2: Special transport with additional cargo [Heidenstecker]

3 Infrastructure

3.1 Network of navigable waterways and waterway reaches

The structure of the Western European and German networks of waterways is influenced by the rivers Rhine, Ems, Weser, Elbe and Danube, as well as their tributaries such as the Moselle, Main and Neckar for which extension work has already been completed. In addition, these natural waterways, which mainly run on the North-South axis, are interlinked by canals.

Almost all major industrial regions and cities have their own high-capacity connections to the network of inland waterways (see Figures 3.1-1 and 3.1-2). The large German seaports on the Elbe, Weser and Ems rivers as well as the seaports in the Rhine delta thus have high-capacity links to the hinterland. Moreover, a dense and effective network of canals in Belgium and the Netherlands, which has repeatedly been adapted to new requirements, has complemented the infrastructure for more than a century.

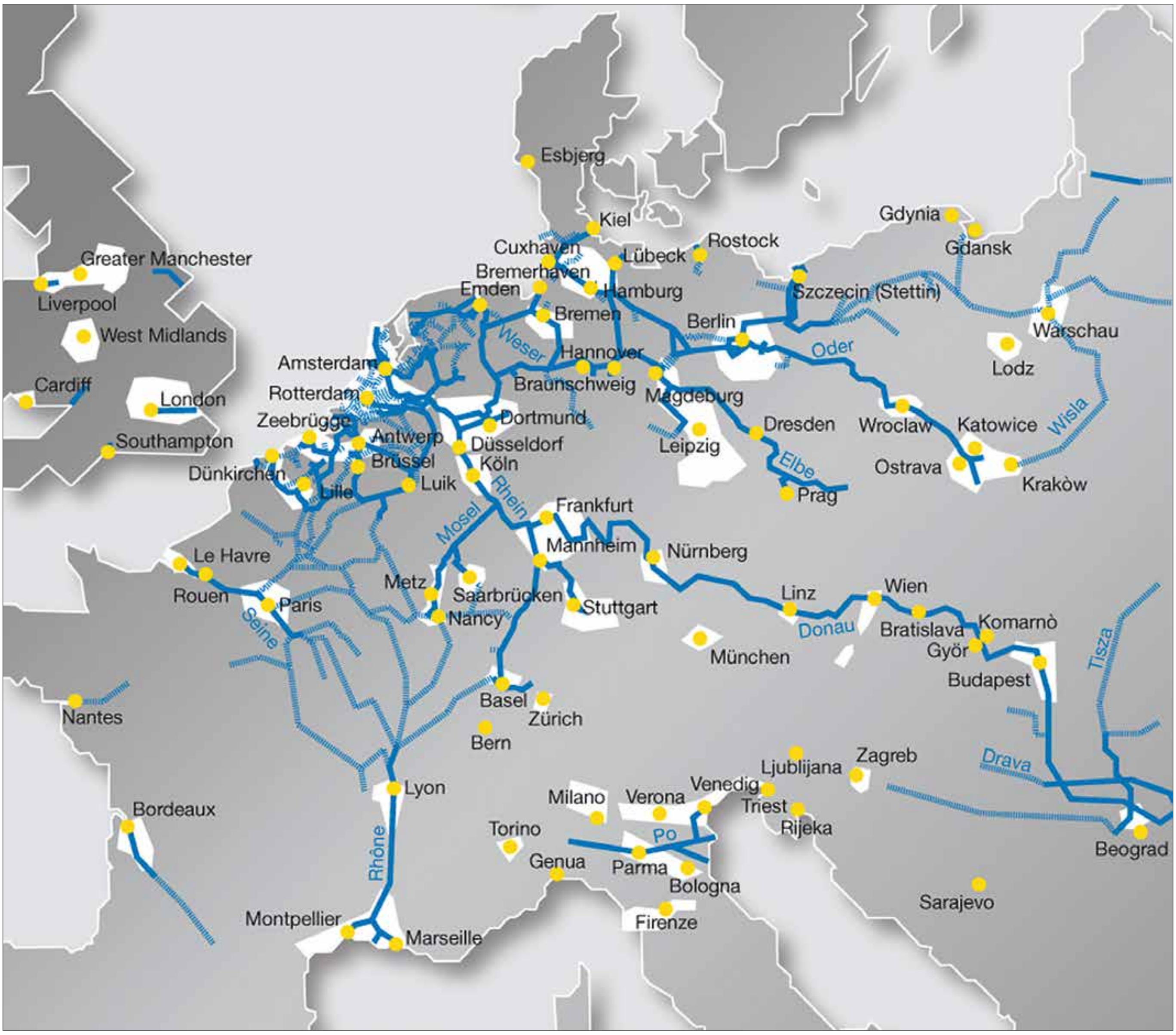


Fig. 3.1-1: Inland waterways in Central Europe [VBW]

Federal Ministry of Transport and Digital Infrastructure

WSV.de

BONN	■ Residence of General-Directorate of Waterway and Shipping (GDWS)		Border between branch officed of the GDWS
MAINZ	▪ Residence of a branch office of GDWS		Not classified inland waterways (BinWaStr)
Bingen	◆ Residence of a Waterway and Shipping Office		CEMT classes I-III
KARLSRUHE	● Residence of a federal technical institute		CEMT classes IV-VI

Fig. 3.1-2: Chart of Germany's federal waterways [BMVBS 2008] with organisation of the Federal Waterways and Shipping Administration

There is a standardised classification of the Western European and German networks of navigable inland waterways (see Fig. 3.1-3). This classification is based on a multi-level system (waterway classes I to VII) that was adopted by the European Conference of Ministers of Transport in 1992 (CEMT System). While classes I to III tend to be important on a regional scale only, classes IV to VII refer to waterways of national and international importance. When the classification system was introduced in the Waterways and Shipping Administration in 1993 by the former German Ministry of Transport (BMV), all of the German inland waterways were classified according to it.

CEMT classification of inland waterways in Germany

Symbol	Classification	Motor vessels und tugs, Type of vessel: General properties: Vessel	Length L (m)	Breadth B (m)	Draught d (m)	Tonnage T (t)	Air draft
	I	West of Elbe River	38.5	5,05	1.8-2.2	250-400	4.0
		East of Elbe River	41	4.7	1.4	180	3.0
	II	West of Elbe River	50-55	6.6	2.5	400-650	4.0-5.0
		East of Elbe River	57	7.5-9.0	1.6	500-630	3.0
	III	West of Elbe River	67-80	8.2	2.5	650-1,000	4.0-5.0
		East of Elbe River	67-70	8.2-9.0	1.6-2.0	470-700	4.0
	IV	Johann Welker	80-85	9.5	2.5	1,000-1,500	5.25 od. 7.0
	Va	Large Rhine Vessel	95-110	11.4	2.5-2.8	1,500-3,000	5.25 od. 7.00 od. 9.1
	Vb						
	VIa						7.0 od. 9.1
	VIb		140	15	3.9		
	VIc						9.1

Symbol	Classification	Push tow unis (convoys), Type of convoys: General properties: Formation	Length L (m)	Breadth B (m)	Draught d (m)	Tonnage T (t)	Air draft
	IV		85	9.5	2.5-2.8	1 250-1 450	5.25 od. 7.0
	Va		95-110	11.4	2.5-4.5	1,600-3,000	5.25 od. 7.00 od. 9.1
	Vb		172-185	11.4	2.5-4.5	3,200-6,000	
	VIa		95-110	22.8	2.5-4.5	3,200-6,000	7.0 od. 9.1
	VIb		185-195	22.8	2.5-4.5	6,400-12,000	
	VIc		270-280	22.8	2.5-4.5	9,600-18,000	9.1
			195-200	33.0-34.2			

Note:
The designation of vessel types as well as the ship lengths, beams and draughts listed in Fig. 3.1-3 are only indications and may vary.

Fig. 3.1-3: Classified inland waterways [BMVBS 2008]

3.2 Standard cross sections and flow characteristics

The navigability of waterways in terms of safety and capacity is determined by ship-related factors (dimensions, equipment) on the one hand, and factors relating to the depth, size and shape of the waterway cross sections as well as flow velocities on the other. These parameters influence possible manoeuvres and ship speeds. The nautical parameters which are relevant for free-flowing and impounded rivers are described in the following section based on examples of the different types of waterways in Germany.

3.2.1 Cross sections of free-flowing rivers

In contrast to impounded rivers where the water level is maintained by a weir so that navigability is also ensured in periods of low water, the water level in free-flowing rivers and thus the water depths in the fairway are a result of the discharge conditions. To improve navigability in low water periods, the discharge is in most cases concentrated in a narrow low-water channel, for example by means of river training measures such as groynes (spur dikes) or longitudinal dikes (see also Chapters 4.1.4 and 4.1.9). The actual fairway depth is determined by the width between these training structures, the bottom gradient and the roughness of the river bed and banks. At a given discharge, larger fairway depths can be achieved with smaller widths and gradients and a higher roughness. However, even very “strict” river training measures cannot guarantee navigability throughout the year for free-flowing rivers because the discharges can be extremely low, even if this is rarely the case.

Statistical parameters are therefore used to determine the navigability of free-flowing rivers, i.e. the water level or discharge which has a specific probability of occurrence. This water level or discharge is often identical with the mean low water (MNW), and/or with a five percent probability over the year that the water level will fall below this fixed water level. The MNW of the River Danube is referred to as "Low water level by training" ("Regulierungs-Niedrigwasserstand", RNW), while the term used for the River Rhine is "Equivalent low water level" ("Gleichwertiger Wasserstand", GIW). Hence, if a ship is designed so that it is just about able to navigate at

MNW, for example, it is accepted that for about five percent of the year navigation will not be possible.

Non-impounded waterways are therefore especially characterised by variations in the water levels and the associated flow velocities to which shipping has to adapt. Large rivers allow navigation almost throughout the year, even by modern ships with deep draughts which are an economically efficient means of transport. One example is the River Rhine with its overall high discharges and balanced water conditions (compared to the River Elbe, for example, which is a typical low mountain range river with much greater discharge fluctuations than the Rhine or the Danube) due to its alpine tributaries carrying glacial meltwater. On smaller free-flowing rivers and rivers with large water level fluctuations like the Neckar or the Moselle, economically efficient navigation has only become possible since their impoundment.

To ensure economically efficient navigation which mainly depends on the possible draughts, shipmasters are allowed to determine the draughts at their own discretion on nearly all natural rivers, provided that safety and ease of navigation aspects particularly those relating to navigation channel conditions are observed. The possible load draught depends on the lowest water level and/or fairway depth (depth bottleneck) on the route, taking account of the minimum dynamic underkeel clearance and the squat of the vessel in motion. The latter mainly depends on the ship speed and thus, especially when navigating upstream, on the flow velocity in the section with the lowest fairway depth because to pass such a bottleneck the speed relative to the water must be high enough to sail with an acceptable speed over ground, i.e. to overcome the flow velocity. This means that it is not possible to limit the squat up to every extent by reducing the speed when navigating upstream in a river.

The minimum dynamic underkeel clearance the second parameter which can limit the possible load draught also has to be taken into account, in particular where the river bed is coarse or rocky. This is to allow for uncertain depth conditions to ensure the ship is not disabled in case of ground contact, for example because the rudder is bent when the ship touches the tip of a rock, or to prevent stones from being sucked into the propellers (Söhngen, 1999 & 2001). The available load draughts therefore depend not only on the local cross section, flow and bed conditions but also on short-term, unpredictable water level fluctuations (see also Chapter 4.1.2).

In the following figures these relationships are illustrated using examples of cross sections from river reaches with a high traffic density (source: charts of Germany's federal waterways, BAW flow models). In each example, the first figure shows the survey map. In the second figure several graphs are combined, depicting the cross sections (bottom left) at low water level (NW, green line), mean water level (MW, blue line) and the highest navigable water level (HSW, red line), the related flow velocity distributions (top left) as well as the duration curves for the flow velocity in the centre of the fairway (top right) and the possible load draughts (bottom right). A duration curve indicates the number of days per year on which a given value, e.g. the flow velocity, falls below this value (probability of occurrence).

As explained above, the probability that the reference low water level for fairway maintenance is not attained is low and at around five percent. The probability of occurrence of the HSW, i.e. the probability that it is exceeded, is also low with around one percent for the year. As a rule, the HSW is defined such that safe navigation is still possible, e.g. to ensure that the headroom below bridges is high enough and that the larger swept area widths of vessels sailing downstream at high flow velocities do not exceed the fairway widths. However, in most cases local boundary conditions determine the HSW, for example to protect river banks against wave impact from passing vessels during floods.

The maximum possible ship speeds shown in the graphs are determined taking engine power into account and are based on the prevailing flow velocities, the maximum possible draughts which are in most cases defined geometrically and the cross section conditions. In the first example, the maximum ship speeds of a GMS are shown for the three water levels mentioned above (see chart in the top right). The speeds indicated here are based on the assumption that the ship's engine power is sufficient to attain these speeds. The abbreviation KF refers to the underkeel clearance and vSüG to the speed over ground.

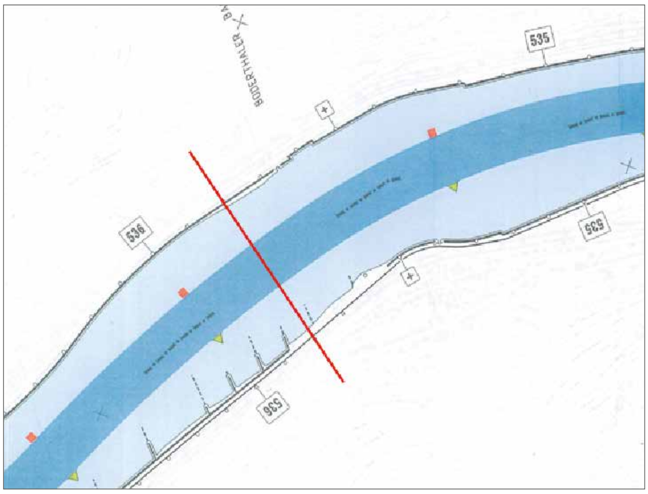


Fig. 3.2.1-1: Course of the River Rhine near Trechtingshausen (not far from Bingen, direction of flow from right to left); Rhine km 535.8 is marked by the red line [BAW]

The grey shaded area below the red line (representing the potential load draughts which are theoretically possible) shows the relevant draughts for a typical GMS, taking into account minimum draught and the design-related maximum draught (assumed to be 3.2 m). The mean draught of an empty vessel (assumed to be 0.8 m) is the lower limit of the grey area, which accordingly shows the portion of the theoretical draught that has an effect on tonnage, i.e. which share of the tonnage is accounted for by cargo and not by the ship's deadweight.

Rhine km 535.8

Figure 3.2.1-1, the first example, shows the course of the River Rhine near Trechtingshausen (Middle Rhine). On the left bank there are training works (groynes). The corresponding flow-reduced areas downstream of the groynes are reflected in the cross profile in Figure 3.2.1-1 (dotted line). The groyne heads

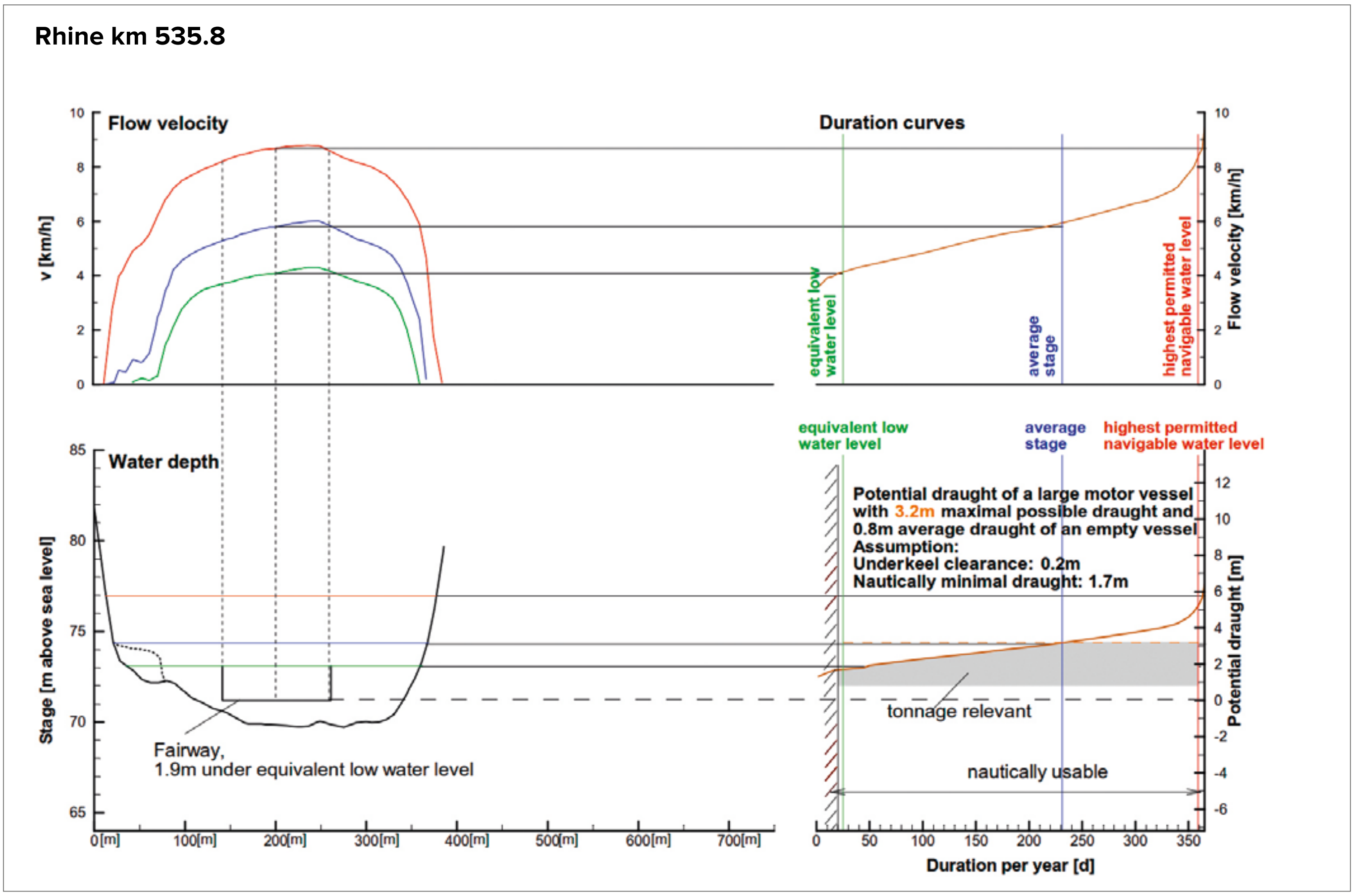


Fig. 3.2.1-2: Depth conditions, flow velocity and duration curves at Rhine km 535.8 [BAW]

are at mean water level (blue line). The groynes' impact on the water level and the flow field thus is not limited to low water but is also maintained up to such a level and corresponding fairway depth, where typical inland vessels can sail just with their design-related maximum draught. At higher water levels there is no need to increase the fairway depths by groynes.

The cross section in Fig. 3.2.1-2 shows the typical trough shape generally found in the mountainous reach of the River Rhine which is due to erosion into the rock. The existing water depths inside the fairway are much deeper than the official fairway depth. Hence, the possible maximum draught is not determined by this cross section. In fact, the load draughts permitted on the Middle Rhine primarily depend on the passage of the Rheingau area, which is characterised by great river widths and corresponding shallower water depths. The flow duration curve values were therefore calculated using the standard load draught rules of the gauges in Kaub (relevant for the reach between Bingen and, roughly, St. Goar) and Oestrich (relevant for the Rheingau). According to these rules, the load draught permitted at GIW is approximately 1.7 m and at MW up to approximately 3.0 m.

The GIW, which is the low water level significant for fairway maintenance on which the load draught decision is based, is represented by a green line. The other green line representing the flow velocity distribution at GIW shows that even at this water level ships have to sail against a strong flow field with a velocity of about 4 km/h. The latter was measured in km/h rather than m/s which are normally used in fluvial hydraulics, in order to enable a comparison with the ship speed values generally used for inland navigation purposes.

The flow velocities in the cross section considered are the result of the deep water depths and high longitudinal water level gradients of the Rhine (up to about 0.4 %) downstream of Bingen, where the river makes its way through the low mountain range. At HSW, the flow velocity can reach 9 km/h. Thus, to be able to make any way at all sailing over ground, ships have to sail at least at this speed relative to the water, which is equivalent to the design speed for canals and quite high for vessels with little engine power. However, the duration curve for the flow velocities also shows that these high values only occur for a short period of time per year which, on average, lasts just a few days. It may therefore often make more sense under such boundary conditions to use tug assistance if necessary, for instance in the case of pushed convoys, instead of increasing engine power, in order to be able to traverse this mountainous reach in an acceptable time.

The high flow velocities are also reflected in the calculated ship speeds. For upstream navigation the maximum values over ground assigned to a modern GMS are about 10, 8 and 5 km/h at GIW, MW and HWII respectively. This means they decrease with higher water levels and the example shows that a higher water level will not always allow faster travel. By contrast, in downstream navigation higher flow velocities facilitate navigation. The related values over ground were calculated to be about 18, 20 and 23 km/h respectively for the three above-mentioned water levels.

Given that the fairway has a width of 120 m in this particular reach and that flow velocities towards the left bank of the Rhine are approx. 0.5 km/h lower than in the fairway centre, it would be advisable for a ship sailing upstream in this profile to navigate as close to the left bank as possible. On the other hand, because the flow velocities are highest near the right bank, vessels navigating downstream should stay as close as possible to this bank to attain a high ship speed over ground.

Rhine km 673.0

The next example is a cross section of the Lower Rhine which is larger than the first example. It is located near Cologne-Godorf at the end of a long drawn-out right-hand bend, just at the transition to a left-hand bend, see Figure 3.2.1-3. This reach of the river has a movable bed consisting of sand and gravel. The bed consequently has a profile that is typical of the transition between two bends with an almost flat bed, i.e. it is a ford. The ford is created by the movement of bed load, which due to secondary flows mostly occurs on the inner side of a bend, which, in the present case, would be the right bank of the cross section illustrated here. At the transition itself the bed load moves to the other side, however, and thus has to pass the middle of the river. This explains why the bed of the cross profile is mostly flat and shallow.

The echo sounding data used to draw the cross profile in Fig-

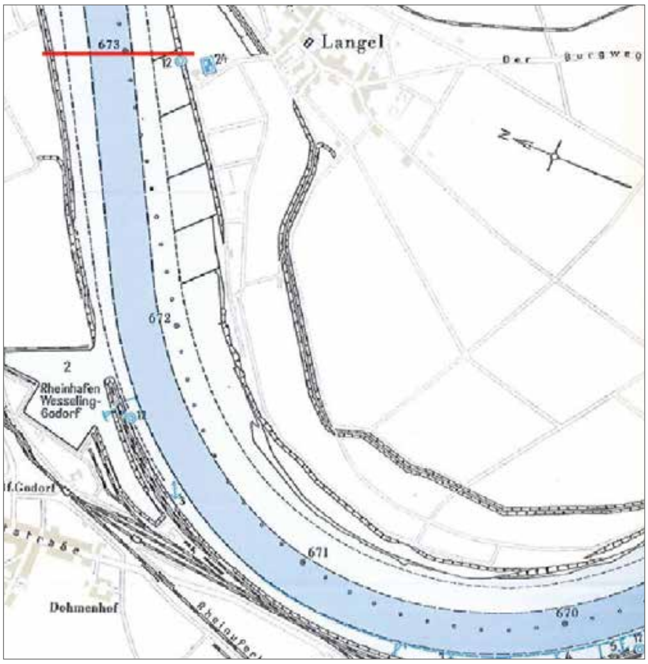


Fig. 3.2.1-3: Course of the River Rhine near Cologne-Godorf (direction of flow from right to left); the red line marks Rhine km 673.0 [BAW]

ure 3.2.1-4 show that on the right side of the fairway the depth requirements of the fairway are not met. The training effect of the groynes (whose cross section is visible as a "hump" on the right-hand side of the cross profile) was, at the time when the echo soundings were made, evidently not sufficient to avoid sedimentation typically occurring in fords over the entire 150 m wide of the fairway. Information about such insufficient depths is communicated to inland navigation vessels, e.g. by public notices, because it will never be possible to maintain the specified fairway depth in all places and at all times, for example after floods which cause major changes in the river bed. Hence, for organizational and economic reasons, in particular, fairway maintenance is limited to what is "possi-ble and reasonable" according to the wording of the Federal Waterways Act (WaStrG). This is to say that the fairway depth in a river with a movable bed is not guaranteed.

As in the previous reach of the Rhine, the flow velocities are relatively high with values of up to 10 km/h at HSW, i.e. even higher than in the Middle Rhine. This is due to the fact that in

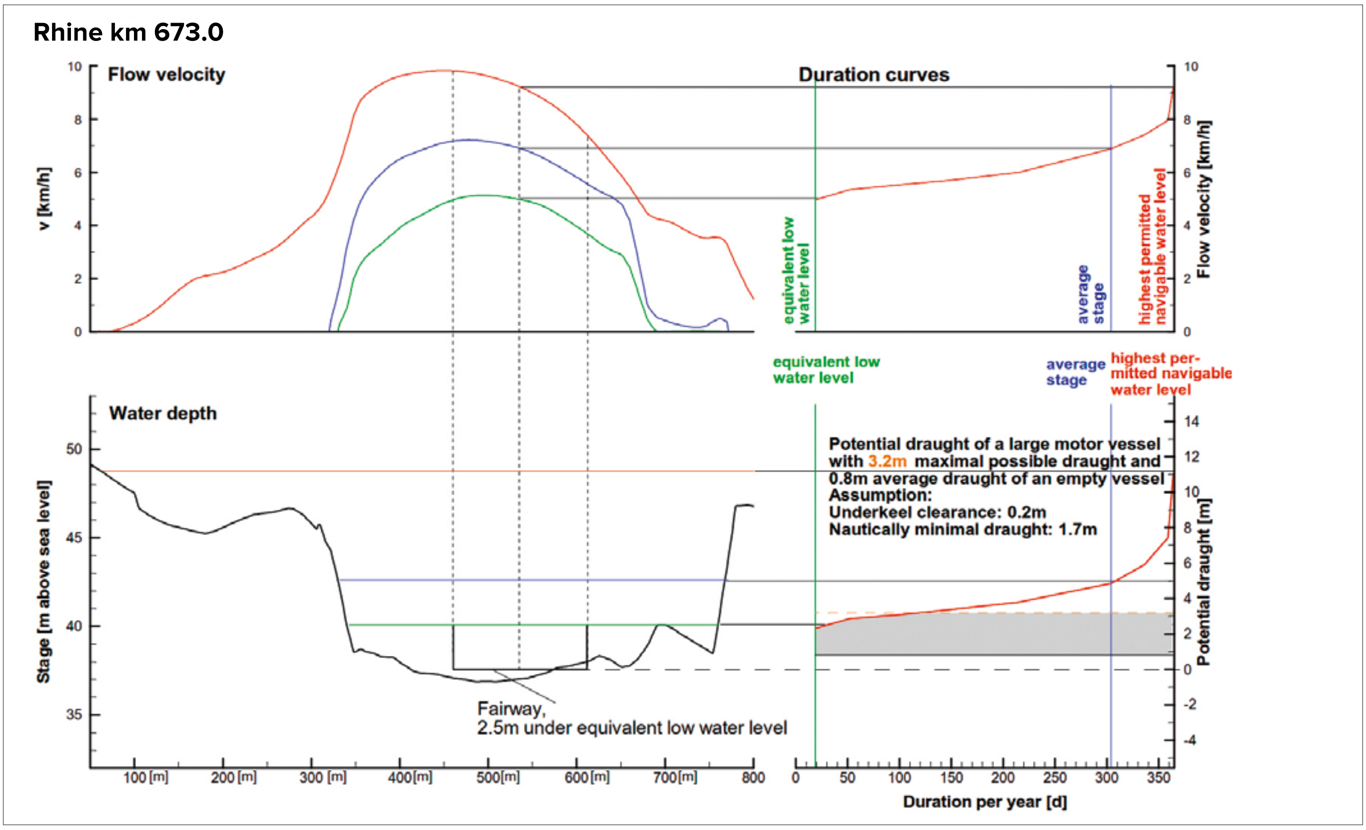


Fig. 3.2.1-4: Depths, flow velocity and duration curves at Rhine km 673.0 [BAW]

the reach investigated the HSW is very high. In the profile for the Godorf area the HSW is about 11m higher than the elevation of the fairway bed, while in the profile previously discussed (Trechtingshausen) it is only 6m. Also, the height difference between GlW and MW, amounting to not much more than 1m in Trechtingshausen, is greater in the Godorf area with about 2.5m. Although with these cross sections the depth conditions are favourable overall, high flow velocities in particular for example in the reach near Cologne adversely affect navigation and call for ships with more installed engine power.

On the other hand, the fairway depth allows load draughts far deeper than those in the Middle Rhine. Even when the water level is low, more than 2m is possible. The typical, design-related maximum draught of about 3.2m (i.e. a fully laden ship) of modern vessels which is marked in the duration curve in Fig. 3.2.1-4 can be reached and exceeded on average on 70% of the days in a year. On the Middle Rhine this is only the case during about 40% of the year. Moreover, as a long-time average, the HSW is exceeded on less than one day per year. With the Middle Rhine example, on the other hand, the average was around 5days. Thus, navigation by modern large motor vessels on the Rhine near Cologne is possible almost throughout the year.

Danube km 2,256.9

The following cross section profile of the River Danube near Hofkirchen belongs to the reach between Straubing and Vilshofen which is the only free-flowing reach of the Ger-

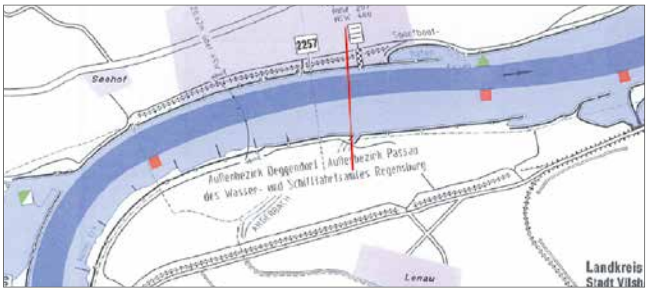


Fig. 3.2.1-5: Course of the River Danube near Hofkirchen (direction of flow from bottom to top); the red line marks Danube km 2,256.9 [BAW]

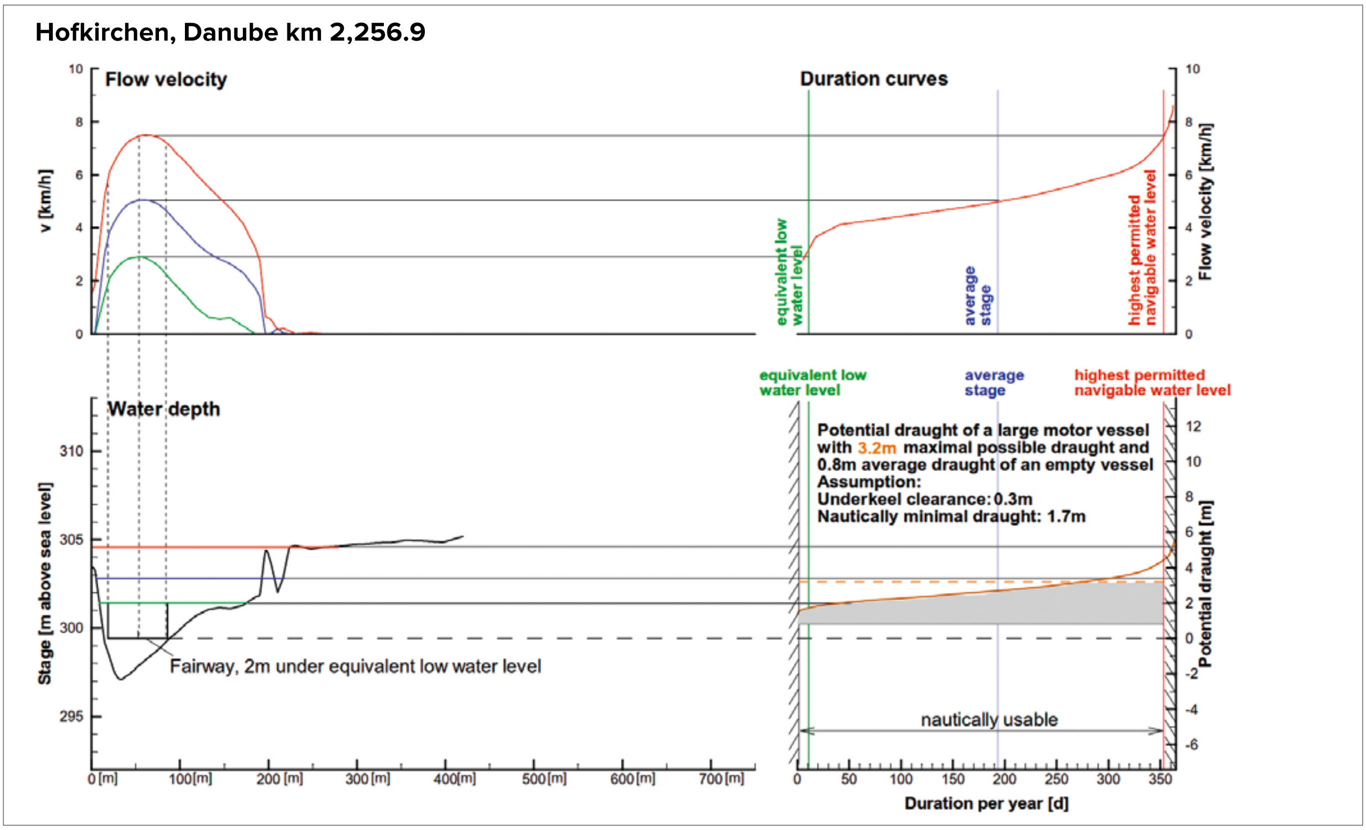


Fig. 3.2.1-6: Cross profile, flow velocity and duration curves, Danube km 2,256.9 [BAW]

man part of the Danube waterway (Söhngen, Witte 1999). The cross profile is located at the end of a narrow right-hand bend and was specifically chosen here because it has the triangular shape typically found in narrow bends of rivers with movable beds (Figures 3.2.1-5 and 3.2.1-6). This shape is supported by the groyne regulating structures on the inner bank, which additionally divert the water towards the outer bank, also referred to as the undercut bank.

River training with groynes is necessary in this reach to obtain the required depths, although this is only achieved in a 70 m wide fairway, which is extremely narrow in comparison to the Rhine. As initially mentioned, in a free-flowing river with a given discharge and slope a general decision has to be made favouring either fairway depth or width. The approach chosen for the Danube is focused on depth because the discharge during low water likewise amounts to only half the volume recorded at the Middle Rhine, the first example discussed here.

Since the available fairway depths are limited, especially in narrow bends, downstream navigation of pushed convoys in the Straubing-Vilshofen reach of the Danube is only permitted for side-by-side formations (two lanes, one ship length) because the swept area required in narrow curves is smaller than is the case with long formations (in the meantime, exemptions have been implemented for some convoys assembled in “long” formation, depending on the water level). However, upstream navigation is permitted for single-lane push-tow units with two barges since the additional widths resulting from drifting during bend navigation are much smaller in comparison to downstream navigation (see also Chapter 4.1.5).

The triangular geometry of the cross profiles is also reflected in the flow velocities, although due to the narrow dimensions they do not vary much inside the fairway. Nevertheless, shipmasters often prefer to keep the bow close to the inner bank when navigating upstream because it is in the bow area that the majority of the ship resistance is created and consequently any differences in flow velocities even minor ones have a supporting effect. However, the bow is also kept very close to the inner bank in downstream navigation in narrow rivers, because the transverse force during drifting in the bend is increased by the smaller water depths. The gravel bank on the inner side of the fairway is used as a kind of a control point to support the turning motion in narrow bend navigation.

The load draughts calculated for low water are similar to those used on the Middle Rhine, see Fig. 3.2.1-6 on the right. However, this is only the case with GMSs on which the calculations are based and does not apply to the larger vessels navigating on the Middle Rhine because the fairway is too narrow in this particular reach of the Danube. At the same time, the period during which a fully laden GMS can navigate on the Danube is restricted to about 20% of the year and consequently much shorter than is the case on the Middle Rhine. This is mainly due to the Danube’s generally lower discharges throughout a year.

Moreover, vessels passing the reach considered generally sail over very long distances from the ports of departure to the destination ports. During this long travel time, the water levels and fairway depths may vary in ways unforeseeable. Thus it is seldom possible to make full use of the potential load draughts along the entire route. Therefore, the difference between these and the mean load draughts actually used in commercial shipping is much greater on the Danube than, for example, on the Rhine. For a realistic assessment of the navigability of a particular reach, the potential load draughts in the cross profiles shown must therefore always be interpreted in the context of all water depth conditions over long stretches as well as their possible temporal variations during the trip.

Elbe km 241.0

The depths and widths available in the River Elbe are even less than in the above-mentioned Danube stretch. The following cross profile of km 2,41.0 is located near Coswig, in a reach with a minor water level slope and a sand and/or gravel bed. Figure 3.2.1-7 illustrates that there are groynes on both sides of the fairway. This is not reflected in the profile because the cross section line runs not directly across the groynes, but is located a little farther upstream. The fairway’s width is only 50 m; thus it is even narrower than in the case of the Danube (see above). This limits the range of permitted vessel types and sizes.

On the other hand, owing to the water table gradient, the flow velocities in the fairway are comparatively low at no more than approx. 3 km/h during low water and 4.5 km/h at HSW. This enables navigation by ships with less powerful engines than those required on the Danube and the Rhine. Furthermore, in upstream navigation squat is not as significant as, for example, on the Middle Rhine where the higher flow velocities require higher ship speeds. A comparatively small minimum dynamic underkeel clearance is also sufficient because the sediment of the river bed is more fine-grained than in the reaches of the Rhine and the Danube discussed above. The calculated potential load draughts (Fig. 3.2.1-8) are therefore reasonable during low water despite the small fairway depths. Even full navigability as defined above would be possible during 20 to 30% of the year, similar to the aforementioned reach of the Danube. Nevertheless, the depth conditions in the Elbe have to be considered as even less favourable than in the free-flowing Danube because of the stronger and more frequent water level fluctuations, especially due to the lack of Alpine tributaries, which are not reflected in the duration curves as represented here. In addition, the fairway widths are further reduced.

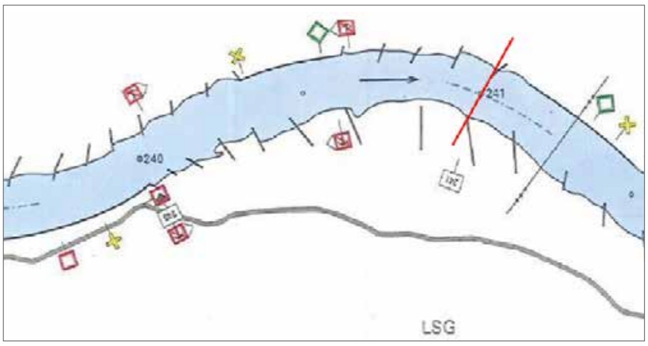


Fig. 3.2.1-7: Course of the River Elbe in the Coswig area; Elbe km 241.0 is marked by the red line [BAW]

3.2.2 Cross-sections of impounded rivers

The water level differences resulting from discharge fluctuations are less significant in impounded rivers than in free-flowing rivers. These differences are greatest in the area just downstream of a barrage because the next barrage is located some

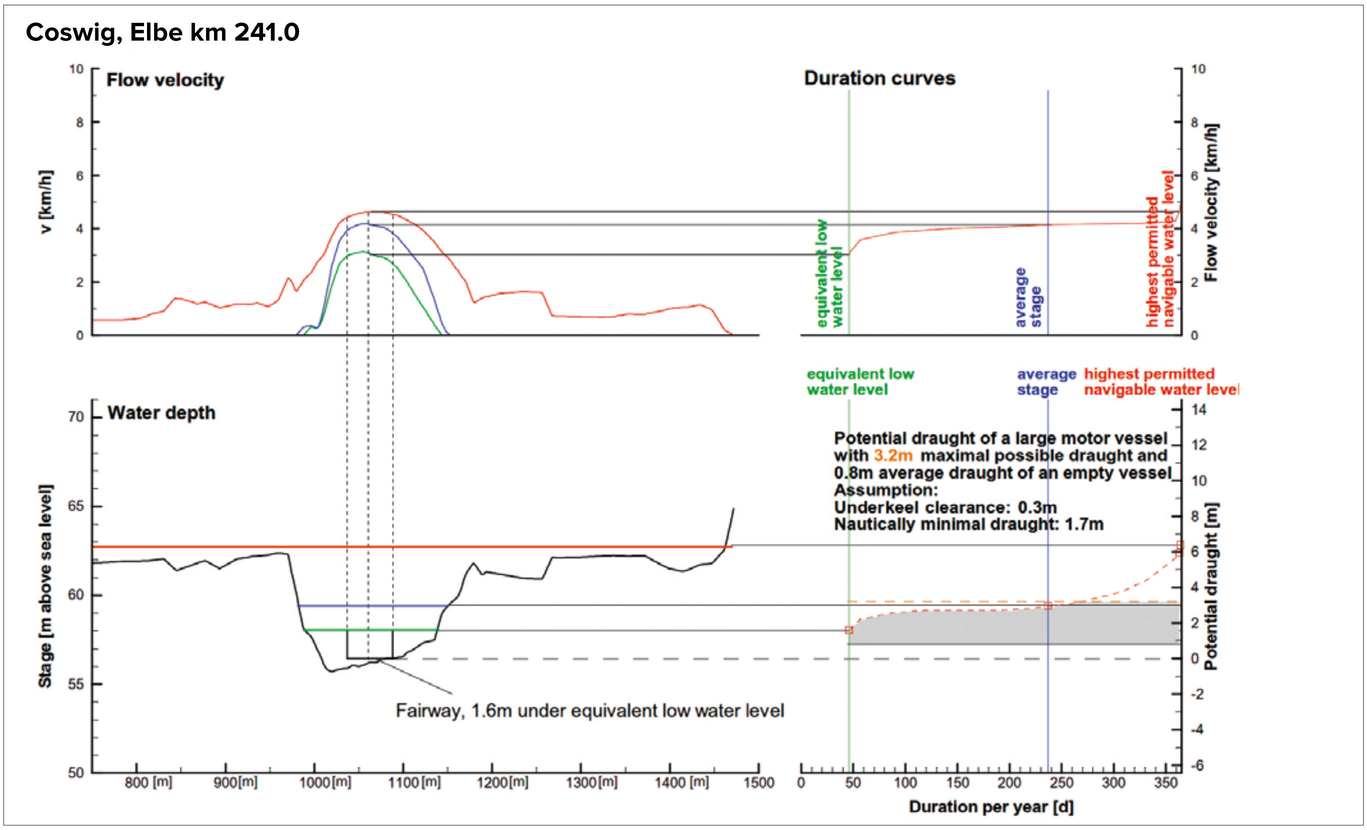


Fig. 3.2.1-8: Depths, flow velocity and duration curves at Elbe km 241.0 [BAW]

distance away. By contrast, upstream of a barrage there are only minor water level differences compared to the downstream reach. Just above the weir the differences are even zero during navigable discharge conditions, if the design water level is maintained also when the HSW is reached or even the defined high water level at which the weir gates have to be opened.

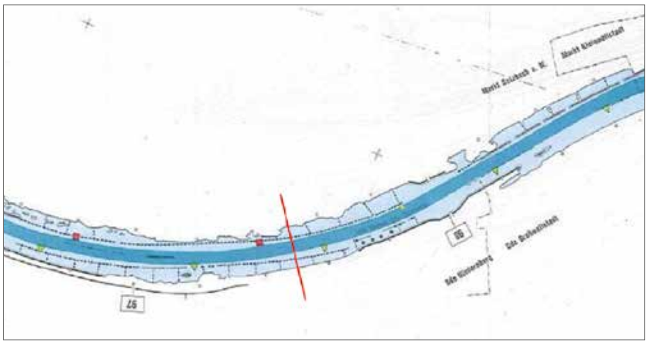


Fig. 3.2.2-1: Course of the Main near Niedernberg (direction of flow from right to left); Main km 97.5 is marked by the red line [BAW]

Minor fluctuations of the normal water level are often accepted for economic reasons, for instance because they allow higher power generation at peak times of electricity consumption (run-off river operation). Filling and emptying lock chambers also has a short-term effect on the water level and can lead to short-term water level fluctuations (surges) especially in periods of low water and in rivers like the Saar with generally low water supply meaning that even in impounded rivers water level changes cannot always be avoided.

Whether, and in which reach, there are deeper water depths at times of higher discharges, for example at mean water level, varies from one impounded reach to another. As a rule, it is therefore not possible to provide ships with complete information about the different water depths in impounded waterways. Hence, to make use of the scope for navigating in periods of higher water levels, shipmasters have to take into account the facts discussed above and their experience regarding navigation in critical reaches.

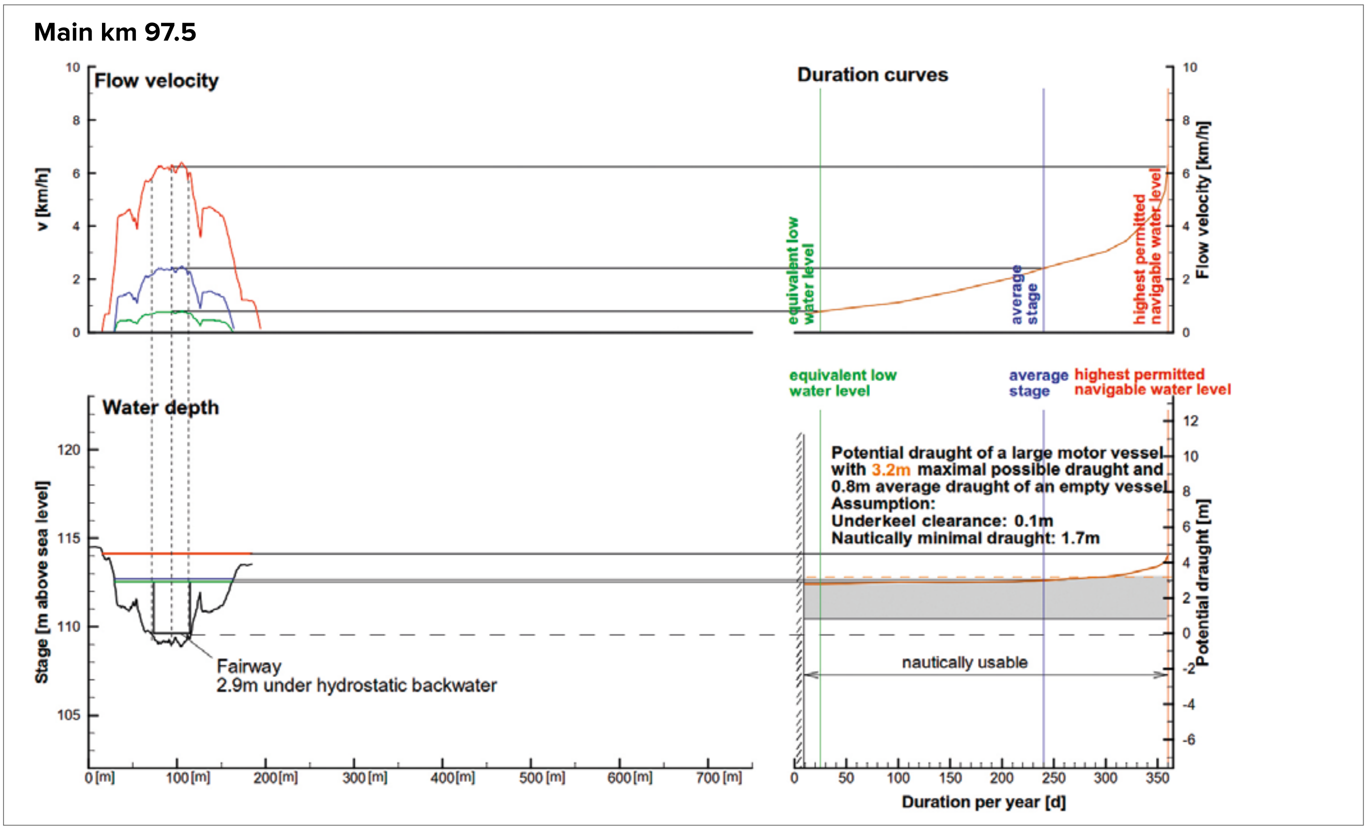


Fig. 3.2.2-2: Depths, flow velocity and duration curves at Main km 97.5 [BAW]

Main km 97.5

The River Main at km 97.5 is the first example of an impounded river considered here. If its water level were not maintained by impoundment structures, navigation on the Main by large ships would be impossible because the water supply is much lower than that of the Danube (about 30% of the mean low water discharge, MNQ) or the Middle Rhine (about 10% of the MNQ), for example. The widths are much smaller, too. Figure 3.2.2-1 shows that this cross section, located approximately 60 km upstream of the city of Frankfurt in the area of the Niedernberg gravel plant, has a water surface width of about 130 m and a fairway width of 40 m. These values are even smaller than those of the narrowest cross section example from the Elbe considered so far. However, the fairway has been widened in the narrowest bends to enable at least one-way traffic for the pushed convoys (single-lane, pusher with two barges or GMS pushing one barge) under low-water conditions and also during periods of higher water if they use their bow thrusters.

Nevertheless, the NW and MW levels shown in Fig. 3.2.2-2 are very close together, on the one hand because the considered cross section is just a few kilometres upstream of the weir at Obernau, and, on the other hand, because even at MW, the discharge in the Main is very low, at about 45% of that of the aforementioned Danube profile, so that only a small dynamic rise in the impounded water level due to flow resistance is observed (see Figure 3.2.2-2). This applies almost throughout the year, since a significant increase in water depths only occurs during about 20 % of the year as evidenced by the duration curve. By contrast, at HSW the increase compared to low water is about 1.7 m due to the Main's fluctuating water levels resulting from pronounced floods.

However, the overall depth conditions in the Main are extremely stable, corresponding to a 2.8 m fairway depth under hydrostatic backwater. Thus, this depth is maintained throughout the year, regardless of the discharge. Despite the slightly larger depths in times of higher discharges, the load draught in the reach discussed is limited to 2.7 m.

Although the NW and MW levels are very close together, the flow velocities at MW are more than twice as high as at NW: the maximum flow velocity at NW is just 1 km/h while at MW it is approximately 2 km/h. Even at HSW it is not more than 6 km/h. Thus, the low water discharge of the Main also has nautical benefits because it has relatively little influence on the range of possible ship speeds.

Neckar km 182.3

The following cross profile is located in the upper navigable part of the River Neckar, near Bad Cannstatt (a borough of Stuttgart) downstream of the Bad Cannstatt lock (Figures 3.2.2-3 and 3.2.2-4). The impoundment sections in this reach are short because of the even lower water supply compared to, for example, the Main river level (only a quarter of the MNQ mentioned in the previous example) and the strong bed slope of the natural Neckar River. This is why the water level differences in periods of higher water levels are also low in this cross profile compared to periods of low water and/or hydrostatic backwater although due to the location far upstream of the impounding weir a higher dynamic rise in the impoundment level would be conceivable.

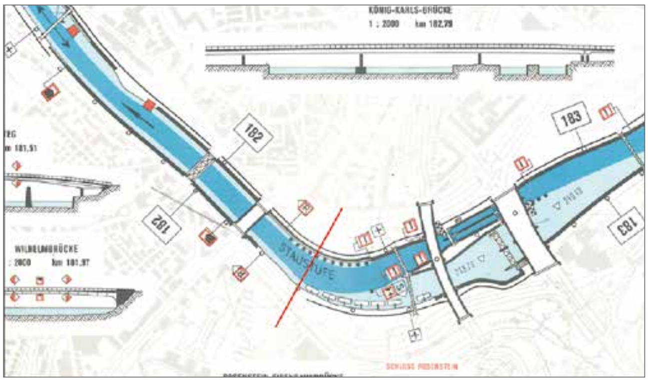


Fig. 3.2.2-3: Course of the Neckar near Bad Cannstatt (direction of flow from right to left); Neckar km 182.3 is marked by the red line [BAW]

Here the flow velocities are also very low at less than 1 km/h at NW and MW. This is the case with all impounded rivers, but it is especially due to the very low water supply in the upper navigable reach of the River Neckar. At HSW, the maximum flow velocity, namely about 4 km/h, is attained in the fairway centre. Navigation in this reach of the Neckar there-

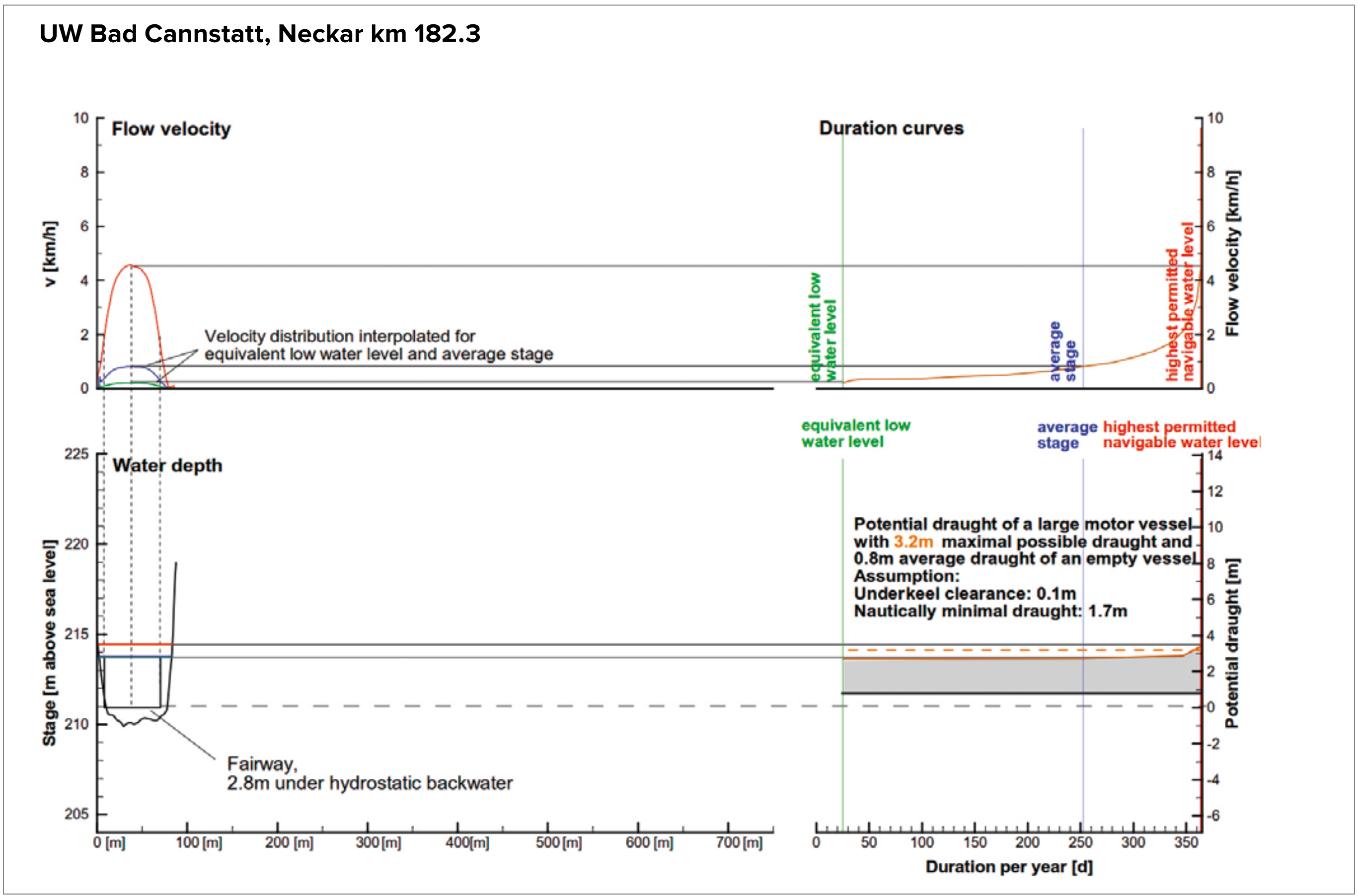


Fig. 3.2.2-4: Depths, flow velocity and duration curves at Neckar km 182.3 [BAW]

fore basically resembles navigation in a canal, also because the cross sections are not much larger than in profiles pursuant to the current German Guidelines on Standard Cross Sections of Inland Navigation Canals (2011 edition). This is of particular importance, amongst other things, for bank stability in the River Neckar.

Danube km 2,345

In contrast to the previously discussed, extremely narrow cross sections, the following example refers to an impounded reach of the River Danube upstream of the Straubing barrage, which was the last one built. The cross section shown in Figure 3.2.2-5 is located in the community of Irling, more or less half way between the Geisling and Straubing locks. Following the recommendations issued by the Danube Commission, the fairway width was defined envisaging a continuous extension of the impoundments in the Danube.

In the cross section, the fairway width is about 100 m. By comparison; the fairway width in the free-flowing Danube as shown in Figure 3.2.1-5 only amounts approx. to 70 m. Thus, besides improving the depth conditions, the impoundment structures have also enabled larger fairway widths.

The illustrated cross section in Figure 3.2.2-6 shows the typical triangular shape of a river at a left-hand bend. Despite the flow impoundment this shape has remained intact because the water level was raised so high to avoid fairway dredging which would have altered the cross profile significantly. Moreover, the morphodynamics which shape the river bed prevail even in flood periods when the impounded water has to be released. Hence, an altered, but basically triangular profile will always form again.

For this reason, the usable fairway depth on the right edge of the fairway is consequently about 2 m deeper than at the left edge. This results in different flow velocities within the fairway as illustrated in Figure 3.2.2-5 an effect which is particularly noticeable at HSW. At this water level, the velocities on the right side of the fairway can reach as much as about 7 km/h and thus are comparable to the velocities in free-flowing rivers. The usually adopted strategy of staying close to the inner bank (on the left of the figure) when navigating upstream or to the outer bank when sailing downstream is therefore efficient also in impounded rivers because it saves fuel costs and helps to achieve a higher speed over ground. Depths do not seem to play a major role in choosing the course in a dammed river since they are large everywhere. In addition, because of the adjacent reaches, i.e. the Main-Danube Canal and more particularly when continuing through the section with the smallest fairway depth between Straubing and Vilshofen, ships in any case cannot make full use of the depths in the impounded reach presently.

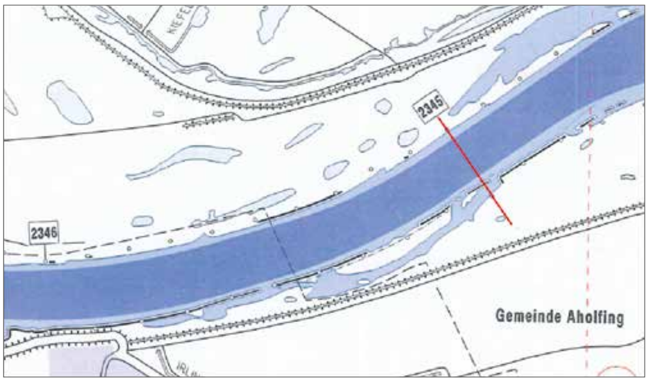


Fig. 3.2.2-5: Course of the Danube near Irling (direction of flow from left to right); the cross section profile at Danube km 2345 is marked by the red line [BAW]

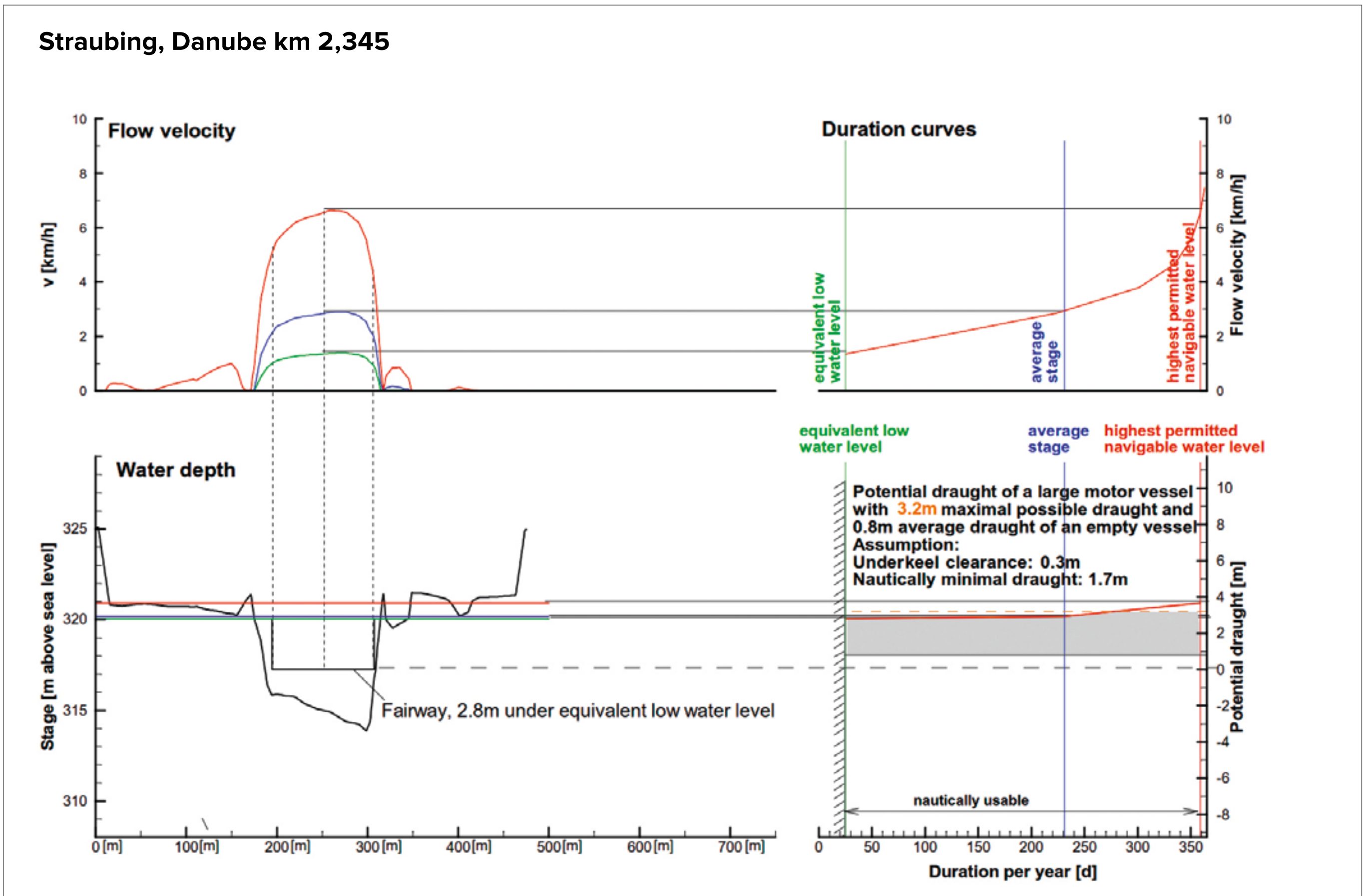


Fig. 3.2.2-6: Depths, flow velocity and duration curves at Danube km 2,345 [BAW]

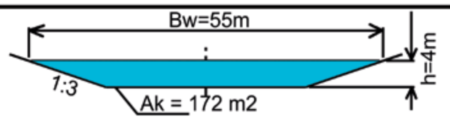
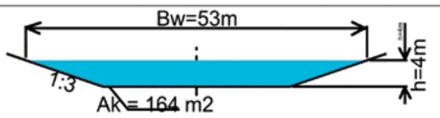
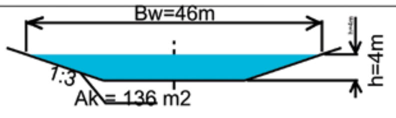
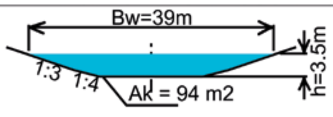
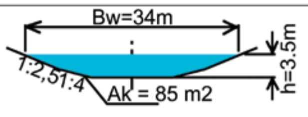
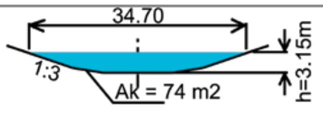
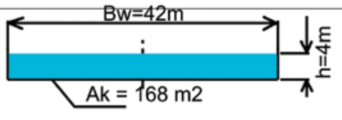
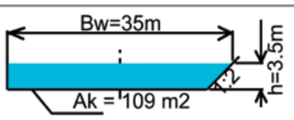
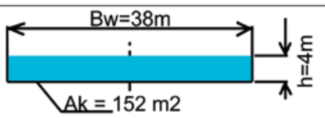
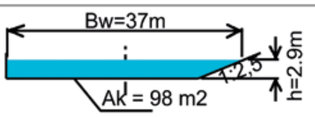
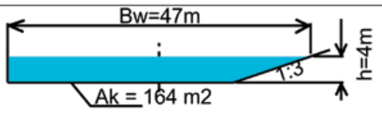
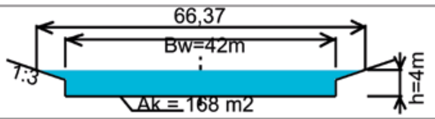
Canal	Canal cross-section A_c	Ship cross-section A_s	$n=\frac{A_c}{A_s}$	Critical ship speed V_{crit}(km/h)	max Squat (m) 90 % V_{crit}
Trapezoidal profile Mittelland Canal (East) Dortmund-Ems Canal Main-Danube Canal		9.50 x 2.50 11.40 x 2.80	7.2 5.4	10.26 9.07	0.31 0.32
Trapezoidal profile Mittelland Canal Elbe Lateral Canal		9.50 x 2.50 11.40 x 2.80	6.9 5.2	10.03 8.81	0.31 0.32
Older trapezoidal profile Rhine-Herne Canal		9.50 x 2.50 11.40 x 2.50	5.7 4.8	9.09 8.27	0.30 0.31
Trapezoidal profile Mittelland Canal (East) (not constructed)		8.20 x 2.20 9.50 x 2.00	5.2 4.9	7.93 7.61	0.26 0.25
Trapezoidal profile Elbe-Havel Canal (not constructed)		9.00 x 2.00	4.7	7.5	0.26
Trapezoidal profile Oder-Havel Canal		8.20 x 1.85	4.9	7.19	0.23
Rectangular profile of several extended canals		9.50 x 2.50 11.40 x 2.80	7.1 5.3	11.30 9.95	0.37 -
Combined rectangular - trapezoidal profile Dortmund-Ems Canal (not constructed)		8.20 x 2.50 9.50 x 2.50	6.3 4.6	8.92 8.1	0.35 0.31
Restricted rectangular profile		9.50 x 2.50 11.40 x 2.80	6.4 4.8	10.86 9.41	0.38 0.39
Combined rectangular-trapezoidal profile Teltow Canal		9.00 x 2.00	5.4	8.27	0.26
Combined rectangular-trapezoidal profile Wesel-Datteln Canal		9.50 x 2.50 11.40 x 2.80	6.9 5.1	10.58 9.32	0.34 0.36
KRT- Combined standard rectangular-trapezoidal profile Mittelland Canal (East)		9.50 x 2.50 11.40 x 2.80	7.1 5.3	9.22 8.12	0.25 0.27

Fig. 3.2.3-1 Typical canal cross sections and dimensions of the ships sailing on the canals; the table also shows 90% of the critical ship speed and corresponding max. squat (calculated by the BAW) [BAW]

3.2.3 Cross-profiles of canals

The definition of the cross profiles required for canals has always been dependent on the ship movements and related impacts onto the canal bed and banks resulting from ship-induced flows and the wash of the waves. New ship sizes, types, engines and propulsion systems have caused these impacts to change. The extension and maintenance of canals takes these changes into account. Historically, several different aspects including geological factors as well as planning and environmental policy have contributed to the development of different canal designs. Today, trapezoidal and rectangular profiles as well as a few mixed types derived from the former are relevant for canal extension. The dimensions of these profiles are standardised and also take account of vessel dynamics.

The parameters of typical German canals are summarised in Fig. 3.2.3-1. In addition, the table contains the dimensions (ship beam B and draught T) at the midship section (in most cases at the centreline) of the ships navigating in these canals. These values were used to calculate the so-called n-ratio, i.e. the ratio of the cross section of the water body A_K to the submerged midship cross section area A_S. The reciprocal value of n is the blockage ratio.

In wide water bodies or if the ship is short in relation to the canal width, A_K has to be replaced with the so-called effective cross section, which is relevant for the return flow. This cross section is obtained by marking off about one ship length on each side from the centreline. Taking account of the canal banks, all areas outside the zone defined in this way are not relevant for the return flow.

The smaller the n-ratio, the greater the ship-induced impacts while sailing at the same speed. The n-ratio and the mean water depth also determine the "critical ship speed" v_{crit}. At this speed, the water displaced by the ship and pushed backwards (GBB, 2004) cannot flow any more under subcritical conditions. The transition from subcritical to supercritical flow begins at this speed. In general, displacement craft cannot exceed v_{crit} and ship speeds in the range of v_{crit} will seldom be observed in field investigations. This is why the values in Table 3.2.3-1 refer to 90% of the critical ship speed, which is a "typical peak value" of observed vessel speeds. Table 3.2.3-1 also contains the maximum squat (drawdown of the vessel due to water level depression) at this speed. It is related to the height of the ship-induced waves.

As can be seen in the table, regular profiles such as rectangular, trapezoidal or combined rectangular-trapezoidal profiles are mainly used for man-made waterways. There are also canals with combined rectangular-trapezoidal profiles, which are designed with a rectangular profile in the lower part of the cross section and with a bank slope in the upper part.

The overview of canal geometries and the values recorded there for critical ship speed and squat show that, assuming the same cross-sectional area, a rectangular profile is superior to a rectangular-trapezoidal profile while a rectangular-trapezoidal profile is in turn superior to a trapezoidal profile in terms of ship dynamics, i.e. with regard to the critical ship speed and the available navigational width at the level of the bottom of the ship in motion (including squat). Amongst other things, this is on account of the higher wave propagation velocity in a rectangular canal due to the larger average water depth and hence higher critical ship speed.

Despite this, if the adjacent infrastructure allows and the terrain required is available, a trapezoidal profile is used in most cases because:

- It is simpler to construct and requires no sheet pile walls,
- Sloped banks are more nature-like, and
- Bank protection maintenance is easier, with riprap being used as a rule.

3.3 Locks

3.3.1 Lock structures

Locks are waterway navigation structures in canals and canalized rivers that help ships overcome the height difference (lift height) between the upstream and downstream levels of two stretches of water. In waterways, the lock dimensions (usable length and width) and sill depths have an influence on the permissible ship dimensions and load draughts. An example of a lock is shown in Figure 3.3.1-1.

The most important elements of a single chamber lock are depicted in Figure 3.3.1-2. The relevant planning parameters relate to the hydraulic system, the gates and the structure. The system for filling and emptying the lock chamber (the "hydraulic system") must meet two key requirements: on the one hand, rapid filling and emptying of the chamber must be possible to ensure short lockage times and high lock capacity while on the other hand, the movement of the water in the chamber must be kept to a minimum to avoid unacceptable forces on moored ships during the lockage process.

The lock gates and valves mainly include the gates at both heads of the lock structure, the culvert valves and the emergency closure gates for maintenance work and inspection. The complete lock area comprises the lock itself with the chamber and its heads as well as the upstream and downstream lock approach channels. The latter consist of the entrance area, lock approach harbour with berthing areas (optional) and the transitional area between the lock and the river or canal reach. The dimensions of a lock depend on the size of the ships and convoys for which it is built. In view of the dimensions of the modern GMSs, the chambers in new German locks designed for large ships have a clear width of 12.5 m. The usable widths of river locks are even larger in some cases (Rhine and Danube: 24 m). In Germany, the usable length of a lock chamber, i.e. the clearance between both gates minus a safety distance on both sides, is generally in the range between 100 m and 300 m.

Regarding navigational issues, various problems can occur

Fig. 3.3.1-1: Uelzen lock (Elbe Lateral Canal) [Waterways and Shipping Office Uelzen]

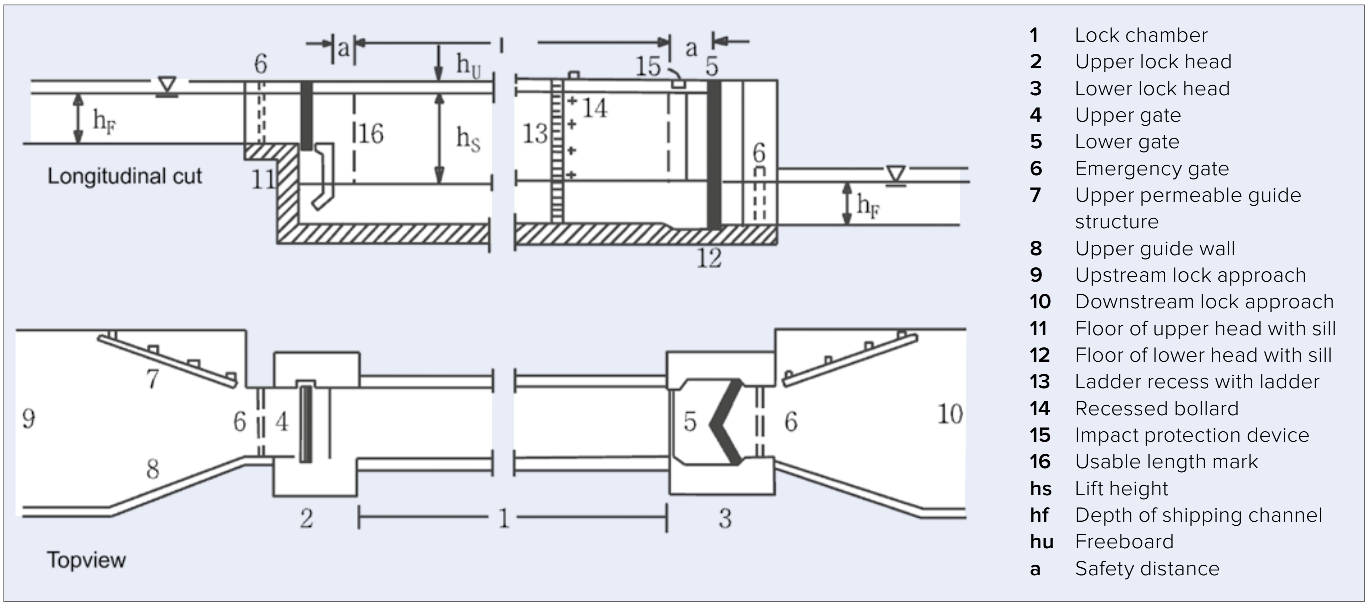


Fig. 3.3.1-2: Structure of a single chamber lock [adapted from Kuhn, 1985]

at locks. These may be caused by high mooring loads due to flow forces and the slope of the water surface in the chamber when the lock is emptied and filled as well as cross flows in the entrance area of double locks or groups of locks and positive or negative surges in lock approaches and adjacent canal or river reaches. Cross flows from fish passes and the operation of pumping stations on canals can also have a negative impact on navigation in lay-by areas. Moreover, river locks are faced with additional problems related to ship dynamics coming from the crosswise approach flow to the weir especially at the entrance of a lock approach channel.

3.3.2 Surges during lock operation

During lock filling and emptying operations water is withdrawn and released upstream and downstream, respectively. This creates waves that propagate at wave celerity from the lock to the canal or river reaches, leading to a lowering or rise of the water level. During lock filling, the withdrawal of lockage water upstream results in a negative surge, while during emptying a positive surge is created.

Based on the assumption that there is an infinitely long channel, which is almost fulfilled in lock approach channels with the adjacent canal or river reaches (as opposed to lock chambers), a wave profile is created in the lock approach channels, which in a first approximation represents an affine transformation of the curve depicting the discharge into the lock chamber during lock filling and/or the discharge from the lock chamber during the emptying cycle. The maximum water level elevation or lowering corresponds to the highest rate of discharge from lock operations. It is directly proportional to the magnitude of maximum discharge and inversely proportional to the wave celerity and water surface width of the lock approach channels, due to the kinematics of surge wave propagation and for continuity reasons.

In the downstream canal or river reach the prevailing water surface widths and water depths are the decisive factors for surge wave propagation. Hence, any change in the channel cross section has the effect of deforming the wave in the course of surge wave propagation. Generally speaking, a narrowing of the cross section amplifies the approaching wave, while a wider cross section reduces its height (Partenscky, 1986). If, for example, a positive surge wave approaches a suddenly narrowed cross section as, for instance, at a canal bridge, this wave continues travelling as a positive surge wave with an increased height. In addition, a secondary wave corresponding to the scale of the increase is reflected backwards from the point where the cross section narrows. This means that severely narrowed cross sections as can be found, for example, at the canal bridges spanning the Main-Danube Canal have the effect that, due to the reduced water depths resulting from negative surge during lock emptying, ships are obliged to slow down in order to reduce squat and thus prevent contact with the bed in the shallower water. The return surge due to lock emptying causes the vertical clearance underneath bridges downstream of the lock to become smaller. To ensure that changes in the water level do not exceed the acceptable maximum, the discharge into the lock during lock filling and/or the discharge from the lock during lock emptying may be restricted if the canal width cannot be altered.

In the literature, the permissible depth of a single negative surge and the permissible height of the positive surge due to lock filling and emptying are often specified as 0.20 m. It should be noted, however, that because of the above-mentioned effects of superposition at channel expansions and contractions, which lead to a total reflection of the approaching positive or negative surge wave at the solid boundaries of the subsequent lock, this permissible surge depth may be exceeded. This is especially significant in short canal reaches like the Eckersmühlen reach in the Main-Danube Canal, where the reduction in wave height due to friction is insignificant because of the low wave-induced flow velocities and the reduced roughness of the channel boundary in comparison to free-flowing waters.

The integration of water-saving basins in canal locks with a large lift height as, for example, on the Main-Danube Canal is an effective means of saving water and reducing the related pumping costs and also has welcome effects on the reduction of positive and negative surges in the canal reaches. For example, with three water-saving basins only 40% of water needs to be supplied to lockage from upstream or downstream for filling or emptying, leading to smaller wave heights and shorter periods of positive and negative surges. As a result, the risk of critical superposition of reflected waves is lower than in locks without water saving basins.

The following sections discuss the most important propagation characteristics of positive and negative surge waves in more detail. The numerical example refers to a water-saving lock on the Main-Danube Canal with a regular trapezoidal cross section and a water depth of 4 m (see Figure 3.3.2-1).

- The negative surge wave depicted in Figure 3.3.2-1 results from opening the gate at the upstream end to fill the chamber of lock A for an upstream lockage. Upstream of the lock, the wave front moves through the canal at a rate of approximately 20 km/h (i.e. about double the average ship speed) according to the depth and width conditions in the Main-Danube canal.
- The inflow into the lock increases rapidly up to the maximum value of currently approximately 70 m^3/s, then remains constant for a certain time and at the end of the filling process falls to zero (after about 7.5 minutes in the example shown here). Accordingly, a negative surge wave develops with a maximum depth of about 0.25 m and a length of approximately 2.5 km.
- If the canal cross section is uniform, the wave travels at almost constant speed and with a constant length. The wave front is stretched because its front part is in deeper water and thus moving faster than the back part, which is located in the wave-induced depression. The wave end becomes steeper for the same reasons. The depth of the wave decreases during the propagation time due to friction.
- At the end of the reach, the complete wave is reflected at the neighbouring lock B and continues travelling in the opposite direction until it arrives back at lock A, where it is reflected again.

When a negative surge wave travels through the cross section of a reach, a current is created in the opposite direction with a velocity of about 0.4 m/s (1.5 km/h). This corresponds to the withdrawal rate from upstream required for filling the lock, divided by the canal cross section.

If this negative surge overtakes a ship sailing at about half the wave speed, the return flow around the vessel superposes to the surge-induced flow. Therefore both the water level drawdown of the moving ship and the negative surge wave height increase and form a deeper water level trough in the area of the moving vessel. This in turn increases the dynamic sinkage of the vessel (squat) which reduces the dynamic underkeel clearance. The superposition of drawdown and surge is generally nonlinear and the clearance may be reduced even more.

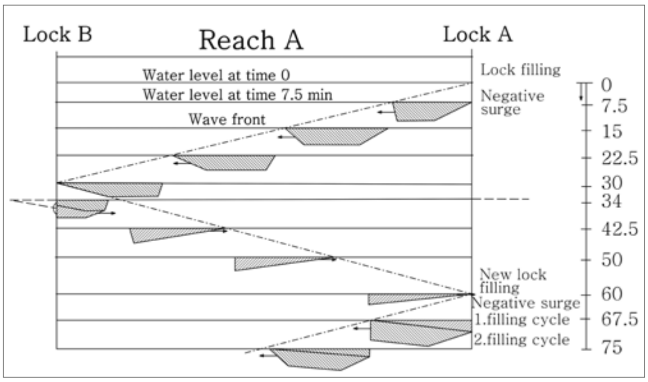


Fig. 3.3.2-1: Propagation of a negative surge wave upstream of a lock which has just been filled [VBW]

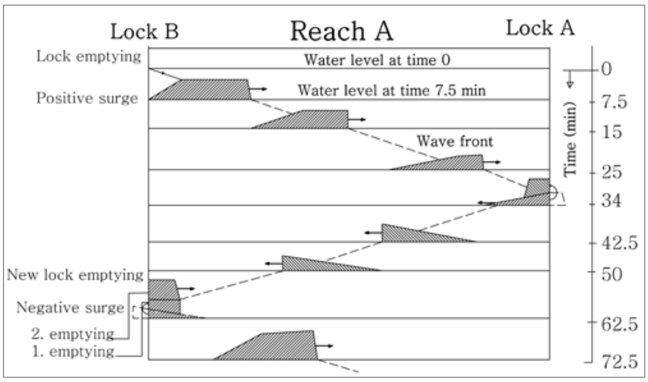


Fig. 3.3.2-2: Propagation of positive surge wave downstream of a lock which has just been emptied [VBW]

In extreme cases the ship will start to sail unsteadily. Unsteady sailing was induced on purpose in a test with a ship navigating close to the critical ship speed and exceeding this speed for a brief moment due to the impact of a negative surge wave. Similar situations can also arise at lower ship speeds, for example if the negative surge wave is amplified up to 0.5 m during several consecutive lock filling operations in short reaches, as has been observed in a test. If this happens, the ship must slow down to regain a more steady condition. On the other hand, an oncoming negative surge wave creates fewer disturbances because the return flows are in the opposite direction.

Analogously to the negative surge, emptying a lock chamber (lock B) during downstream lockage creates a positive surge wave. As in the example described above, its height and shape correspond to the release of water from the lock chamber and it travels along the reach in the downstream area at the same velocity of about 20 km/h (like the negative surge wave in the upstream area) before being reflected at the end of the reach (see Figure 3.3.2-2).

In contrast to a negative surge, the steepness of the wave front rises during the propagation of the positive surge wave. The back of the surge wave, on the other hand, becomes flatter. Instead of a return flow, there is a flow in the propagation direction of the positive surge in accordance with the inflow of water into the canal. The impact on a ship sailing in the same direction is less strong because the ship is lifted by the wave crest and the surge-induced flow is diminished due to the enlarged channel cross section.

Several positive and negative surge waves can occur simultaneously in the same reach, with each wave travelling almost independently of the other waves. Figures 3.3.2-1 and 3.3.2-2 also show how a new lockage process can lead to the superposition of a negative or positive surge wave. In critical reaches the superposition of several positive and negative surge waves can be effectively reduced by matching the lockage times at the two ends of a reach or by stretching the curves for the water inflow and withdrawal rates over a longer period of time.

In addition to superimposed lock- and ship-induced flows and the related changes in the water level, water level changes or flows due to positive or negative surges can have an impact on:

- Ships entering a lock with an oncoming wave and which are thus slowed down or, for example, accelerated unintentionally just before reaching the lock gate;
- Stopping or turning manoeuvres which cause ships to drift;
- Ships in mooring and waiting areas: the space available at berths and induced hawser forces may be affected;
- The available space for making manoeuvres during a temporarily lowered water level when passing or overtaking other vessels;
- The angle of trim of pushed convoys in the front areas of positive and negative surge waves and thus on the coupling forces or, in particular,
- The vertical clearance underneath bridges when positive surge waves are superimposed; ship-induced waves, for example from an accelerating ship causing another surge wave to form, or wind buildup can also play a role here.

The above-mentioned influences of surge waves and the impact of wind buildup (with a water level that is increased on the leeward side and decreased on the windward side) mainly occur in still water canals, which typically have small water surface widths and often also short reaches and low flow resistances. The negative impacts of these processes have to be identified in each individual case. They need to be taken into account when designing a waterway to ensure that shipmasters can master these challenges by using their nautical skills.

3.3.3 Berthing conditions in lock approaches

The safety of moored vessels at a berth in a lock approach is threatened by the following impacts (Oumeraci, 1988):

- Contact with the bed as a result of vertical motions (rolling, pitching, heaving),
- Contact between the ship and the mooring structure or between ships moored next to each other – influenced by the thickness of the fender mainly due to the rolling motion;
- Rope breakage due to horizontal motions (longitudinal and transverse movements)

Where maximum limits are determined for ship motions to ensure safe berthing conditions, they always need to take account of the respective ship size and type as well as the mooring and fendering systems. Since no precise data regarding such limits are available, the values specified in the literature are only based on experience and open to discussion.

The above-mentioned motions of ships in mooring and waiting areas are primarily caused by lockage operations and the passing of ships. During lockage operations, the motions in the upper lay-by basin are caused by the negative surge resulting from lock filling while in the lower lay-by basin they are due to the positive surge as a result of lock emptying.

The forces acting on a ship moored at a berth resulting from the passing of large motor vessels and pushed convoys are determined by the primary wave of the passing vessel due to the confined water body. The impact of the secondary wave system is negligible in such cases. In addition, the reflection of lockage, ship and wind waves and their superposition leads to secondary loads owing to the disturbances and long-period oscillations in the lay-by basin.

The changes in the water level caused by passing ships and surge waves resulting from lockage operations lead to closely corresponding vertical motions of the ships berthed in the mooring and waiting areas. The loads acting on the horizontal plane have a significant influence on the practical design of the mooring system. These loads are determined by the longitudinal water level gradient resulting from the propagation of positive and negative surge waves and, in the case of passing ships, the longitudinal and transverse forces as well as the torque. Vertical displacements or rotations, on the other hand, have only a minor impact on the mooring system (Haffke, 1983).

Where the geometric conditions are simple, the size of the waves caused by passing ships depends mainly on the following factors:

- Geometry of the lock approach area
- Draught and beam of the passing ship
- Ship speed and velocity of the return flow
- Distance between the passing ship and the bank

If the waterway's geometric boundary conditions are more complex, parameters related to the topography are highly significant for the development of incoming waves. This includes wave transformations such as

- Wave shoaling close to the banks,
- Wave deflection at obstacles like moored boats, jetties and wharves (diffraction);
- Changes in the direction of wave propagation resulting from the topography (refraction).

3.4 Bridges

European and German inland waterways are crossed by bridges in many places. Most of the older bridges in particular are still supported by piers in the fairways or at their edges. Their impact on the ship's behaviour and the nautical skills required for passing them are often underestimated.

First, bridge piers are man-made installations in the river cross section, disturbing its discharge pattern. A typical phenomenon is the so-called backwater effect at bridge piers: upstream of the pier, the water level rises while along the pier's longitudinal axis the water level in the vicinity of

Fig. 3.4-1: Backwater effect at a pier of the Cologne Südbrücke in the Rhine; direction of flow from right to left [Waterways and Shipping Office Cologne]

the pier decreases and thus is lower than in the larger area around the bridge (Fig. 3.4-1). Downstream, immediately after the pier, the flow separates and forms vortices, which vanish at a travelling distance of about 10 times the pier width. The water surface increase upstream of the piers, a local drawdown near the bridge's piers and the formation of vortices downstream of the piers have considerable implications for the navigation behaviour of passing vessels.

Especially when passing a bridge close to its piers, ships are forced away from the upstream pier heads and exposed to suction forces in the area of the pier and the wake downstream of it. These effects must be borne in mind, particularly when passing close-by bridge piers or when passing or overtaking other ships in the area of a bridge.

Depending on the pier shape, the magnitude of the effects can vary. The interactions with passing ships are strongest if the piers are short and have sharp edges and corners, and they are less pronounced if the piers are longer and have a very streamlined shape.

Besides the hydraulic interaction between bridge pier and ship, a shipmaster's visual perception changes with the conditions (daytime, night-time or foggy weather). The illumination and radar image render different reflections, depending on the design of the bridge and the material used. It is therefore advisable to acquire good knowledge of the optical image of the bridge, for example by consulting a radar atlas.

Bridges over canals restrict the allowed height, in particular for the modern larger vessels. On canals, the usable headroom below most bridges is about 4.50 to 6.50 m. Large ships or those without cargo frequently have to lower the steering stand when passing a bridge. Moreover, the water levels of canals are managed with changing operating water levels in most cases. Hence, shipmasters are obliged to find out the regular and current vertical clearance of a bridge in due time before passing it. The necessary safety clearance between the lower edge of a bridge and the top of the ship is often ignored or shipmasters try to compensate insufficient clearance by accelerating the ship to increase its squat. This is the main cause in a large number of usually severe accidents.

4 Ships in Motion

The theoretical background of ships sailing in navigation channels with limited width and depth is presented in detail in Chapters 4 and 5. The wave system generated by the moving vessel plays a crucial role for the interaction between ship and waterway. This wave system may cause severe impacts, in particular onto river banks. Therefore it will be examined more closely, especially from the infrastructure perspective. The waves also have repercussions for the ships themselves and determine the possible ship speeds as well as the ship's resistance and its squat when in motion. These interactions are described in Chapter 4 whereas Chapter 5 deals with manoeuvres, taking the physics of ship movements as a starting point.

4.1 Hydraulics of ship movements

4.1.1 Ship-induced waves and flows

Sailing steady at normal speed in a waterway (not manoeuvring) results in temporary changes both to the water surface and to the flows around the ship. When describing the deformation of the water surface, a distinction is made between primary and secondary waves. The temporal (for a stationary observer on the bank) or the spatial (from the bow towards the stern) sequence of bow wave, drawdown and stern wave as well as the associated flows is referred to as the *primary wave*. It has roughly the same length as the ship (Söhngen et al. 2008, GBB 2004). This sequence is easier to understand if the observer is standing on the moving ship. In this case the water approaches the vessel at the ship speed v relative to or "through" the water. The ship acts as an obstacle to the relative flow around it, like a pier of a bridge in a river. The water accordingly builds up in front of the ship. The local build-up forms part of the bow wave. But some part of the the build-up goes farther ahead as at a bridge pier. It is known as backwater at the bow and can be seen in Figure 4.1.1-1 by the darker colour of the water surface when viewed against the light.

The water which has built up at the bow then accelerates laterally and downwards, and above all towards the stern, in its endeavour to get past this "bottleneck". High flow velocities occur especially around the bow, mainly because the ship contour has a pronounced curvature. This flow due to side- and downward displacement of water is highest with large draught-to-water depth ratios T/h (Söhngen et al., 2008). According to Maynord (1990, 2000), the local flow velocity relative to the ship can be as much as 1.4 times v in shallow water with the typical T/h of 0.7 for fully laden ships. In relation to the bed this corresponds to 0.4 v. Assuming a typical ship speed in shallow water of approximately v = 13.5 km/h, as measured on the Rhine for instance, this leads to a displacement velocity of about 1.5 m/s. In a river, the natural flow velocity must be added to this value when sailing upstream, so that up to 3 m/s may occur at water levels with a large T/h, e.g. in the Middle Rhine region. These high values stress the channel bed and, if the ship is sailing close to the bank, the toe of the embankment.

In a canal the local displacement flow at the bow is superposed by the return flow. This describes the increase in ship-induced flow velocity which occurs not only at the bow but all round the ship, caused by the bottleneck effect as described above. This effect increases with an increasing blockage coefficient. The latter describes the submerged (blocked) cross sectional area of the ship in relation to the canal cross section. Taking account of the return flow, flow velocities corresponding to ship speeds of up to approximately 3 m/s have been measured under experimental conditions in canals by the DST (2006) for typical, fully laden inland navigation vessels at T/h = 0.7.

Since these possible flow velocities are very high, it is important to ensure that the fairway does not extend right up to the bank. However, the local displacement flow, which is reflected in the bow wave system, declines very quickly adjacent to the ship. This is clearly visible in Figure 4.1.1-2, in which the calculated deformation of the water surface perpendicular to a large motor vessel (GMS) is shown in the bow area for various canal widths b and ship positions (distance from the bank u) relative to the bank (source: model calculations, BAW).

Figure 4.1.1-3 shows the wave heights (ship cut out) for two of the widths shown in Figure 4.1.1-2, namely for a ship sailing in a 200 m wide waterway with a distance of 20 m between the course of the vessel and the bank (on the left in the diagram) and a ship sailing in the middle of a 40 m wide canal (on the right), at the same distance to the bank. The GMS was sailing at the same speed in both cases.

It can be seen that the distance d from the ship up to where the build-up in front of the bow (apex of the curves) vanishes and turns into drawdown at the sides of the ship is more or less independent of b and u, even though the absolute height of the water level adjacent to the ship or the height of the backwater at the bow may be completely different for the various canal widths. This distance d measured from the vessel axis to the side is about 20 or 30 m for a GMS or, put more generally, equivalent to between 2 and 3 ship beams B.

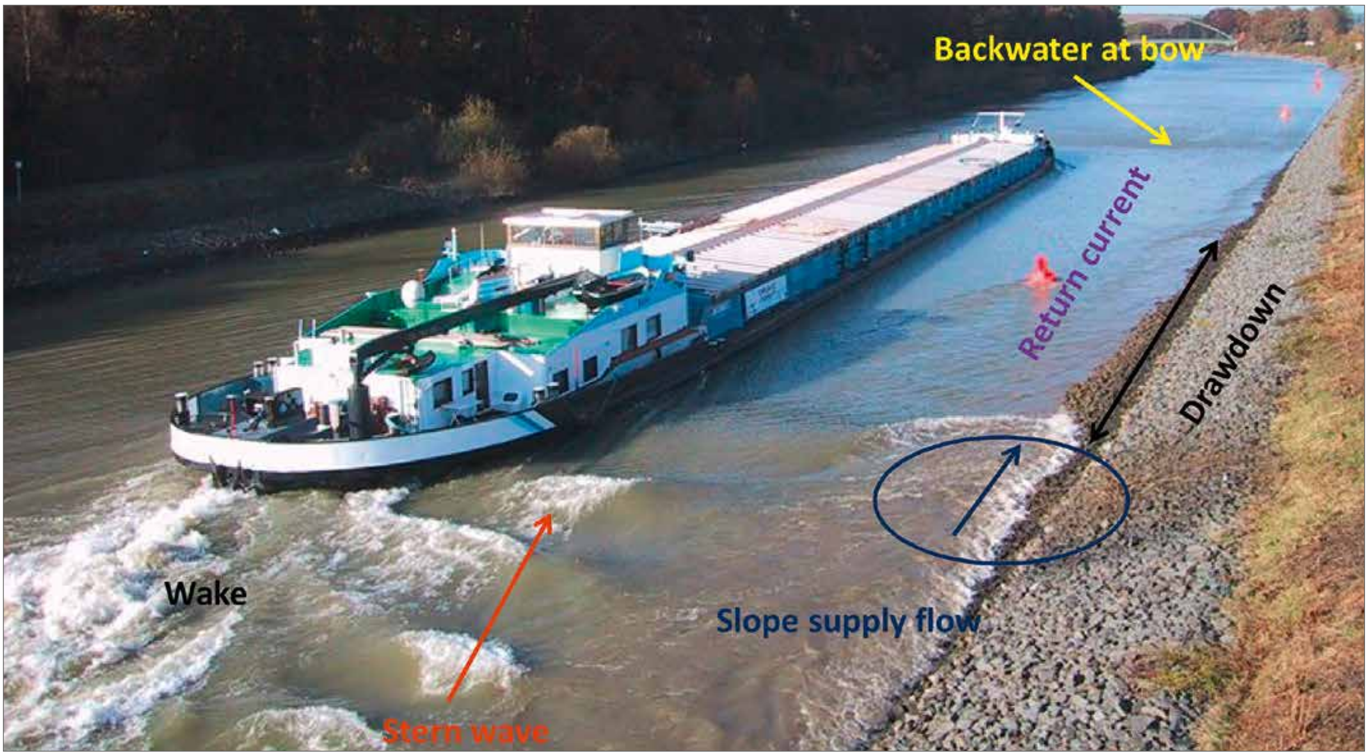


Fig. 4.1.1-1: Ship-induced flows and waves from the primary wave field during displacement motion in a navigation channel of limited width and depth [BAW]

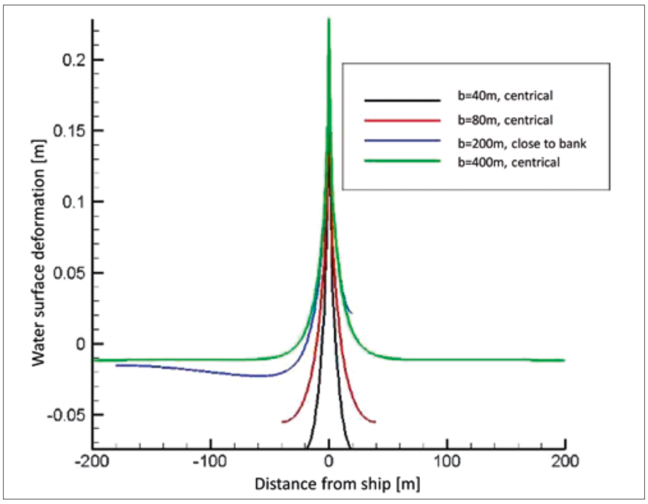


Fig. 4.1.1-2: Development of the water surface perpendicular to the ship in the bow area of a GMS [BAW]

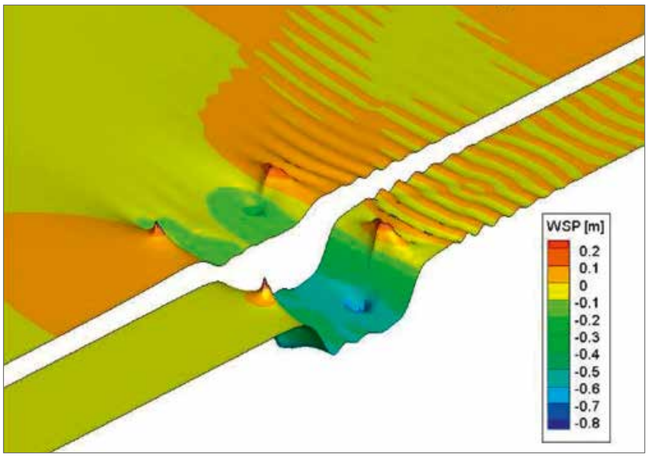


Fig. 4.1.1-3 Wave pattern of a GMS sailing at the same speed either close to the bank in a 200 m wide waterway (left) or in the middle of a 40 m wide canal (right) [BAW]

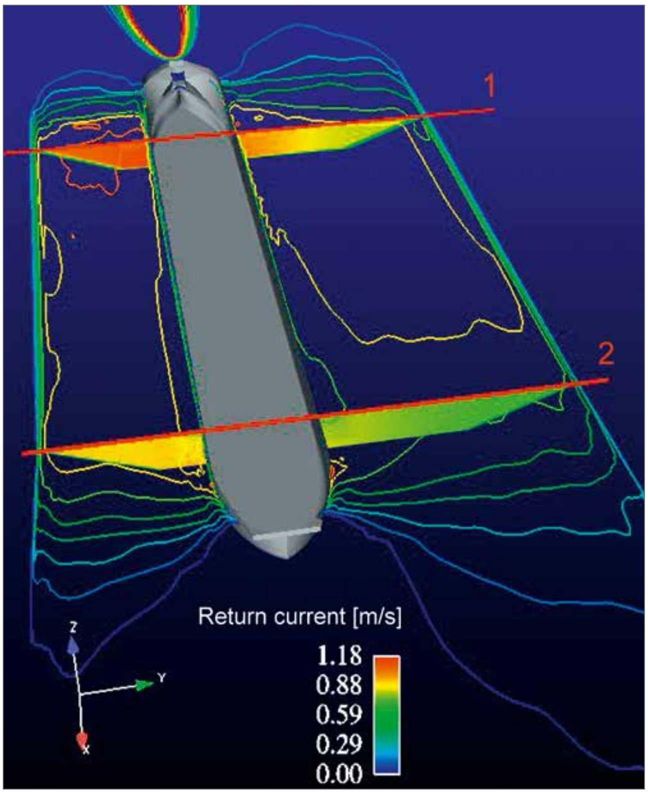


Fig. 4.1.1-4: Distribution (speed marked in colour and isovels) of the ship-induced flow velocities relative to the canal, caused by a laden GMS (trapezoidal profile) [BAW]

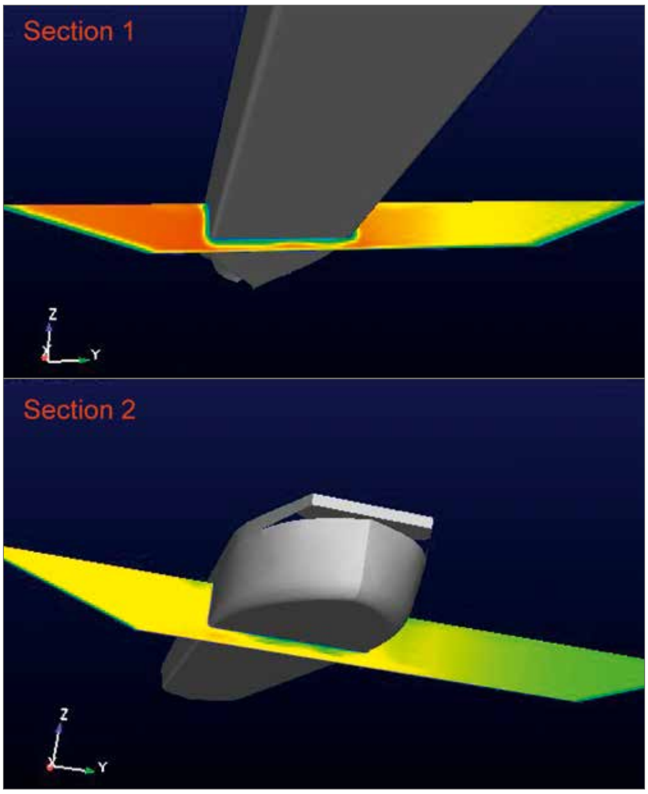


Fig. 4.1.1-5: Velocity distribution indicating the boundary layers on the ship and the bed – example based on Figure 4.1.1-4 [BAW]

Thus, if the fairway is further away from the toe of the bank protection than the corresponding related net distance (d – B/2, i.e. 2 times B), the high displacement flow velocities and the associated waves in the vicinity of the vessel are not relevant at the bank and can be neglected when choosing an appropriate bank protection.

This does not apply to the return flow, which is dominant in the midship section and declines much less with growing distance to the ship than the local displacement flow. For typical inland navigation vessels the return flow is still relevant up to approximately one ship length L on both sides of the ship. This means firstly that a significant influence of the return flow on the bank is generally unavoidable in almost all German navigable rivers, and secondly that the return flow in narrow cross sections extends across the entire canal width and is in fact almost constant in narrow canals as is the case in German standard canals, but also in narrow rivers as the Neckar upstream of Heilbronn or the Middle Weser (in other words channels with small water surface widths to ship length ratios B/L).

This is clearly visible in Figure 4.1.1-4, in which calculated isovels of near-surface flow velocities for a GMS, sailing in the trapezoidal profile as defined in the German Guidelines on Standard Cross Sections of Canals (water surface width b = 55 m, embankment slope = 1:3, water depth h = 4 m) are presented. Although the return flow velocities are not as high as e.g. the natural flow velocities occurring during a flood – though values of up to 2 m/s have been observed in canals – their influence onto the banks far exceeds that of a natural flow. One reason for this is the much thinner boundary layer of the return flow field, which means the full return flow velocities apply almost right down to the bed or right up to the bank. This is due to the fact that the velocity profile between the ship and the bed first has to develop.

By contrast, the boundary layer thickness of a natural flow is much bigger and corresponds approximately to the water depth. Hence, its influence is significantly less in general compared to all ship-induced flows such as the return current, the displacement flow, the slope supply flow or the propeller jet. In the bow area the boundary layer is particularly thin, as illustrated in Figure. 4.1.1-5. This can be seen from the way the colour, indicating the flow velocity, changes towards the bank and the bed. The result is a high flow velocity close to the embankment.

In the stern area, on the other hand, the boundary layer is slightly thicker, reaching a value of approximately 0.5 m in Fig. 4.1.1-5. It is therefore important to dampen the return flow by protecting the banks with coarse, stable structures to ensure that areas vulnerable to erosion are not directly exposed to this flow.

The approach velocity of the vessel is increased by the velocity of the return flow, causing the water level adjacent to the ship to be lowered. As is the case with the return flow field, this drawdown extends roughly one ship length on either side. For a definition of drawdown and wave heights in general refer to Figure 4.1.1-6. The lower water level usually only results in small hydraulic loads on the bank, but it can cause excess pore water pressure to develop in the soil.

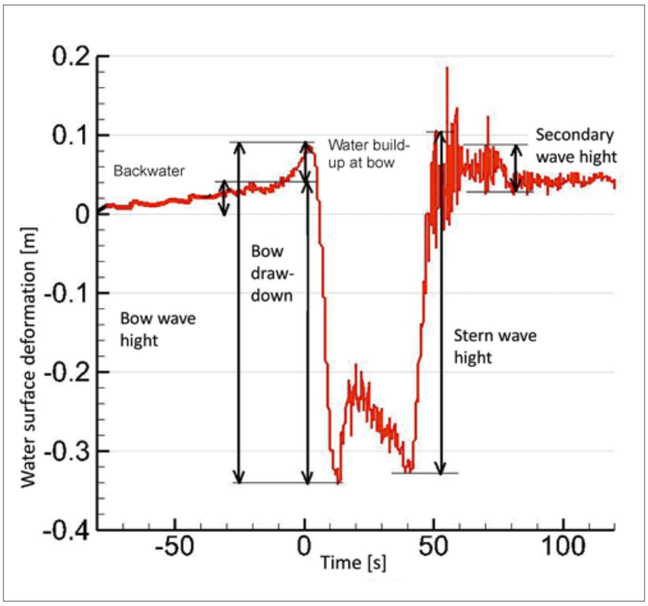


Fig. 4.1.1-6: Definition sketch of ship-induced wave heights [BAW]

This happens if the water level drops rapidly, in combination with low soil permeability. In this case, the "old" pressure (before the vessel passes) which is still present deep down in the soil cannot adjust fast enough to the lower pressure in the drawdown area (depression trough) around the moving vessel. This overpressure therefore reduces the normal stress acting on the soil and hence the maximum resisting shear force. If the soil is critical in this respect (refer to Chapter 3.5), hydrodynamic soil displacement or sliding of the embankment along a near-surface gliding area can occur if no countermeasures – e.g. an additional load to increase the normal stresses in the soil – are taken. Along with protection against erosion this is one of the reasons for building bank revetments (Söhngen, Kayser, 2005 & 2010).

The lowering of the water level around the ship also causes it to squat, which means the ship sinks into its self-induced drawdown trough. The squat results in a reduced distance from the bed and dynamic underkeel clearance. If the water is comparatively shallow, ships which are laden according to the water level thus have to sail slower than in deeper water to reduce their squat. Partially laden or unladen ships, on the other hand, or ships which are ballasted with water at the stern to make sure the propeller remains sufficiently submerged, do not fully utilise the full water depth available even at low water and are therefore able to sail much faster than laden ships, leading to more drawdown and higher waves.

The amount of the drawdown can indeed be large enough to cause the flow relative to the ship to change from subcritical to supercritical flow. With a uniformly laden ship – or with a ballasted ship where the drawdown trough deepens from the bow towards the stern, in part due to the flow resistance – this flow transition usually takes place just before the stern. At this point the full displacement effect is still present and the water level is very low.

Like a hydraulic jump, the transition from subcritical to supercritical flow is discontinuous. A breaking stern wave is the visible sign of this transition. The wave is breaking as its propagation velocity is too low to run against the supercritical flow velocity.

Since the wave propagation velocity is identical to the ship speed relative to the water and the wave is forced to follow the ship at the same speed (because it is produced by the ship), the speed of a displacement craft is limited. This speed is referred to as the critical ship speed v_{crit} and is proportional to the wave propagation velocity $c = (g*h)^{½}$. The constant of proportionality between v_{crit} and c is about 0.5 in standard canal profiles and 0.75 in shallow water for a fully laden ship and between 0.65 and 0.8 for an unladen ship.

This critical sailing situation is linked to a significant increase in the ship's resistance, because the vessel now has to sail up the sloping water plane of the drawdown trough towards the bow. Additionally it has to be moved against the rapidly increasing return flow velocity and part of its propulsion power is dissipated in the breaking wave. This is why cargo vessels do not generally sail faster than approximately 90% of v_{crit}.

Velocities closer to v_{crit}, e.g. at 97% – the value used to design revetments according to German guidelines (such as GBB) and codes of practice (e.g. MAR) – tend to occur inadvertently, for example if a ship passes from deep into unexpectedly shallow water or approaches the bank rapidly during an evasion manoeuvre. Nevertheless, this aspect must be considered in the revetment design.

The stern wave shoals more and the supercritical flow is reached faster because the energy in this wave is now distributed over a smaller width, so that its height increases. Moreover, the wave field of the local displacement flow moves closer to the bank, causing the wave to become even higher. This is shown, for example, in Figure 4.1.1-7. The effect is in fact greater when sailing close to the bank in shallow water than it is in a canal because higher ship speeds are possible.

In spite of this, the highest hydraulic loads on the bank generally occur when sailing in a canal, where narrow cross sections and the resulting low critical ship speed prevent the vessel from sailing any faster (Doychev, Söhngen, 2013). One reason is that it is almost impossible to reach v_{crit} in rivers, even for

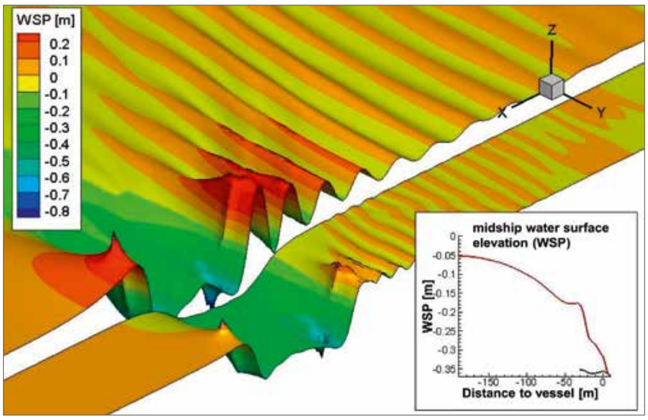


Fig. 4.1.1-7: Wave pattern induced by a GMS sailing at different speeds but with the same average drawdown in the midship area in a 200 m wide waterway (left) and in a 40 m wide canal (right) [BAW]

modern ships – especially at higher water levels – owing to the necessary propulsion power. By contrast, reaching the substantially lower v_{crit} in canals requires muss less engine power. Even fully laden, a typical GMS powered with a 1200 kW engine can reach the critical ship speed in German standard canal profiles – not just partially laden, ballasted or unladen vessels, as is the case with less powered Europe ships.

In order to limit wave shoaling close to the bank, the ship should sail at least two to three beams away from it, as explained above, see Figure 4.1.1-8. The diagram shows how

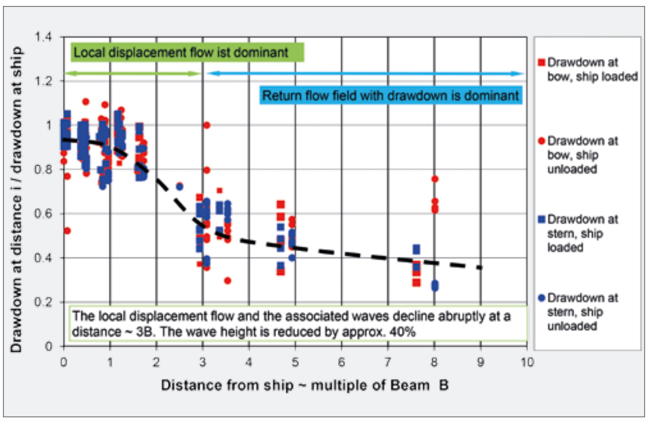


Fig. 4.1.1-8: Decline in the wave heights between the ship (midship) and the bank, taking the drawdown measured in canals of various widths as an example [BAW, data from DST]

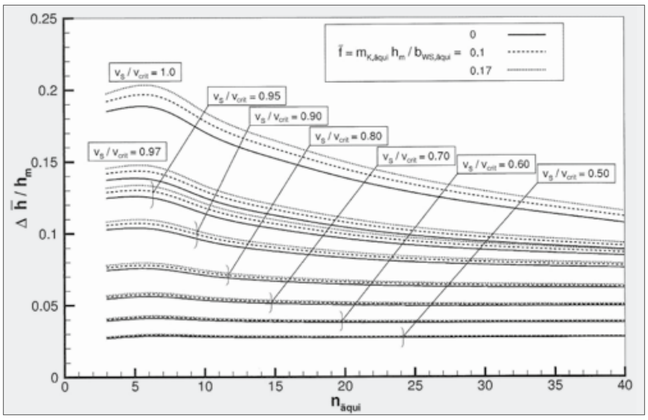


Fig. 4.1.1-9: Relative average drawdown $\Delta\overline{h}$ (related to the water depth h_m) as a function of the equivalent n ratio (inverse blockage coefficient) $n_{äqui}$ (areas with no significant return flow cut off) [BAW]

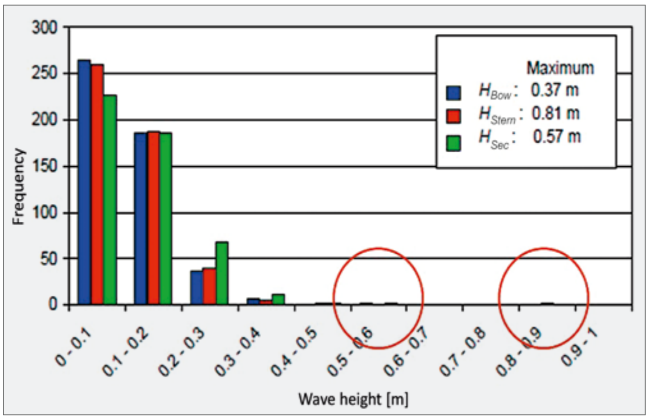


Fig. 4.1.1-10: Frequency distribution of the wave heights (bow, stern and secondary waves) observed on the bank of the Rhine near Worms, km 440.6 (mean ship-to-bank distance: approx. 75 m) [BAW]

drawdown declines as a function of the distance from the ship. This distance is plotted on the horizontal axis (abscissa). One unit corresponds to one beam. The lowering of the water level, which is related to the drawdown directly at the ship, is shown on the vertical axis (ordinate).

The plotted measurements show that the drawdown hardly changes between the side of the ship and roughly one beam distance to it. From there it then declines rapidly up to a distance of about 2.5 beams, where the drawdown decreases to approximately 60% of the value directly at the ship. The rate of decline slows down as the distance increases further. This reduced decrease corresponds to the dimension of the primary wave field, which is scaled with the ship's length. Therefore, in wide channels like the Rhine a reduction of the wave impact on the bank slope can only be achieved by relocating the fairway at a distance of more than about 2.5 B from the bank. In narrow canals, the impact of the primary wave field can generally not be avoided.

In many impounded waterways like the Neckar, the Main or the Moselle, the possibilities for displacing fairways are very limited anyway, owing to the available widths. If it is necessary to limit the wave heights in narrow rivers like those mentioned above. This can effectively be achieved with speed restrictions in combination with rigorous speed controls only. However, in most cases it is not necessary to reduce the permissible speed very much, since even with a minor reduction of about 10% relative to the critical speed the wave heights in narrow cross sections could be roughly halved (see Fig. 4.1.1-9).

If it were possible to persuade only the 3% of all cargo vessels which, according to BAW surveys, sail in the v_{crit} speed range to sail just 10% slower, ship-induced loads could be dramatically reduced. This would reduce the average ship speed by only 0.3%, with a negligible effect on the national economy. But maintenance costs could be saved and the use of alternatives to riprap or sheet-pile walls, e.g. willow plantings, to protect the bank slopes against erosion could be significantly extended.

This is particularly evident when taking a look at wave measurements undertaken, for example, on the Rhine in 2009 along a test section for alternative bank protection methods near Worms (see Fig. 4.1.1-10) where only few wave events higher than 0.5 m were observed. The vast majority of wave heights were in the range from 0.1 to 0.3 metres.

The slope supply flows or refill velocities associated with critical speed situations, which occur in the breaking stern wave and derive their name from the fact that they refill the drawdown trough from backwater, generally result in the highest hydraulic loads on the bank. These flows are visible in Figures 4.1.1-1 and 4.1.1-16 as the "tongue" of bubbling water

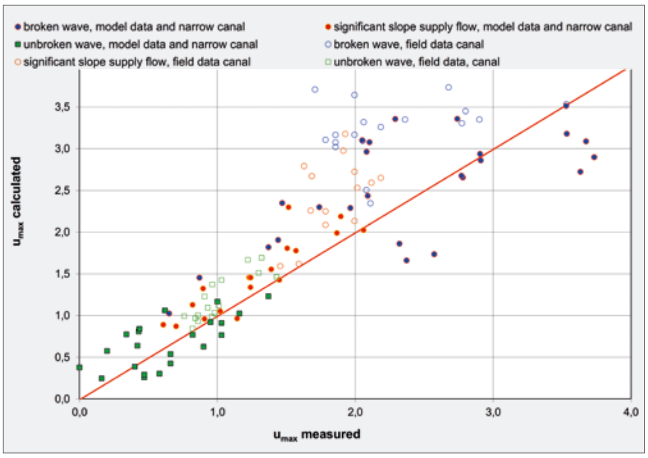


Fig. 4.1.1-11: Comparison of measured slope supply flow velocities (based on field tests on the Weser-Datteln Canal and the Salzgitter Branch Canal as well as model tests at the DST) and slope supply flow velocities calculated using GBBSoft for various stern wave conditions (unbroken to broken) [BAW]

which runs along the bank parallel to the ship. According to measurements in connection with model and field tests, flow velocities u_{max} up to 3.5 m/s were observed (see Fig. 4.1.1-11).

The loads arising from u_{max} are this high because the flow hits the revetments with almost no relevant boundary layer (Söhngen, Pohl, Gesing, 2010). Adding to this is the pressure shock that results from the gushing water in the breaking wave.

The highest u_{max} values occur either with fully laden ships in narrow cross sections where the stern wave which runs against the return flow as in the case of a hydraulic jump breaks earlier than in wider cross sections, where the resulting flow velocities may be higher than the ship speed due to the kinetic energy of the gushing water and the oblique direction of the wave front. Alternatively, the highest u_{max} values may occur in conjunction with high v values, e.g. when sailing with ballast (artificial water ballast at the stern to ensure that the propeller remains submerged while sailing without cargo), even if the wave breaks only partially because the upper limit for u_{max}, which is linked to the ship speed, is higher.

The key to limiting heavy loads on the bank as a result of high velocities u_{max} is preventing the waves from breaking. This can be achieved either by sailing as far away from the bank as possible or by reducing the permitted ship speed and implementing rigorous speed controls, assuming this is economically acceptable and does not affect the steerability of the vessel. Account must also be taken of the nautical minimum speed, which can be close to the critical ship speed for one-way traffic in narrow canals such as the Havel-Oder Waterway.

This speed is required to execute standard manoeuvres within a permitted time window and can be specified as roughly 6 km/h for modern inland vessels. Because v_{crit} is in the range of 6 km/h in very narrow canals, it will be very difficult to avoid reaching v_{crit} along with breaking waves and high u_{max} values in these canals.

If we look at the vessel-induced hydraulic impacts in more detail as they occur from the bow to the stern, the flow around the stern leads to an elevation of the water level astern of the vessel as part of the transverse stern wave. In front of the stern the drawdown due to the return flow field is superimposed on the waves from the local flow around the stern. This effect is less pronounced than in the bow area because the flow around the stern is not always able to follow the contour of the ship due to inertia effects. Nevertheless, wave shoaling also occurs in the stern area. The water level is additionally lowered owing to the propeller suction, and this increases the tendency of the waves to break. Finally, the influence of stern-heavy trim angles must be considered in narrow canals, as they further enhance the drawdown at the stern.

The height of breaking transverse stern waves and the corresponding flow velocities are highest with deep-laden or very stern-heavy ships sailing close to the banks at approximately v_{crit}. This situation and the high waves associated with it can occur inadvertently, e.g. if inland vessels enter shallower navigation channels and if the channel cross sections suddenly become smaller in the direction of motion. The same effect is observed when one ship passes or overtakes another while sailing very close to the bank, so that the effective cross sections available to the reverse flow alongside the ship are reduced.

In addition to primary waves the ship also causes regular wavelets, referred to as secondary waves. These are compared to the primary wave field in Figure 4.1.1-12. The secondary waves are caused by changes in the ship contour both in the bow section, where the hull widens from the bow tip

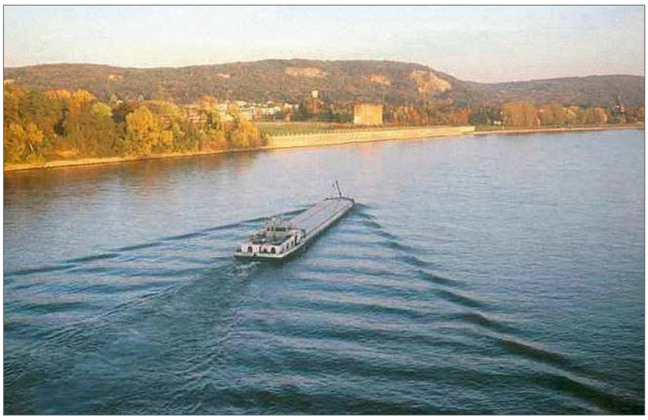


Fig. 4.1.1-12: Primary and secondary waves. Left: Ship in a waterway of limited width and depth. Right: Ship in shallow water [BAW]

towards the full, prismatic cross section, and in the stern section, where the full, prismatic cross section of the ship's hull tapers towards the stern again.

Besides the wave length, which for inland navigation vessels is generally much smaller than the length of the primary wave system, another important characteristic of the secondary wave system is that – in contrast to the primary system, which only occurs in close proximity to the ship – it is also observed at a great distance from the vessel. Although all ship-induced waves must follow the ship, since it is the ship that produces them, secondary waves propagate like open water waves from the vessel towards the banks. As a result only a small amount of the wave energy is lost down this way before the secondary waves reach the banks. Secondary waves are therefore a relevant design aspect for bank protections whenever ships sail at a large distance from the banks.

Nevertheless, the secondary wave heights H_{Sec} decrease as the distance u from the ship increases, namely at a rate of $u^{1/3}$ with diverging bow waves or $u^{1/2}$ with transverse waves, see Figure 4.1.1-13. The diagram shows this decrease at the interference peaks of superimposed transverse and diverging waves, where the secondary waves besides the vessel are greatest. This decrease is caused mainly by a spatial distribution of the wave energy over an increasing width of the wave system and not by dissipation.

Figure 4.1.1-14 shows another important characteristic of secondary waves. With certain vessel shapes and at speeds

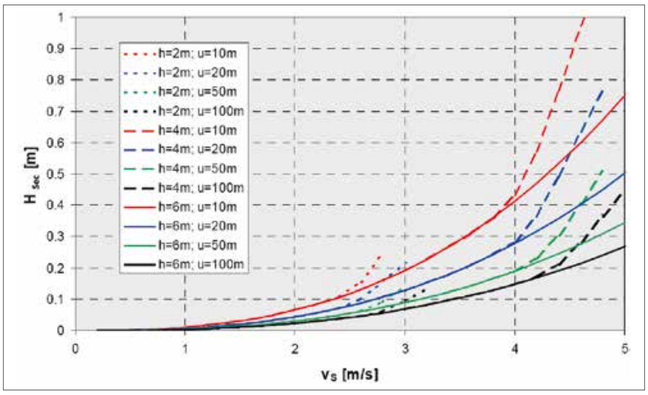


Fig. 4.1.1-13: Height of the diverging secondary waves H_{Sec} at interference peaks, calculated for a GMS (T = 1.6 m) in shallow water conditions sailing at various distances from the midship to the bank u (displacement motion) [BAW]

Fig. 4.1.1-14: Conventional Europe ship sailing at 12 km/h ≈ v_{crit} during tests on the Main-Danube Canal (source: GBB, 2004) [VBW/BAW]

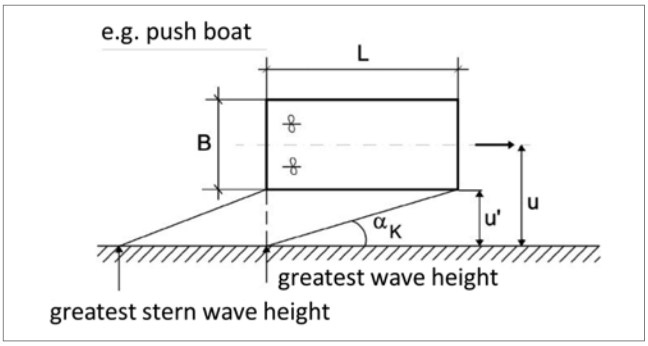


Fig. 4.1.1-15: Schematic sketch showing the wave fronts for the worst-case superimposition of diverging secondary bow waves with the transverse stern wave and the primary wave system ($\alpha_K > 19°$) at the stern [BAW]

Fig. 4.1.1-16: Superimposed bow and transverse stern waves of a tug boat sailing close to the bank – situation according to Fig. 4.1.1-15 [BAW]

exceeding approximately 80% of v_{crit}, the calculated wave heights may increase more with the ship speed than is normally the case.

The secondary waves of large ships are usually independent of the primary wave field, though they can be superimposed on it if the diverging bow waves reach the bank at the same point as the transverse stern wave, as shown in Figure 4.1.1-15. The resulting stern wave height is approximately equal to the sum of the primary stern wave height and half the secondary wave height.

This situation is depicted in Figure 4.1.1-16 which shows a tug boat sailing close to the bank and producing waves about 1.5 m high. These waves wash up the embankment.

There is another feature of distinction between secondary and primary waves. Whereas the latter form basically a lowering of the water level, the former overtop the water table by approximately half of its height. Together with randomly occurring fluctuations in the water level, the height of secondary waves and the corresponding wave run-up determine – amongst other criteria – the required freeboard height in a canal.

Observations have shown that the biggest secondary waves are caused not by cargo vessels but by fast-moving passenger boats and recreational craft; see Figure 4.1.1-17 (Söhngen, Pohl, Gesing, 2010, Maynord, 2005, Söhngen et al. 2008). Considering the ever more powerful recreational motor boats and a growing number of owners – a trend which is predicted to continue in future – the relevance of secondary waves from these boats for the design of bank protection systems will increase along with the safety problems relating to sports boat traffic (Stamm et al. 2012). Furthermore recreational motor boats often sail at high speed very close to the banks in ignorance of the bank impact this creates.

Fig. 4.1.1-17: Secondary waves produced by displacement (vessel right, top and middle) and planing boats at corresponding speeds [BAW]

The dependence of the secondary wave heights produced by recreational craft on the ship speed at the stages of displacement drive through attainment of hull speed to full planing is shown in Figure 4.1.1-18 with reference to model tests at the DST in Duisburg. The wave heights H_{Sec} are relative to the associated values when planing speed is reached. The Froude number Fr_V, a parameter used in ship hydromechanics, replaces the ship speed for a more general representation of the measurements. This number is essentially defined as the ratio of inertia forces to gravitational forces.

The measured values show an initially weak increase in the secondary wave heights with the speed of the craft (region 1). The maximum values are reached in the pronounced transitional region from displacement drive to planing (region 2). For even higher boat speeds at full planing, the secondary wave heights drop down (region 3 in Fig. 4.1.1-18), but the decrease is weaker than the increase at displacement drive. Large yachts, which must not be denied the opportunity to sail at planing speed, should therefore sail as far away from the banks as possible, so that their high waves are decreased.

Small and more compact recreational motor craft like inflatable boats can likewise be classed as critical with regard to the wave

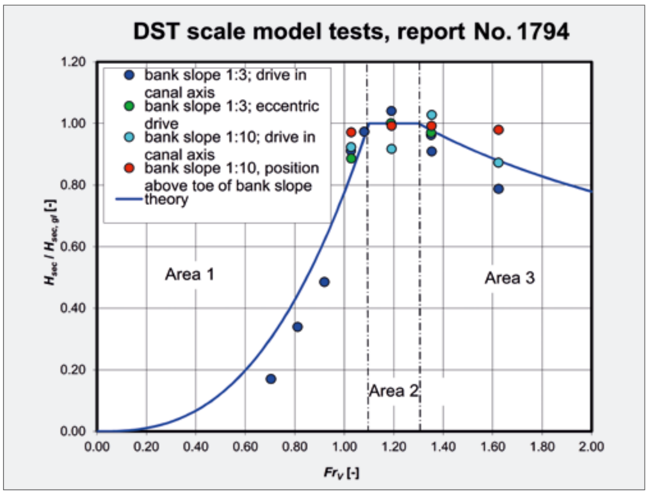


Fig. 4.1.1-18: Dependence of the relative secondary wave heights of recreational craft (i.e. relative to the value during planing) on the Froude number (calculated by using the ship speed and the water displacement to the power of 1/3 as the characteristic length) [BAW]

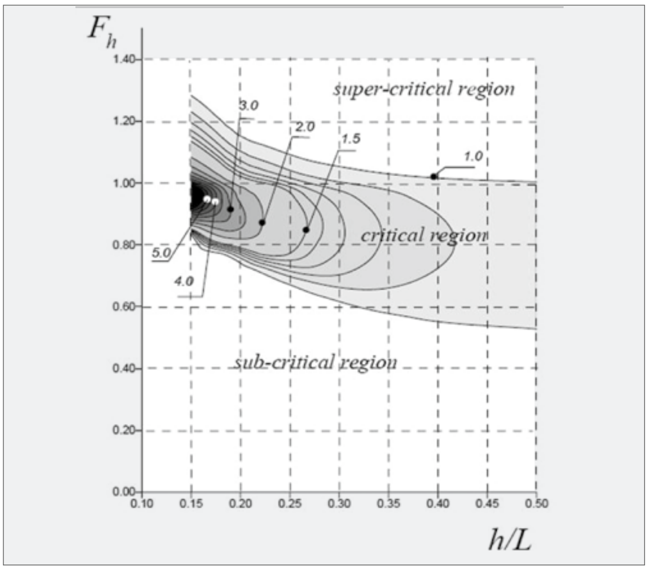


Fig. 4.1.1-19: Ratio of the wave resistance of a recreational craft in shallow water to the corresponding value in deep water as a function of the depth Froude number (ordinate) and the ratio of the water depth to the ship length (abscissa) [BAW]

attack on the banks, because they enter the planing phase even at low speeds and usually also have a distinct stern-heavy angle of trim. Thus, more engine power is necessary to reach the planing mode, i.e. overcome their own high bow waves, and higher waves are produced compared to boats with slim hulls. Additionally, these boats frequently sail very close to the bank, e.g. out of ignorance of the negative impacts. The same applies to scooters as well as to water skiers with their pulling boats. In other words, in large waterways with intense water sports activities the stress on the banks from recreational craft can exceed that from commercial navigation and ultimately determine the stability of, for example, alternative bank protection measures. Regular contact with local motor sports organisations is vital here, for instance in order to limit the load on the banks by implementing suitable codes of conduct (Stamm et al. 2012).

If the waterway is very shallow, as it is in the inner city waters of Leipzig for example (only muscle powered and small recreational motor boats are allowed), it should also be noted that the wave resistance – and thus the wave heights – may increase significantly at boat speeds corresponding to depth Froude numbers around 1.0 and at low relations of water depth to ship length (roughly 0.1 to 0.3), as illustrated in Figure 4.1.1-19 (Hofman, Kozarski 1999, Stamm et al. 2012). In this case, the only suitable remedy to restrict wave heights to an acceptable

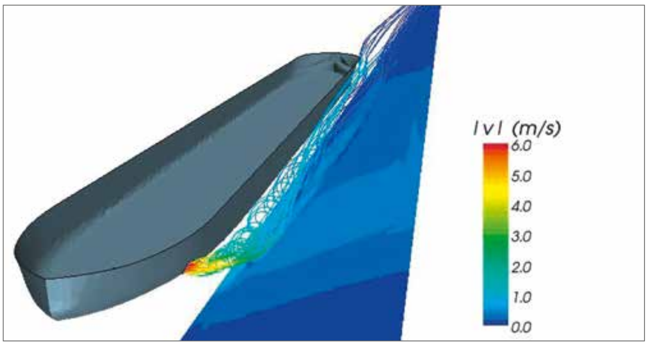


Fig. 4.1.1-20: Calculated flow velocities arising from the bow thruster of a GMS sailing at 6 km/h and a distance of 4 m between vessel bilge and bank slope [BAW]

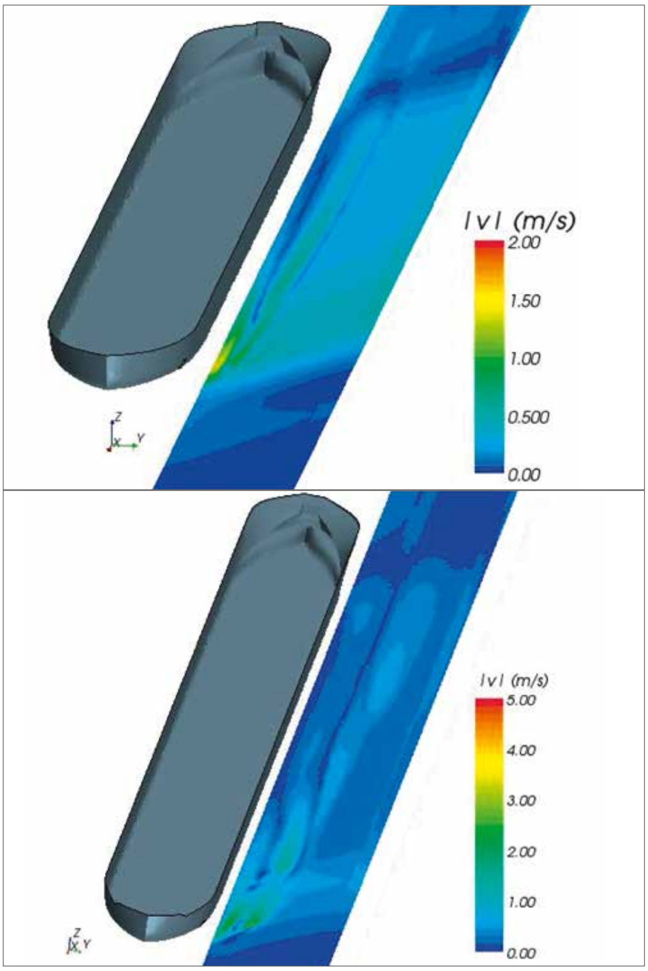


Fig. 4.1.1-21: Calculated flow velocities (values for a stationary observer standing on the bank) close to the bank slope (bank parallel plane 7.5 cm above the bank revetment) for a GMS (top) and for a powerful, modern Rhine ship with a length of 135 m (bottom); note the different scales used to represent the flow velocities [BAW]

limit, e.g. to ensure safe navigation of human-powered boats is a rigorous speed limit, possibly differentiated according to vessel types. The city of Venice, for instance, limits the speed of boats on its narrow canals to just 5 km/h and imposes stiff penalties in the event of proven non-compliance, because the stability of its historic buildings depends on it.

Other important vessel-induced impacts on the waterway beds and banks result from the jet velocities of the bow thruster as well as the main propulsion system of inland navigation vessels. Particularly when a ship is sailing slowly in a narrow canal section, using the bow thruster can place heavy loads on the banks (Schokking et al. 2003). The slower the ship is moving and the smaller the distance to the bank, the lower is the deflection of the bow thruster jet towards the aft through the flow around the vessel and the expansion of jet beam, and consequently the higher are the jet velocities approaching the bank (see Figures 4.1.1-20 and 4.1.1-21).

Loads from the bow thruster are therefore mainly relevant in narrow waterway stretches with manoeuvring situations performed at reduced vessel speed. These are encounters of big vessels or overtaking as well as berthing manoeuvres. Damages are severe, especially where bank protection measures only protect the zone of fluctuating water levels but not the toe of the embankment. A sufficient distance from the banks is the key to limiting attack from propeller jet to an acceptable extent. For modern inland navigation vessels this distance can be estimated as approximately one vessel beam width.

It should be noted that some of today's bow thruster systems are comparable in terms of power with the main propulsion system of a conventional Europe ship. In the case of four-channel bow thrusters, the most common type of active bow rudder, the water is sucked in from below through the ship's bottom and then accelerated forwards (e.g. for stopping), backwards or to the left or right by means of a pump for steering. A concentrated jet is produced, with velocities at the outlet similar to those of the main propulsion system. It can therefore be assumed that the impact on the channel bed and banks arising from newer types of bow thrusters, which are larger than those of conventional ships, will significantly increase in future.

The loads due to the propeller wash of the main propulsion system are also likely to increase further (Aberle et al. 2008, Spitzer et al. 2012) – not just because of the increasing size of the vessels, which demand more propulsion power but also as a result of the unbroken trend towards more powerful engines when replacing an existing one. The highest loads are caused by the strongly swirling flow field of the rotating screw in combination with small dynamic underkeel clearances and low ship speeds. Thus, high flow velocities close to the channel bed from the propeller wash are - as is the case with the bow thruster - mainly caused by manoeuvring ships. But also the banks can be affected because modern twin rudder systems can deflect the wash almost orthogonal to the bank in the full rudder position. The loads are similar to those produced by a bow thruster, though often on a much higher level. In conjunction with high water levels and shallow draughts, even near-bank vegetation or alternative, technical-biological bank protections may also be affected because the propeller jet can reach higher areas of the bank in this case.

Together with bank protections extending right down to the canal bed and appropriate ship speeds ensuring that the vessels are not permanently forced into manoeuvring situations, a large distance from the bank prevents scouring from the propeller wash. On the other hand, if the highest navigable level (HSW) is only slightly higher than the usual level, as is generally the case in impounded waterways and canals, any loads induced by the ship's propulsion system and steering systems are generally not relevant for the stability of bank protections because they do not reach the toe of the bank protection.

If a ship is sailing under normal cruising conditions, that is at a significant and more or less constant speed (normal speed), the load on the bed and the banks from the propeller wash is much less than in manoeuvring situations. This is because the displacement and return flow deflect the propeller wash away from the channel bottom and because the area of the river bed affected by high loads is small compared to, e.g. the affected area of the return flow. Moreover, as the vessel moves quickly forward, the load duration is short. When specifying the permissible ship speed it is therefore important not to look only at the demands of safety and ease of navigation and the bank impacts from waves, but also to consider the loads induced by the propeller wash.

4.1.2 Squat and power demand

The weight of the inland navigation vessel is compensated by the vertical components of the water pressure on the hull, leading to the hydrostatic buoyancy (floating condition). If the water level is dynamically lowered in the area around the ship, the ship will also move downwards, because it still has to be sufficiently submerged in the surrounding water body to produce enough hydrostatic uplift.

As described in Chapter 4.1.1, the water level drops as a result of the flow field generated by the moving vessel. The reason for this is that the local velocity of the water flowing around the ship is higher than the vessel's approach velocity and the higher kinetic energy of the flow close to the ship must be compensated by a reduced potential energy, in other words a lower water level, on account of the energy balance. This lower water level can be seen in Figure 4.1.2-1. The amount

Fig. 4.1.2-1: Pushed convoy on the Main-Danube Canal near Riedenburg. The drawdown is visible from the flow from the ox-bow in the foreground towards the canal [BAW]

by which an inland navigation vessel sinks into its self-created drawdown trough is referred to as "squat". In the literature this term is normally used for the maximum value of the sinkage which can occur at the bow or stern of a single ship or at that part of a convoy, e.g. the stern of the barge, which is coupled just in front of the pusher as shown in Figure 4.1.2-2.

Stern-heavy trim angles mainly occur close to the critical ship speed. Squat and the risk of grounding are greatest in this situation.

With plump bow shapes, however, the local wave system at the bow due to the displacement flow can likewise lead to a strong suction effect, so that the ship has a bow-heavy trim angle even if the drawdown trough becomes deeper on average from the bow towards the stern. This especially applies in shallow water, i.e. in channels of limited depth but almost unconfined width. The waves produced by the local displacement flow around the bow may be much higher in this case than the drawdown in the prismatic midship section. Consequently, it is possible that the same ship has a stern-heavy trim angle in a canal and a bow-heavy trim angle in shallow water.

Barges usually also have a bow-heavy angle of trim as they tend to have a fuller bow shape than large motor vessels to enable them to carry more cargo. The bow-heavy angle of trim of a convoy's leading barge is particularly pronounced if two barges are breasted up stern to stern. In this case, there is no suction effect from the flow around a slim stern or from the propeller as with a self-propelled ship, which would compensate the suction at the bow. There is also no suction effect at the coupling point to the second barge, but a strong suction effect at the bow of the second barge, together with the one at the bow of the pusher. This leads to an increased squat at the front and aft of this convoy and a small squat at the coupling point between both barges, see Figure 4.1.2-2.

The trim angle is also influenced by the bed roughness and, in rivers, by the driving direction. Squat calculations as indicated in Figure 4.1.2-3 show e.g. a strong stern-heavy trim angle at high vessel speeds of a large motor vessel, sailing upstream in the mountainous part of the Rhine Valley near Clemensgrund with a partly rocky river bed. The vessel is

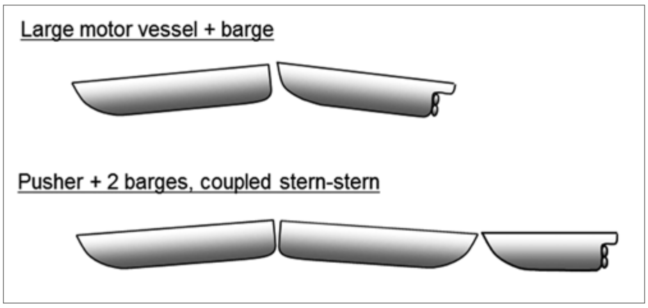


Fig. 4.1.2-2: Trim of a single-lane, pushed convoys based on model tests at the DST [DST]

laden according to the possibilities of the assumed water level GlW (similar to RNW on the Danube) + 1.25 m (this is approximately mean water level). The navigational effective width of the channel here is about 170 m, the water depth approximately 3.4 m, the average flow velocity is about 1.6 m/s and the equivalent sand grain roughness of the river bed is assumed to be 0.2 m.

The calculations were performed for various ship speeds v relative to the water, showing an increase of the stern-heavy trim angle towards the critical ship speed. Amongst other things, this stern-heavy trim is a result of the steep water surface slope in this reach of the Rhine river, which is increased strongly by the vessel-induced return flow field. This water level gradient has to be overcome by the ship when sailing upstream. The ship's resistance and the power demand are accordingly high; a typical GMS powered with a 1200 kW engine would be unable to reach the critical ship speed. The latter is indicated in the graph by the sharp increase in squat and is calculated to be about 4.3 m/s in this example relative to the water (15.5 km/h). The restricted engine power allows only 3.8 m/s speed through the water or, due to the flow velocity of 1.6 m/s, only 2.2 m/s over ground (approximately 8 km/h). A steep water gradient, together with high bed roughness, can thus have a greater influence on the ship's behaviour than the cross sectional relations.

In contrast to this, downstream sailing is facilitated by the water level gradient. Together with the fact that there is no significant backup of water in front of the bow due to the reduced return flow, this leads to a pronounced bow-heavy trim angle, even at critical speed. This can be seen from Figure 4.1.2-4 where calculations with the same boundary condi-

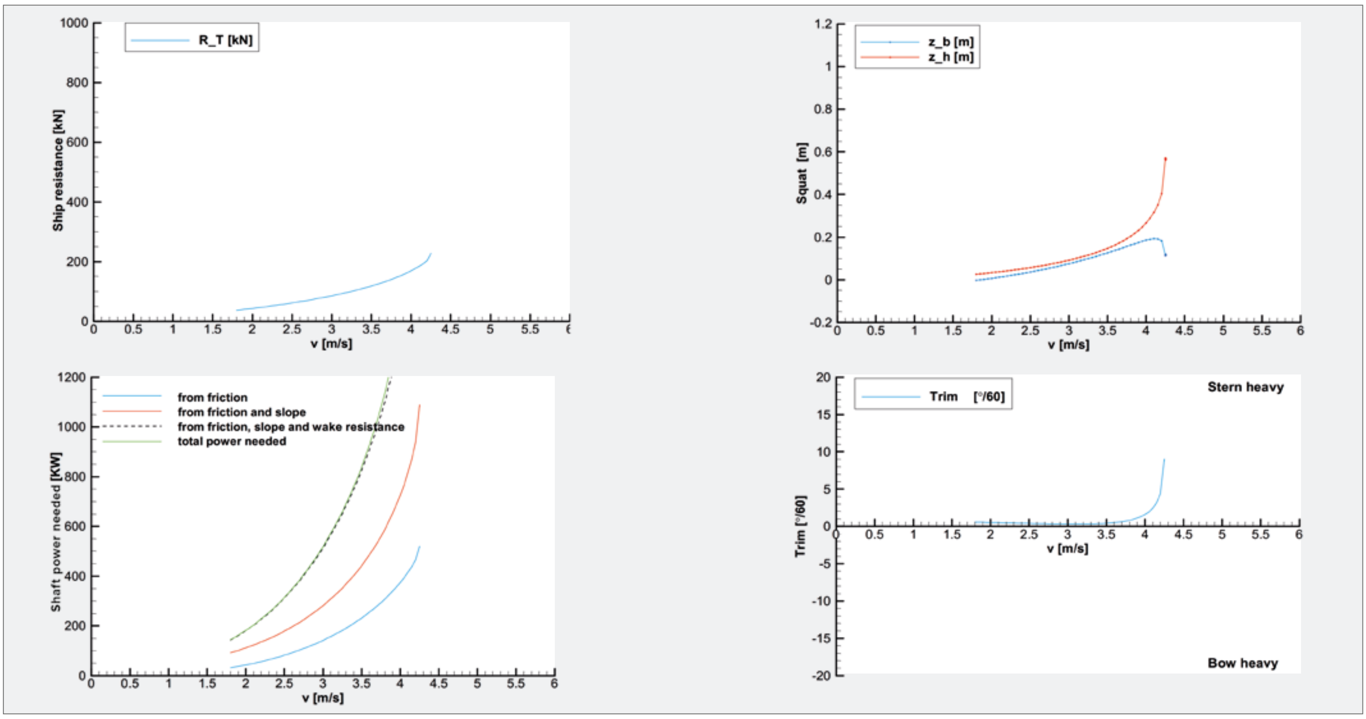


Fig. 4.1.2-3: Calculations concerning ship's resistance R_T (top left), squat (top right) at the bow z_b (blue) and stern z_h (red), power demand PD (bottom left, measured at propeller shaft) and trim angle (bottom right) of a GMS sailing upstream the Rhine near Clemensgrund at GIW + 1.25 m[BAW]

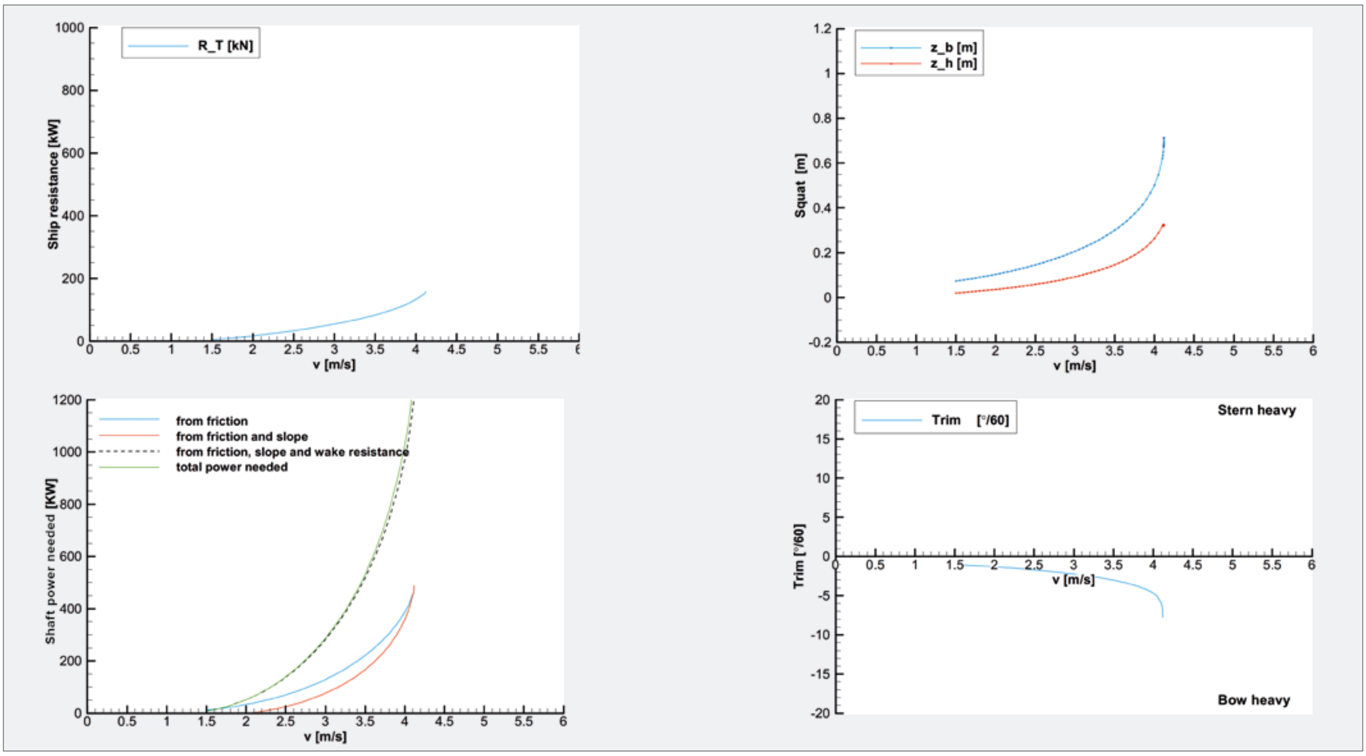


Fig. 4.1.2-4: Downstream drive of a GMS at Clemensgrund – same boundary conditions as in Figure 4.1.2.-3 [BAW]

tions as in Figure 4.1.2-3 but with the opposite driving direction are shown. The critical speed is slightly smaller in this case compared to the uphill drive, because of the reduced backwater effect, and it can now be easily reached despite the limited engine power, so that the ship can theoretically sail at about 4.1 m/s through the water or, as in this example, 5.7 m/s or 20.5 km/h over ground. Even if only 30% of the installed engine power were used (400 kW), it would theoretically be possible to sail over ground at 17.6 km/h whereas no more than about 4.0 km/h could be achieved upstream with the same power. A sufficiently powerful engine is therefore essential – not only on the Middle Rhine but also when sailing upstream on the Danube – to prevent that fully laden or less powerful upstream craft are obstructing other waterway users while sailing upstream.

Besides the wave-making resistance, which is not important for large inland navigation vessels, the resistance of a moving vessel always consists of the frictional resistance, the flow separation resistance, the propeller suction, the water surface gradient resistance which can be increased due to the return flow and the associated backup of water in front of the bow and the resistance of the rudders. The power demand is calculated from the ship resistance, multiplied by the ship speed through the water and divided by the transmission efficiency and the propeller efficiency. Amongst other things, the latter depend on how close to the design conditions the propeller is operating

An overall hydraulic propeller efficiency of approximately 0.6 can be achieved under design conditions. In practice, however, it is often only around 0.4 as a ship has to sail under a variety of boundary conditions that may be far away from the design point. For example, a ship sometimes forms part of a pushed convoy, rather than sailing individually, in which case it may sail much slower. On the other hand, if it is unladen, it will move much faster than under design conditions. Moreover, a vessel is frequently required to sail in narrow canals or in navigation channels of severely limited depth, so that the approach flow conditions regarding the propeller are impaired. In other situations, it may have to sail upstream with high propulsion power to work against a strong flow or downstream with low power, as shown above in the example of the Middle Rhine. In other words, the boundary conditions under

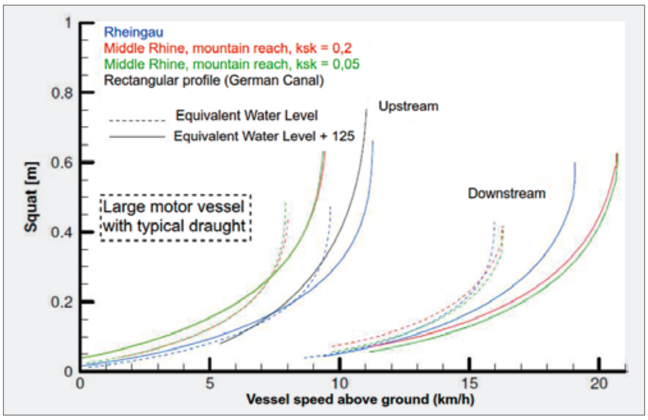


Fig. 4.1.2-5: Calculated squat (maximum values at the bow or stern) at various ship speeds over ground for a fully laden (according to the water level in the Rheingau region as well as in the mountainous stretch) GMS, compared to the standard rectangular profile with a load draught of 2.8 m (no engine power restrictions) [BAW]

which an inland navigation vessel is operating vary considerably compared to those for seagoing ships, leading to a more complicated design and inferior efficiency.

Added to this, the engine sometimes has to run at part load. As a result, not only the propeller's efficiency is generally lower, but also the efficiency of the diesel engine compared to the design point, because the specific (related to engine power) fuel consumption is higher for these lower engine speeds.

Figure 4.1.2-5 shows other typical calculations for various water levels of the Middle Rhine compared to the German standard rectangular canal profile described in the corresponding guidelines (ksk refers to the equivalent sand grain roughness of the channel bottom in m). The significant influence of the flow velocity on the ship speed over ground when sailing upstream is clearly visible. In the Rheingau region with its large cross sections and low flow velocities it is possible to sail much faster over ground than with the same squat in the mountainous stretch with its high flow velocities. However, with the water levels (GlW & GlW + 1.25 m ≈ MW), flow velocities (Rheingau 0.9 and 1.1 m/s, mountainous reach at Clemensgrund 1.2 and 1.6 m/s) and corresponding draughts (1.75 and 2.75 m) applied in this example, and assuming a typical squat of 0.2 to 0.3 m in the Rheingau, the water level has no noticeable influence on the achievable ship speed upstream. Thus, for fully loaded vessels the speed over ground going upstream is nearly independent of the water level considered in this reach of the Rhine river. Figure 4.1.2-5 shows further that the achievable speed over ground, when sailing downstream at low water levels is about the same in the Rheingau and the mountainous reach, because the reduction of speed due to the lower flow velocity in the Rheingau region is compensated by the effect of the larger cross sections in this area compared to those in the mountainous reach. At higher water levels, on the other hand, it is possible to sail much faster downstream in the mountainous reach because the cross sections and the flow velocity also increase.

Assuming again the same average squat as in the Rhine examples, in the standard rectangular canal profile with a water depth of 4 m and a load draught of 2.8 m it is possible to sail roughly as fast as on the Rhine at mean water level. However, the limited cross section in the rectangular profile leads generally to a significant increase in squat at critical speed – to approximately 0.9 m – as opposed to around 0.4 to 0.6 m downstream or 0.5 to 0.7 m upstream in shallow water on the Rhine (the lower values refer to the lower water level GlW and the higher values to MW). In other words, the critical speed is reached with lower squat on the Rhine or generally in shallow water conditions than in a canal, because the difference between the squat at normal cruising speed and the squat at critical speed is smaller in shallow water. This fact, together with the usual exploitation of available water depth for maximising the load draught in rivers, leads to less underkeel clearances at depth bottlenecks for deep draught vessels in rivers than in canals and a higher risk of grounding.

The increase in squat at the critical ship speed v_{crit} is likewise much more marked when sailing upstream in a large waterway than it is in a canal, i.e. the “sucking effect” of the river bottom appears only just before v_{crit}. Thus, if the ship speed is increased only slightly in the critical speed range, an abrupt increase in squat is likely, leading to possible contact with the channel bed. On the other hand, it seems generally possible in shallow water to reduce the squat to a large extent, because the corresponding vessel speed is still acceptable. So, depth bottlenecks in rivers will be passed very carefully with minimum speed to ensure manoeuvrability only to avoid grounding.

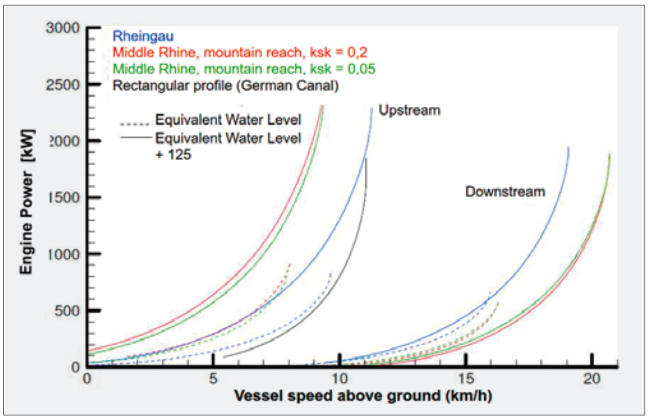


Fig. 4.1.2-6: Calculated propulsion power required for the conditions in Figure 4.1.2-5 [BAW]

It should be noted that the availability of the necessary propulsion power to reach v_{crit} was assumed for all calculations presented in Figure 4.1.2-5. But as Figure 4.1.2-6 shows, the necessary engine power can be very high, which is why less powered ships are not able to reach v_{crit} in shallow water. This holds true even for modern vessels with a medium sized engine of let’s say 1,200 kW. They are theoretically capable of reaching the critical speed, but only at low, not at average water level in the Rhine reach considered herein. Approximately 2,000 kW would be needed for this purpose. Hence, only at low water levels is there a high risk of grounding due to reaching the critical ship speed range, even if the underkeel clearance will be the same for higher water levels too.

Even in the German standard rectangular profile a GMS needs a powerful engine to reach v_{crit}. This power is smaller in the standard trapezoidal profile because the critical ship speed there is lower. Thus, the risk of reaching v_{crit} is higher in the trapezoidal than in the German rectangular canal profile. Older ships with less powerful engines, as the majority of the Europe Ships, are even unable to reach v_{crit} in this profile and hence cannot produce the high waves associated with this critical sailing condition. For this reason, the loads on canal banks did not increase significantly in the past until larger ships with more powerful engines obtained authorization to use these canals that were originally designed for Europe Ships, forcing the design standards to be revised – especially with regard to revetment design. Of course, more powerful engines – which are generally a good idea for nautical reasons as they improve steerability and make sure the ships can be manoeuvred past bottlenecks at a sufficient speed, e.g. at the free flowing Danube River reach between Straubing and Vilshofen or the Middle Rhine Stretch – simultaneously place additional stresses on the channel banks and bed.

Figure 4.1.2-6 demonstrates again the above-mentioned influence of the bed roughness on ship dynamics. The propulsion power increases in the case of an upstream sailing vessel because the ship resistance due to the water level gradient is higher. When sailing downstream, on the other hand, the rougher bed results in a steeper water level slope while the resistance and power are both lower than with a smooth bed.

The above calculations, which serve to demonstrate the various factors influencing squat and power demands, are made under the assumption of a ship sailing steadily in a prismatic fairway. In reality, especially in a river, the cross section shape and area, the water depth and flow velocity change constantly, both over time and along the ship. For example, if the water in the bow area is shallower than at the stern, so that the ship sails from deeper water into shallower water, this can result in a bow-heavy trim angle while the same vessel may trim stern-heavy in a prismatic channel with the same shallow cross section as in the bow area. In extreme cases, this could mean that the flow conditions associated with the critical ship speed – indicated by a breaking wave – are reached at the bow, but not at the stern. This could in turn cause the bow to be pulled towards the bed in the case of small underkeel clearances while a larger clearance is maintained at the stern.

The trim of inland navigation vessels is therefore additionally dependent on prior driving situations, and this particularly affects bow squat. This is one reason why ships in scale model tests can have different trim angles in two tests performed under identical conditions. Even minor events such as the way the model ship will be accelerated or unavoidable disturbances in the towing channel as from reflected ship-induced waves can alter the trim angle. Hence, the bow squat can never be predicted with the same accuracy as the stern squat, which is usually larger and is generally more important in narrow channels than the bow squat, especially because the consequences of grounding at stern with its sensitive propulsion and steering devices are much more severe than running aground with the bow.

Since the available calculation methods used, for example, in ship handling simulators assume generally a quasi-steady driving condition for computing drawdown, squat, vessel resistance and power demand, taking the channel cross section at the actual vessel position to be a virtual prismatic canal, there will always be significant differences between calculations and field measurements in the case of unequal channel geometry, especially when the depth of the cross section is subject to huge changes. However, as all shipmasters are keen to avoid contact with the bed, they reduce their speed on entering shallower water at a ford, for example, although this speed may be still faster than when the complete ship is in the ford.

4.1.3 Swept area width when sailing straight ahead

If a ship's path is plotted, one can see that the vessel "meanders" to a varying extent on either side of a central axis. The amplitude of the pendulum movement increases, the more room shipmasters have to manoeuvre and the more difficult it is for them to orientate themselves (for example, when visibility is poor) and the less attention the helmsmen pay or are able to pay owing to the traffic situation. The amplitude of this sinusoidal vessel course decreases the narrower the cross section, the easier it is to find the way, e.g. in a canal, and the more attention has to be paid, e.g. while sailing past bottlenecks or if one ship passes another. The pendulum motion is thus a human factor which must be considered when designing a fairway. But there are also physical causes like the turbulence in a river or the interaction forces with the bank to which some shipmasters react faster and more efficiently than others.

The most important physical cause of the above-mentioned instabilities in the course taken by an inland navigation vessel, which has a crucial influence on the additional width in combination with the human factor, is the "unstable moment"; refer also to Figure 4.1.3-1. This diagram shows a ship which has inadvertently drifted slightly starboard from its straight-ahead course (i.e. to the right in the direction of travel). The resulting oblique flow of water towards the ship's hull then causes the ship to drift farther to the right (unstable moment). Unless suitable measures are taken to counter this drift, the ship will sail even farther off course. As soon as the shipmaster notices that the ship has drifted off course – which is easier if the bank can be used for orientation – the helmsman will generally apply counter-rudder unless he is distracted or not paying attention, for example, and his reaction is therefore delayed ("human factor"). It is assumed in Figure 4.1.3-1 that the pilot only steers with the stern rudder, even if a bow thruster is available, because this is normal during easy sailing on inland waterways except in manoeuvring situations. The stern swings starboard as a result and the vessel turns to the left. The same movement may then be repeated to the port side when the ship oversteers owing to its big mass inertia and the water which is moved by it (added mass).

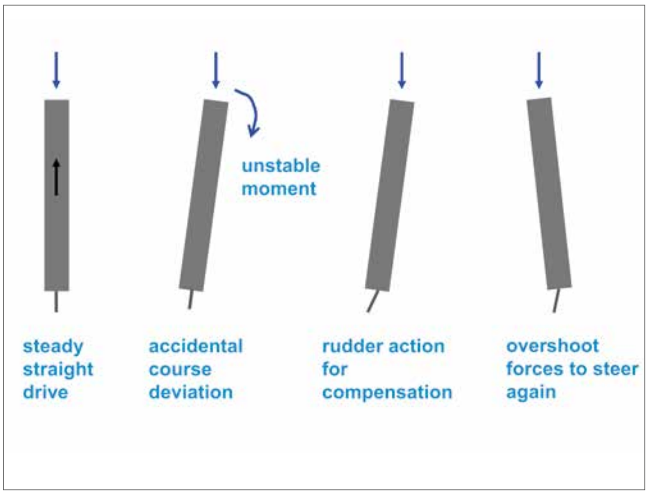


Fig. 4.1.3-1: Phases of a “meandering ship course” and helmsman's reactions [BAW]

As a result the ship generally follows a "meandering course" as mentioned above, the amplitude of which increases with the unstable moment. The latter mainly depends on the geometry of the hull: the plump-shaped bows of older inland navigation vessels have a more pronounced unstable moment compared to slim, more modern ships. Together with the human factors explained above, for example the helmsman’s inattentiveness, the shipmaster's reaction time and difficulty to orientate himself and other physical reasons such as the undesirable transverse forces acting on the ship, e.g. caused by cross flows, these effects scale the amplitude of the meandering motion of an inland vessel.

No generally accepted approach currently exists for the additional widths due to the instability of the ship's path or the shipmaster's inattentiveness. These "meandering widths" moreover vary considerably depending on the reach of the waterway with its specific properties. They are generally derived from field and model tests for this reason, as documented e.g. in BAW studies of the Middle Rhine, of the Neckar or the Hildesheim Branch Canal.

For this purpose, the lateral and rotational acceleration of test ships were derived, based on GPS measurements. They were then analysed by means of a spectral analysis in order to extract the interesting accelerations due to instabilities and human factor from the spectrum of all of the observed accelerations, especially by eliminating the accelerations when navigating bends. The double integration in time of the relevant accelerations leads to the required additional widths.

An evaluation of these observations shows that the additional widths due to the human factor are more or less independent of the curvature of the vessel’s course. Obviously, in the sailing situations studied, bends were navigated with the same level of attention as straight stretches in wide rivers like the Neckar and the Rhine. Assuming the same degree of safety and ease of navigation, roughly the same additional widths are therefore required in bends and straight sections alike.

However, the tests assessed so far indicate that these additional widths are strongly influenced by irregularities in the banks and above all by the ship speed and the flow velocity. To account for these effects, scale model tests concerning one-lane traffic, carried out by the US Army Corps of Engineers for conditions in the Mississippi River, were evaluated by the BAW. The fairway width was reduced in these tests by means of buoyage until safe sailing was no longer possible. The fairway widths which were just acceptable for a safe navigation were then used for analysing the wanted additional widths. The model tests cover a wide range of boundary conditions such as vessels of different lengths and beams as well as extreme variations in the ship speeds and flow velocities both upstream and downstream. They also have the advan-

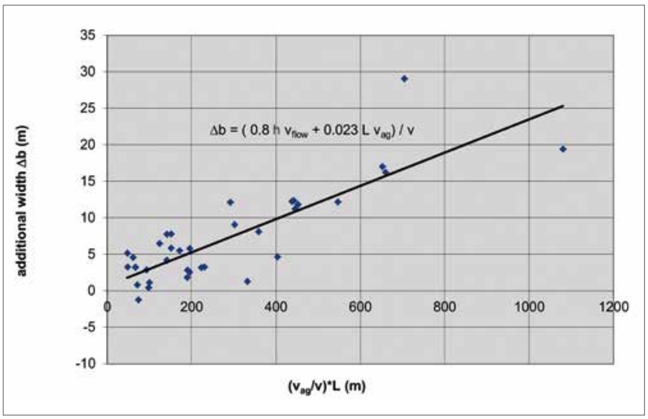


Fig. 4.1.3-2: Additional width due to instabilities and human factor, reduced by the influence of turbulence in a natural flow field ($0.8v_{Flow}/v$) and plotted as a function of the product of the ship length L and the ratio of the ship speed over ground v_{ag} to the ship speed through water v (based on model tests carried out at the ERDC) [BAW]

tage that potential influences from cross flow fields are negligible because the sections of the Mississippi considered and modelled have a largely regular course, although there is a slight influence on the observed additional widths due to an oblique ship course in the fords of the river, because large pushed convoys generally traverse the river from one fairway side to the other after passing a bend to stay in deeper water.

The BAW's first step in evaluating these scale model data was to eliminate the extra width in curves on the observed necessary fairway widths to obtain the wanted extra widths due to instabilities. These data were then analysed to identify the remaining influences of the curvature, the flow velocity, the type of craft, etc. No significant influence was identified either for the curve radius or for the width of the craft. The effect of the flow velocity was unexpectedly great, however, with no major difference between upstream and

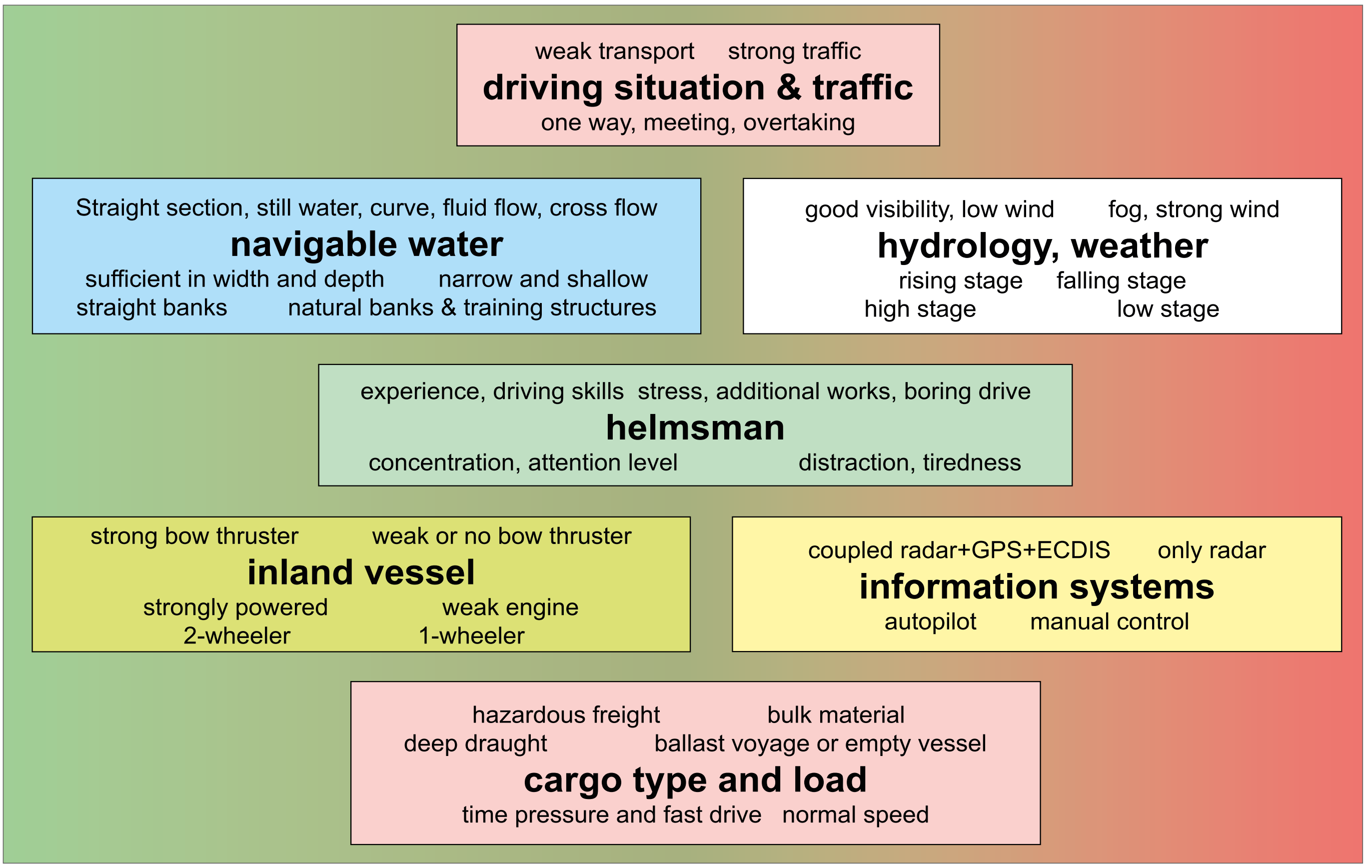


Fig. 4.1.3-3: Aspects to be considered when evaluating the safety and ease of navigation quality – easier and safer on the left (green background), limited ease and safety on the right (red background)

downstream. This indicates that the influence of the flow results mainly from large scale horizontal turbulence and its temporary cross flows, which cause the craft to undergo a lateral shift.

If the additional widths observed are now reduced by this portion and plotted as a function of a theoretically reasonable factor L v_{ag} / v (L = ship or convoy length, v_{ag} and v = ship speed over ground and through water), based on the assumption that a shipmaster only reacts to the ship drifting off course if a specific angle relative to the desired course is exceeded, the very scattered data nevertheless reveals a significant dependency, as shown in Figure 4.1.3-2. This formula can only provide a starting point because there are too many influencing parameters. It should always be verified or optimised with additional field data.

A value of about 15 - 16 m is calculated for a 110 m long breasted-up formation (22.8 m wide) sailing downstream on the Danube at HSW, a speed of approximately 14 km/h over ground, a flow velocity of 2.5 m/s and a water depth of approximately 5.5 m. This is almost four times the amount specified in the German Guidelines on Standard Cross Sections for the encounter of two ships (lane width 15.5 m – beam 11.4 m = 4.1 m) and confirms that the influences of the flow and ship speed must not be underestimated in natural rivers with high flow velocities.

This extra width is smaller in canals where it is easier for the shipmaster to orientate himself because the bank line is very close. It can be specified as approximately 7 m for normal loading and ship speeds in accordance with the German guidelines which demand safety and ease of navigation for one-way traffic over long stretches to be “nearly unrestricted”. This value applies to single-lane push tow units with a maximum length of 185 m. For sections with two-lane traffic by these vessels – a situation providing only limited ease of navigation – which can only be navigated safely if both shipmasters remain very attentive (they must cooperate!) while passing each other, the German guidelines specify a figure of around 4 m.

This value is confirmed by the measurements in Figure 4.1.3-2 which thus correspond to a driving situation where the ease of navigation is limited, if the regression line shown in the graph is used. For vessels passing narrow bridges on the Neckar river, where the utilisation of the extra widths due to instabilities and human factor is not possible, the BAW's evaluation of field data yields an extra width of about 2 m on average. The ease of this driving situation can be classed as "strongly limited” over short distances, which can only be mastered using all available nautical means such as bow thrusters.

In addition to the aforementioned influencing parameters such as ship dimensions, vessel speed and flow velocity, field measurements from the rivers Rhine and Neckar show that unladen or partially laden vessels, corresponding to lower draught-to water depth ratios tend to require larger additional widths compared to vessels with a higher draught-to-water depth ratio. This influence was not varied during the model tests presented in Figure 4.1.3-2 and therefore could not be investigated. But the most important influence on the "meandering width" seems to be the level of attention of the helmsmen and the availability and efficiency of nautical means. From the infrastructure perspective, it has to be decided therefore which level of ease is desirable or which limitations may be acceptable. The safety of shipping traffic should always be ensured, even in cases with limited ease, e.g. the permitted speed should be reduced if necessary.

Figure 4.1.3-3 and Table 4.1.3-4 show criteria based on which the necessary ease quality can be chosen (source: BAW). Depending on the number of aspects mentioned in the right half of the Figure (red background) and the number of criteria favouring a higher level of ease (third, red coloured column from the left in the table) – such as a high traffic volume or high ship speeds – or rendering a lower level acceptable (fourth, green coloured column in the table or left half of aspects in the Figure), such as a good overview of the navigation channel or an optimally equipped ship, the above-mentioned extra widths due to instabilities and human factor should be chosen to be higher or lower. The same basically applies to the required safety distances.

Criterion		Arguments in favour of a higher necessary ease score for design	Cases where a lower ease quality may be acceptable for design
1	Depth exploitation and type of load	Deep draught vessels, especially with dangerous goods in very shallow water	Empty or ballasted vessels, no dangerous goods, sufficient water depth
2	Level of training, personnel skills and experience	Poorly trained pilots, little knowledge on waterway features and infrastructure	Optimally qualified and experienced helmsman
3	Attention level, distraction and stress of the pilot	Long-time or boring drive, permanent manoeuvring conditions	Short manoeuvre situation, e.g. while encountering a vessel or passing a bridge opening
4	Width exploitation of waterway, danger level, possible damages	Small fairway width, buildings, quay walls, floating facilities, vessel berths in the vicinity of the navigational area, danger of life and limb in case of accidents	Sufficient fairway dimensions, sloped banks, guiding walls, parallel dikes or short groynes besides the fairway
5	Uncertainty of waterway conditions	Turbulence, secondary currents, irregular banks, long groynes, rocky or stony river bed, wind, fog	Regular shoreline, sloped sand or gravel banks, low wind speed or wind protections
6	Traffic situation, ship-ship and ship-bank-interaction	One-way traffic, many manoeuvres, e.g. overtaking	2 or more navigational lines, accepted interaction forces
7	Vessel equipment and instrumentation	Main rudders only or weakly powered bow thrusters, sea going ships, low engine power, no information systems	Strongly powered bow thruster or passive bow rudder, high engine power, dual propellers, optimal information systems
8	Vessel speed over ground, individual drive	High target vessel speed, e.g. because of safety reasons to ensure manoeuvrability or to ensure economic navigation	Low acceptable (e.g. because the reach is short) or necessary (e.g. to restrict impacts) ship speed
9	Feasible speed range relative to water between v_{crit} and minimum speed to ensure steerability	Physically possible speed range is small, e.g. because of narrow cross sections, low water depths, low powered vessels, small curvature radius	Sufficiently large possible speed range, e.g. because of low draught, straight channel alignment, highly powered vessels or highly steerable modern vessels
10	Hindrance due to recreational boating	Strong negative effect, e.g. on possible average speed, especially because of many human powered boasts	No significant influence on speed of freight vessels, e.g. because mainly motor boats with good manoeuvrability
11	Traffic density of commercial navigation	High traffic density, resulting e.g. in a significant reduction of possible average ship speed	Low traffic density

Table 4.1.3-4: Criteria for specifying the necessary ease of navigation of freight vessels (e.g. for the design of waterways)

Fig. 4.1.4-1: Two GMSs with good (sailing close to the left bank, early turn into the lay-by basin, photo right) and not-so-good strategies to enter a lock approach (sailing on the outside of the bend and drifting off in the cross flow field, left photo) [BAW]

4.1.4 Additional widths in a cross flow field

Inland navigation vessels float in the surrounding body of water and have the same mass as the displaced water. Therefore they react very strongly to flows. Figure 4.1.4-1 shows the typical effect a cross flow field has on the ship. It depicts a large motor vessel (GMS) manoeuvring into the Hirschhorn lock on the Neckar from the upstream direction at HSW. The ship can be seen sailing with the bow pointing towards the left bank of the upper lock approach area even though another ship is sailing towards it out of the left lock chamber (looking in the direction of travel). In spite of this, the shipmaster must choose this collision course in order to compensate the effect of the above-mentioned cross flow field, which in the photograph runs from the left bank to the end of the dividing dam (in the centre of the photo on the right; the Neckar water is forcing its way to the weir in the top right). This cross flow field would cause the ship to drift towards the weir if the shipmaster did not correct the course by steering to the left and adopting an appropriate drift angle, in other words by positioning the ship at an angle in relation to the actual course. Put simply, the cross flow from left to right will be compensated by navigating to the left. As a result of this, the ship needs a traffic space that is much larger than its own beam in this example.

Since the cross flow velocities increase from left to right in Figure 4.1.4-1 (towards the end of the pier), the shipmaster tries to continue sailing as close as possible along the inner bank on the left. These efforts are supported by suction effects towards the left bank which occur as a result of the ship-induced primary wave field; the drawdown associated with a ship in motion is greater close to the bank than on the opposite side of the ship owing to the faster return flow between vessel and bank. The difference in water pressure therefore causes the ship to accelerate towards the bank. The left bank in Figure 4.1.4-1 (looking in the direction of travel) may consequently be subjected to higher hydraulic loads due to drawdown.

As a general rule it can be stated that the additional width when sailing through a cross flow field with a width b_q increases, the higher the cross flow velocity v_q (averaged over the ship length L if $L > b_q$) or the width of the cross flow field (if $L \leq b_q$), the higher b_q and the slower the ship passes the cross flow zone. The shipmaster may decide to adopt a drift angle in order to compensate the cross flows, for example when sailing slowly upstream; in the most straightforward case this angle should be selected so that the distance travelled against the cross flow per time unit is equal – in relation to the moving water – to the drift in the cross flow field. Alternatively, the ship can simply be allowed to drift sideways, e.g. when sailing downstream, if a narrow cross flow field is passed quickly.

Another indirect effect of the cross flow results from traversing diagonally through a longitudinal flow field. This

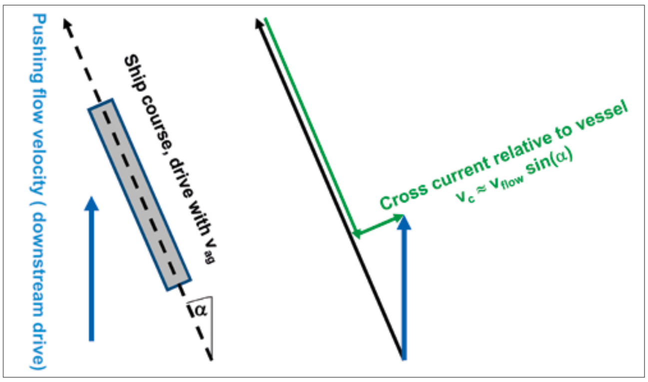


Fig. 4.1.4-2: Flow characteristics of a ship sailing downstream, which traverses a longitudinal flow field (blue arrow) from right to left at an angle α [BAW]

Fig. 4.1.5-1: Container unit (breasted-up formation, GMS and 3 barges, left) sailing downstream in the Rhine near Oberwesel, encountering a towed, single-line pushed convoy with one barge navigating upstream (right) [BAW]

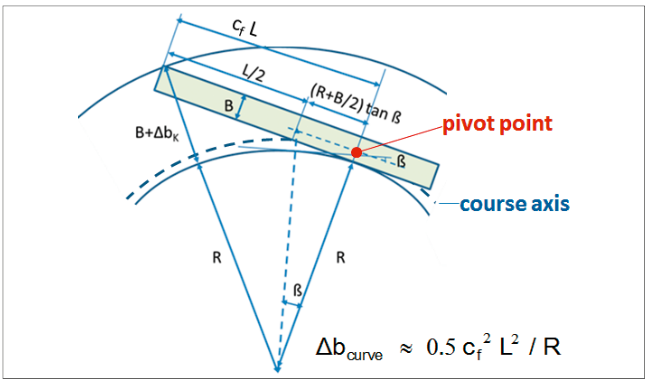


Fig. 4.1.5-2: Definition of the tactical turning point (pivot point) for the circular, steady motion of a ship navigating bends as well as the associated swept area width and approximation equation for calculating the additional width required in bends (lane width minus beam) for a known, relative position of the pivot point (referred to the ship length) forward from the stern c_f [BAW]

is illustrated in Figure 4.1.4-2, which shows a ship traversing from the right hand side of the fairway to the left side (looking in the direction of travel). This is the case, for instance, when advantage is taken of the larger depths at the undercut bank during a transition from a left-hand bend to a right-hand bend as has been stated earlier.

In the downstream driving situation shown here, the pushing flow velocity of the river (vertical blue arrow in the graph) has to be subtracted vectorially from the oblique vessel speed over ground (black dotted line in Figure 4.1.4-2) to obtain the ship's approach velocity. The latter is split into its longitudinal and transversal components in the graph (green coloured arcs). The ship must counter the cross flow component (green arc, pointed to the right) by adopting a drift angle to the left, resulting in an additional swept area width. If not, it will drift to the right.

4.1.5 Additional widths when navigating bends

A similar width problem illustrated in Figure 4.1.5-1 occurs when navigating bends. This photograph shows the chronological sequence of ship positions for a pushed convoy comprising a pushing large motor vessel and a total of three pushed barges, one of which is on the starboard side of the driving ship in this example (on the right looking in the direction of travel) – in other words, in a breasted-up formation – and two in front. The convoy is thus around 185 m long and 22.8 m wide. Since the containers being transported are obviously not so heavy that the ship would be sailing with its largest design draught, the average draught is significantly smaller than this value.

Therefore, the projected lateral area of the ship is smaller than is possible in the case of a fully laden vessel and the crosswise force which can be mobilized while drifting sideways is smaller, too. This increases the necessary drift angle to counteract sideways forces on the ship hull. Furthermore the water in the narrow bend on the Middle Rhine is very deep. As a result, the draught-to-water depth T/h ratio is small. This is another reason why sideways forces mobilized by drifting are small, because they are mainly caused by the undercurrent of the vessel's hull and the corresponding flow velocities underneath the vessel's bottom, which cause these forces mostly, thus are small, too.

As a result, the so-called tactical turning point (pivot point) is located close to the bow in such driving situations, i.e. sailing downstream. The pivot point is defined geometrically as the point at which the ship can be imagined to be guided alongside of its course, the vessel's axis being tangential to the course axis at the pivot point.

For evaluating the relative position of the pivot point c_f (see Figure 4.1.5-2) or for construction of the swept area caused by driving along curves, it is appropriate to approximate the vessel's course by a sequence of circles. Fig. 4.1.5-2 shows a curve with one of such circles to provide a clearer definition of the pivot point.

The relative position of the pivot point referred to the ship length is known as c_f. In the example shown in Figure 4.1.5-1 this point is obviously very close to the front of the ship, if not in front of it, because the swept area width required by the vessel extends over almost half of the available fairway width (120 m).

The most important reason why the pushed convoy sailing downstream needs such a large width compared to a vessel sailing upstream is that the centrifugal force which accelerates the ship towards the outer bank is dependent on the ship speed *over ground*, which is obviously much higher downstream than upstream. The forces that keep the ship on course, mainly the forces while drifting, on the other hand, are mostly dependent on the ship speed relative to water, which is lower downstream than upstream for economic and safety reasons. When navigating downstream, therefore, the ship must adopt a large drift angle (i.e. the angle of the ship axis to the course axis must be large) in order to generate a cross flow relative to the vessel axis, running from the outside towards the inner side of the bend and mobilizing the corresponding transverse forces.

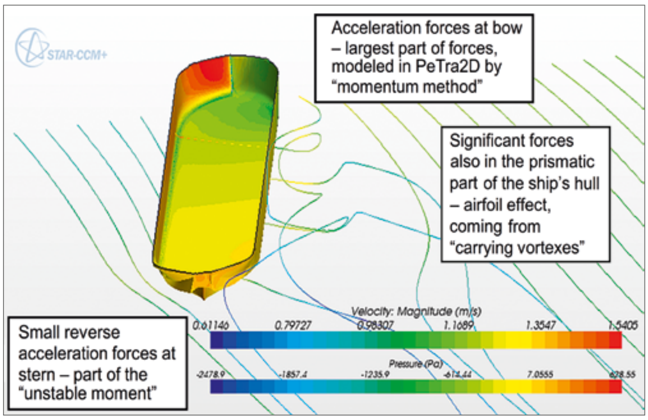


Fig. 4.1.5-3: Three-dimensional calculation of the pressure distribution (red = excess pressure relative to hydrostatic pressure at rest, green = corresponding negative pressure) and flow lines of a drifting GMS (load draught: 2.8 m, angle of drift: 15°) in shallow water (water depth: 3.5 m) [BAW]

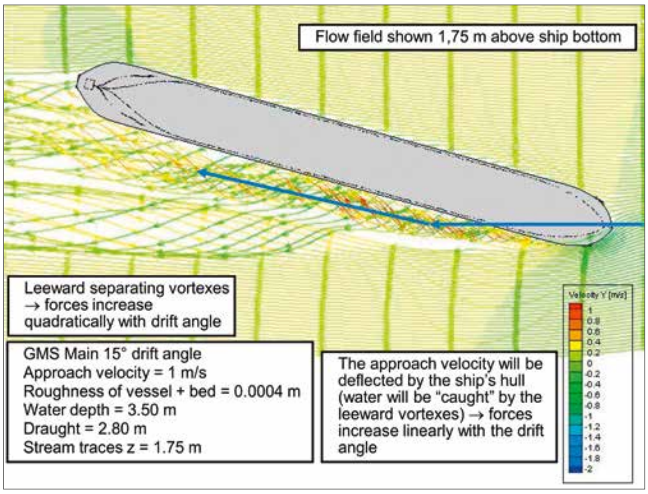


Fig. 4.1.5-4: Flow lines in a depth plane between the water surface and the bottom of the hull (same boundary conditions as in Figure 4.1.5-3) [BAW]

Three-dimensional model calculations of the streamlines and the forces acting on a drifting inland navigation vessel in shallow water (source: BAW) illustrate how transverse forces are produced by drifting; see Figures 4.1.5-3 to 4.1.5-5. One part of the transverse forces results from the flow *around* the ship (Fig. 4.1.5-4). This is called the hydrofoil effect, because the oblique approach flow field is aligned with the ship hull in the same way as would be the case with a hydrofoil .This is the result of the "carrying vortexes" referred to and illustrated in Figure 4.1.5-3. This force is maximal when the underkeel clearance is very small, so that a significant undercurrent underneath the vessel's hull is not possible. But in most practice-relevant cases the underkeel clearance is greater and therefore, most of the crosswise approaching water flows *underneath* the ship. The corresponding forces are mainly caused by the acceleration of water due to the curved vessel's hull shape and displacement (called "acceleration forces" in Figure 4.1.5-3) and because the water is forced to pass the gap between the vessel and the

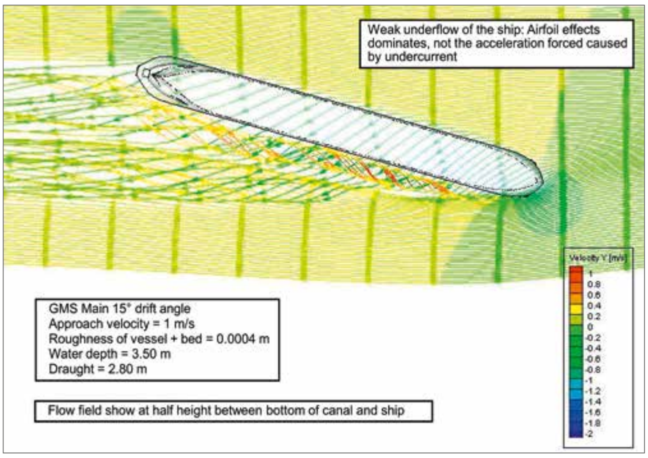


Fig. 4.1.5-5: Flow lines in a depth plane between the canal bed and the bottom of the hull (same conditions as in Figure 4.1.5-3) [BAW]

channel bottom as shown in Figure 4.1.5-5. Another source of these forces is the flow resistance of the undercurrent, causing leeward separated vortexes, illustrated in Figure 4.1.5-4.

The acceleration forces are greatest where the flow changes abruptly, in other words mainly in the bow area and to a lesser extent in the stern area. At the stern of a typical inland freight vessel, the flow is unable to follow the narrowing contour of the aft ship exactly for inertia reasons, i.e. the flow separates. This results in a lower curvature of the streamlines and thus lower acceleration forces compared to those at the bow.

This can be seen in the Figures provided above, especially in Figure 4.1.5-3, which shows the pressure force distribution on the vessel's hull. A bright red (excess pressure, approach flow side) and green (negative pressure, lee side) colour indicates high pressure areas which are located mostly at the bow. The acceleration forces and corresponding torques are largely responsible for the yaw instability of vessels (the "unstable moment"), meaning that these forces and moments make the vessel drift and turn laterally towards the cross flow direction unless countermeasures are taken.

If the approach flow velocities along the vessel axis change – as is the case when navigating bends owing to the curvature of the surrounding flow field and the turning motion of the vessel – similar acceleration forces also occur in the prismatic midship section, where the cross flow is intensified in the gap between the bottom of the hull and the bed, see oblique streamlines underneath the ship's bottom in Figure 4.1.5-5. These forces make a significant contribution to the supporting transverse force in the bend and are highest when the dynamic underkeel clearance is smallest, in other words, when the water underneath the ship is undergoing the strongest acceleration.

With a larger load draught at the same water depth the increase in the transverse forces due to acceleration is even greater than the higher centrifugal force because the ship's mass increases with the draught. For this reason, the drift angles required to compensate the centrifugal forces are generally smaller with a large draught-to-water depth ratio T/h than with a small T/h. An unladen ship with no additional steering units, such as active or passive bow rudders, thus usually needs more navigation space in bends than a ship which is fully laden. The pivot point is accordingly shifted further away from the midship section towards the stern for unladen vessels using the main rudder only for steering.

This is also the case with the second above-mentioned transverse force component linked to the hydrofoil effect. Its influence is greatest in the prismatic midship section. On typical inland navigation vessels with a large midship it is responsible for most of the supporting transverse force in bends, especially in conjunction with a large T/h. In the case of a very deep draught vessel almost touching the bed the transverse forces produced are equivalent to those produced by a hydrofoil with a high aspect ratio, i.e. they are several times higher than with a small T/h. The main rudder may then no longer be able to counteract these high transverse forces and corresponding torques – owing to the uneven distribution of the cross flow velocity with small transverse components at the bow and large ones at the stern. These moments attempt to force the ship out of the bend and have to be compensated with counter-rudder towards the middle of the bend.

Like the acceleration forces the transverse forces on the underwater ship due to the hydrofoil effect increase faster than the centrifugal forces with an increasing draught. Hence, the larger the T/h the smaller the required drift angle, though in narrow bends the limitation of the possible transverse rudder force may have the opposite impact. The hydrofoil effect, in particular, restricts navigability in narrow bends as well as the ability to sail through cross flow zones with a very small dynamic underkeel clearance.

With large dynamic underkeel clearances, on the other hand, a strong vortex system is created by the water flowing underneath the ship. It corresponds to the end vortices of hydrofoils, which reduce the alignment of the flow by means of the ship's hull on the lee side, as shown in Figure 4.1.5-4. The transverse force due to the hydrofoil effect is therefore much lower with large clearances, where the flow underneath the ship – the cause of the above-mentioned vortex system – dominates, than suggested by the hydrofoil theory for high aspect ratios. The hydrofoil effect consequently plays less of a role with small T/h ratios.

Another part of the transverse forces results from the separation of the vortices in the ship's lee section. These vortices are marked in Figure 4.1.5-4. The corresponding forces increase almost quadratically with the drift angle or cross-flow velocity, and determine the transverse forces for very large drift angles. The acceleration forces and the hydrofoil effect, on the other hand, increase more or less linearly with the transverse component of the approach flow and are therefore relevant at small to medium drift angles.

Because of these complex relations, the aforementioned forces acting on an inland navigation vessel in the cross flow field or a bend are still calculated mainly semi-empirically today, especially for real-time simulations in ship handling simulators. The associated parameters of the corresponding simplified formulae must thus be calibrated, e.g. based on scale model or field tests.

This may be necessary even for standard vessel types, particularly owing to the different bow and stern geometries. This is also reflected in the c_f values, which can be calculated from field data, for example, and are often very scattered; refer also to Figure 4.1.5-6, in which the additional widths Δb measured in a bend (swept area width minus beam) are plotted as a function of the bend's curvature (curve radius R). It follows from the kinematics of navigation in bends, as illustrated in Figure 4.1.5-2, that the additional width Δb referred to the ship length L must be linearly proportional to L/R if the c_f value is constant, and this assumption is impressively underlined by the measurements.

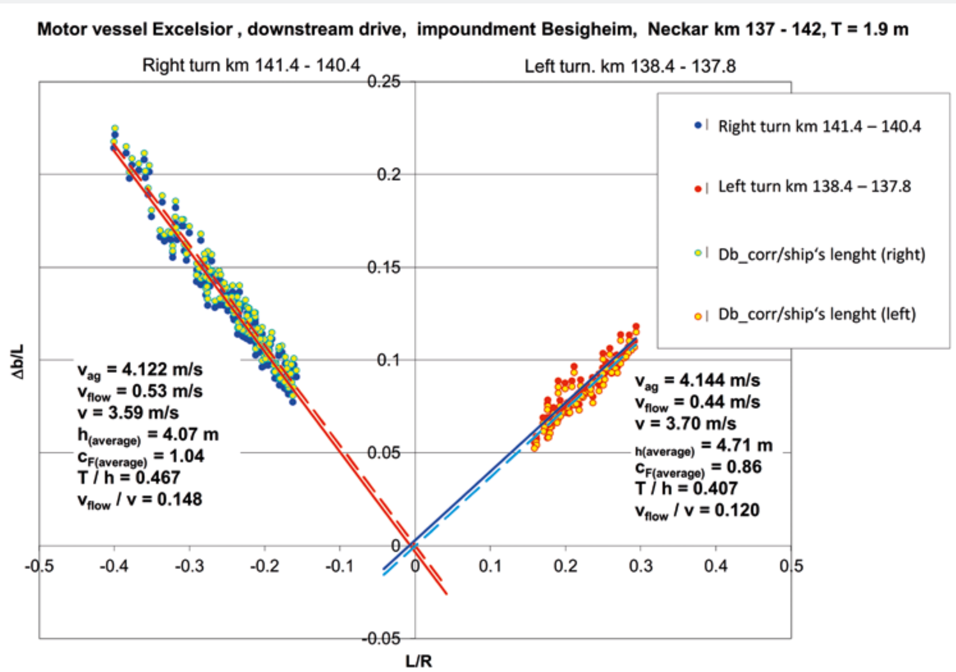


Fig. 4.1.5-6:
Relative additional widths $\Delta b/L$ (referred to the ship length) for the MS Excelsior (T = 1.9 m) sailing downstream in two narrow bends on the Neckar in the Besigheim impoundment, plotted as a function of the relative curvature L/R (ship length / curve radius) of the vessel's course [BAW]

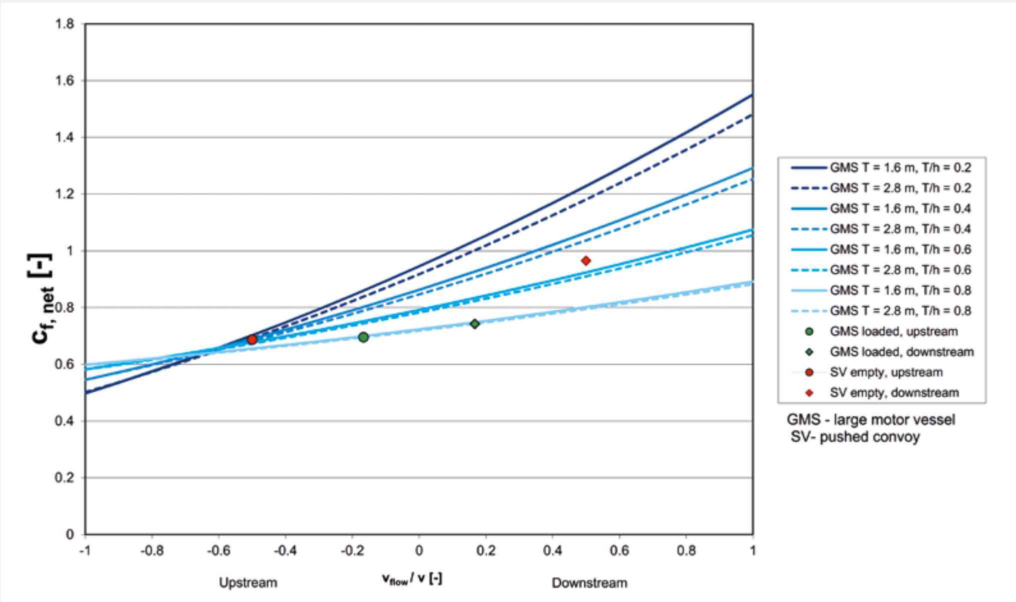


Fig. 4.1.5-7: Calculated dependence of the c_f value without the influence of secondary currents ($c_{f, net}$) for an inland navigation vessel with B/L = 0.1 on the relative flow velocity (referred to the ship speed through the water) for various draught-to-water depth ratios (h based on the selected T and T/h) [BAW]

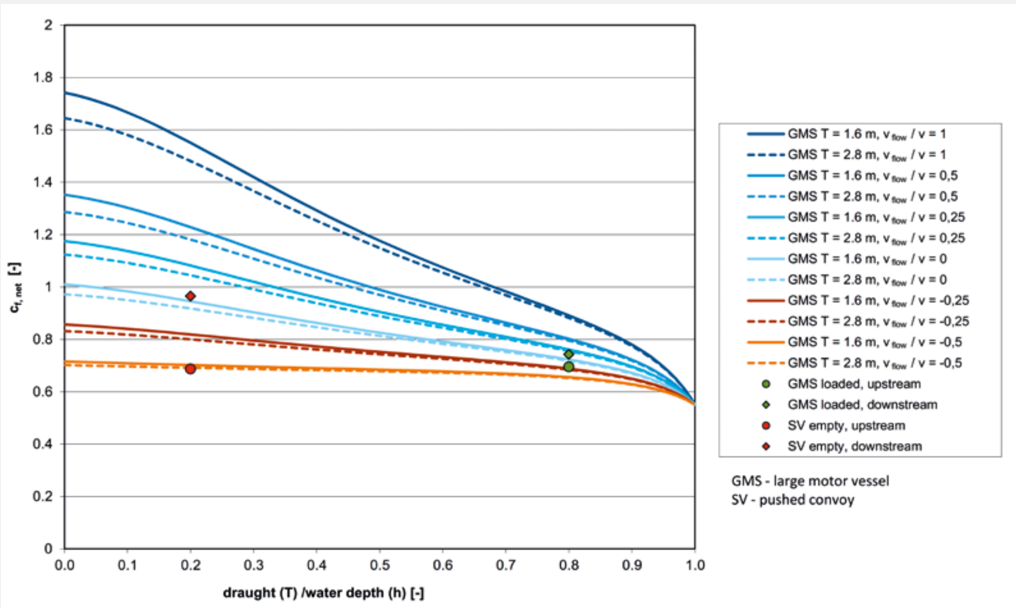


Fig. 4.1.5-8: Calculated dependence of the c_f value without the influence of secondary flows on the relative draught (referred to the water depth) for various v_{flow}/v values – for boundary conditions and a typical application, see Figure 4.1.5-7 [BAW]

The gradient of the straight lines in Figure 4.1.5-6 is linked to the cf value and can be used to determine it. The values measured in canals vary between a minimum of approximately 0.7 for fully laden ships and up to around 1.1 for unladen ships. This corresponds almost exactly to the specifications in the Dutch waterway guidelines (0.7 to 1.0). Values ranging from 0.6 for vessels going upstream to 1.5 downstream have been measured in rivers, with the lowest and highest values occurring at high flow velocities and large or small T/h ratios respectively.

The relationships for assessing the cf value as shown in Figures 4.1.5-7 and 4.1.5-8 are obtained by taking (1) several of such evaluations from field data for calibrating simplified formulae for the forces and torque moments acting on the underwater body of the vessel drifting through the bend, (2) by

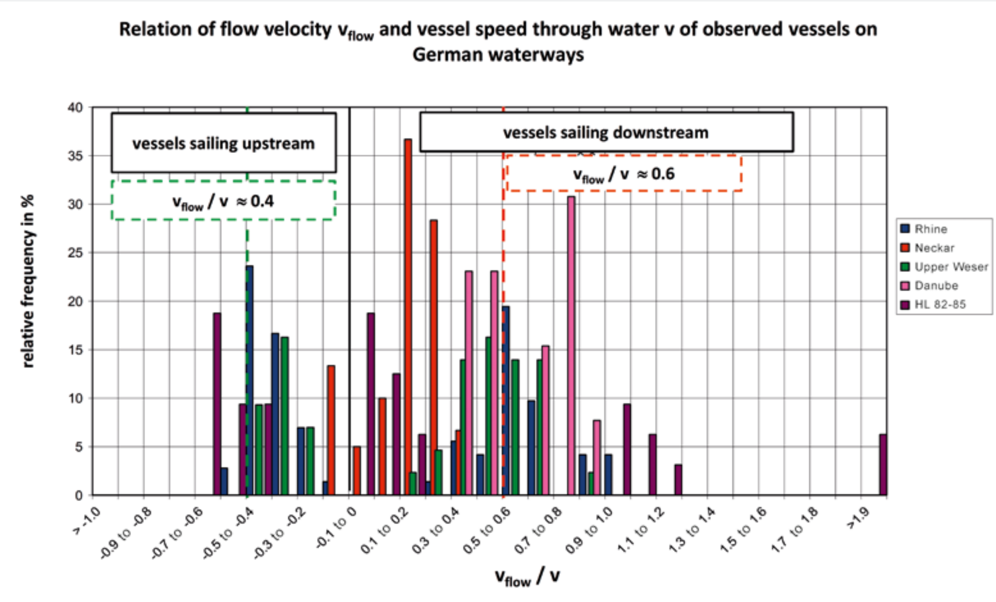


Fig. 4.1.5-9: Frequency distribution of ship speeds measured in bends on various rivers (HL 82-85 refers to the values measured during model tests with slow-moving pushed convoys on the Mississippi) [BAW]

calculating corresponding necessary rudder forces to counteract these moments, (3) by considering the sideways forces which support the vessel in making the turn in a narrow curve due to the lateral water level gradient in a flowing river and (4) by balancing the transversal forces with the centrifugal forces. These relationships were used in Figures 4.1.5-7 and 4.1.5-8 for a typical ship with a beam-to-length ratio of about 0.1. An unladen pushed convoy (L = 185 m, B = 11.0 m, T = 1.6 m, v = 4 m/s), sailing in the vicinity of the Loreley Rock on the Middle River Rhine (h = 8 m, v_{flow} = 2 m/s, marked by red signs) and a fully laden GMS (L = 110 m, B = 11.0 m, T = 2.8 m, v = 3 m/s), driving on the impounded Neckar River (h = 3.5 m, v_{flow} = 0.5 m/s, green sign) were taken as examples.

The figures show that the c_f values increase with the ratio of flow velocity v_{flow} to ship speed through the water v. v_{flow} upstream is given a negative sign to enable upstream and downstream navigation to be represented in the same diagram. The c_f-values moreover decrease as T/h increases. It has always been assumed that the rudder is strong enough to compensate the torque moments, which is evidently the case with the underlying measurements.

These graphs allow the additional width in bend navigation to be estimated for a "typical" ship under the kinematic conditions shown in Figure 4.1.5-2 by specifying the input data T/h and v_{flow}/v. Whereas the water depth and hence T/h are generally known, it is more difficult to choose the appropriate v_{flow}/v. For more information about usual vessel velocities v, refer to Chapter 4.1.2 as well as to the "typical" values based on field measurements, namely 13.5 km/h for the navigation conditions commonly found on the Rhine or approximately 9 km/h in narrow rivers and canals.

A further indication is provided by Figure 4.1.5-9, in which data measured during test runs on various German rivers are plotted in relation to v_{flow}/v. According to these measurements, ships sail upstream, on average, at about v_{flow}/v = 0.4 when there is a strong current, in other words their speed relative to the water is approximately 2.5 times the flow velocity. Theoretically, a vessel speed around 1.5 times the flow velocity would be ideal in order to reduce fuel consumption to a minimum. However, the ships observed were evidently more interested in getting to their destination quickly than in saving fuel. The downstream values are mainly in the region of v_{flow}/v = 0.6, i.e. the ships were sailing downstream “through” the water at approximately 1.7 times the flow velocity. The latter values can be used directly to interpret Figure 4.1.5-7 which shows a high c_f value of about 1.3 for an unladen ship with T/h = 0.2 sailing downstream.

In all of the above diagrams the secondary currents were assumed to be negligible. In natural rivers, however, their influence must be taken into consideration. They are a result of the centrifugal force, which also acts in the bend on the part of the flow not influenced by the ship and produces a cross flow towards the outer bank close to the water surface. The flow on the waterway bed is directed towards the inner bank, where the bed load moved by the water collects, leading to sand or gravel banks.

With small dynamic underkeel clearances the cross flows impacting the ship more or less cancel each other out; however, this does not apply to small draughts, where the outward secondary flow has to be compensated with an additional drift angle. Figure 4.1.5-10 shows an example of a flow field, which is influenced by secondary currents. The flow vectors are deflected strongly towards the outer bank at half draught water depth. The corresponding drift angles of the GMS needed to compensate the cross flow when sailing downstream are very large.

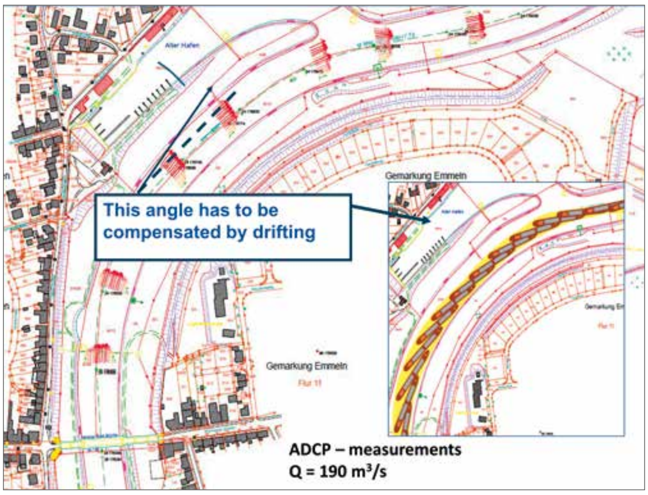


Fig. 4.1.5-10: Flow vectors, at half draught depth below the water level (1.4 m), pointing towards the undercut bank (influence of the secondary flow), measured at bankfull discharge in the Ems, and calculations for bend navigation by a GMS with a draught of 2.8 m (no active bow thruster) [BAW]

This drift angle compensation can be taken into account by increasing the c_f value. This increase is shown in Figure 4.1.5-11 for the examples in Figure 4.1.5-7. The graph shows that no significant increase was calculated for a GMS on the Neckar, where the c_f value without the influence of secondary flows was about 0.7 both upstream and downstream, because the assumed T/h is very high. The increase was bigger for an unladen pushed convoy in the vicinity of the Loreley Rock, where c_f is about 0.1 higher than without secondary effects, leading to c_f = 0.8 upstream and 1.1 downstream.

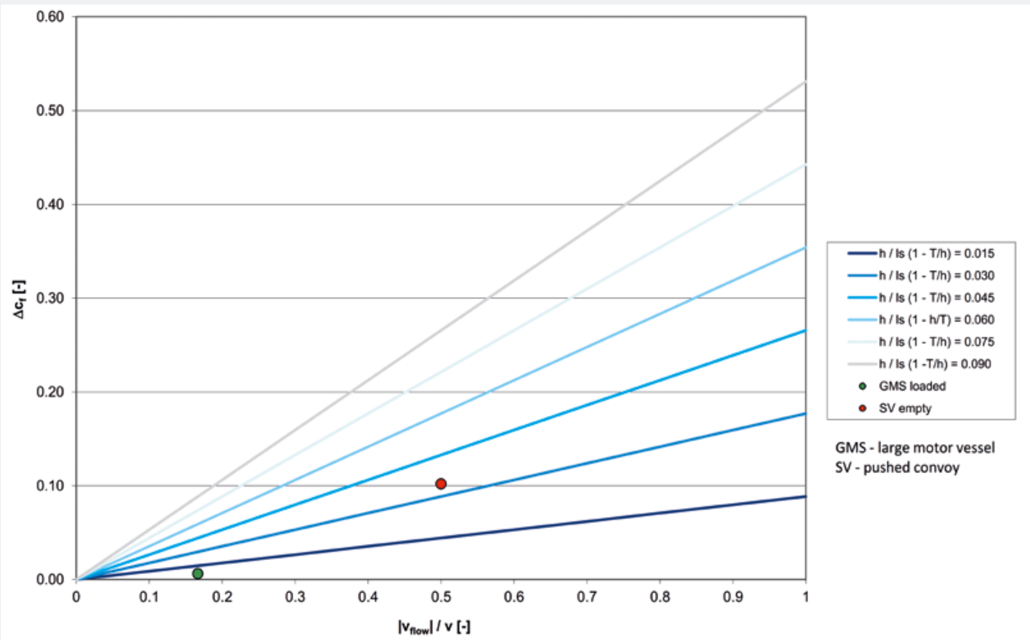


Fig. 4.1.5-11: Calculated increase in the c_f value (Δc_f) due to secondary currents for various combinations of water depth-to-ship length and draught-to-water depth ratios, based on the examples in Figure 4.1.5-7 [BAW]

The resulting additional widths for the examples in Figure 4.1.5-7 are plotted in Figure 4.1.5-12 in the dimensionless variables discussed in Figure 4.1.5-6, and in Figure 4.1.5-13 with their actual size. Amongst other things, the last graph illustrates the huge influence of the curvature on the additional width, especially for unladen ships without effective bow rudders or thrusters. Furthermore, according to Figures 4.1.5-2 and 4.1.5-6, the ship length has an almost quadratic relationship with the additional width. This is particularly important when assessing the ability of long craft to navigate in existing waterways such as the Neckar. The additional width for an üGMS with a length of 135 m, for instance, is 82% larger – nearly twice as much – than for a GMS with the maximum 105 m length permitted presently.

Finally, the influence of the direction of travel needs to be outlined again. A lower supporting transverse force is obviously necessary upstream than downstream to keep the ship on course because the centrifugal force must be calculated with the ship speed over ground, which is lower upstream compared to downstream. The ship therefore adopts a smaller drift angle. This is illustrated in the right-hand part of Figure 4.1.5-1 by the towed craft – a single-lane unit coupled one after the other, which manages with much less traffic space. It is generally true to say that an inland navigation vessel needs the most traffic space when sailing downstream in narrow bends with a small draught-to-water depth ratio or when it is fully laden and in the vicinity of cross flow fields. A ship sailing upstream usually requires less navigational space than downstream, except when there are strong cross flows simultaneously with low possible ship speeds, because these make it more difficult to counter the flows. In both cases, the necessary fairway width can be several times the beam. This is one big difference between a waterways vessel and a friction bound vehicle like a truck, for which a much smaller traffic space suffices. The fairways must consequently be wide enough to enable ships to sail safely and easily in accordance with the mandate of the Federal Waterways Act.

When analysing this information, it is important to remember that the crafts navigating in Germany's inland waterways are getting larger and larger. On the other hand, the available fairway widths cannot be increased any further in the majority of cases. For example private interests prevent the banks of the River Neckar from being widened to increase the existing fairway width. Furthermore, measures planned to improve navigation can result in significant environmental impacts which would reduce the ecological potential of Germany's water

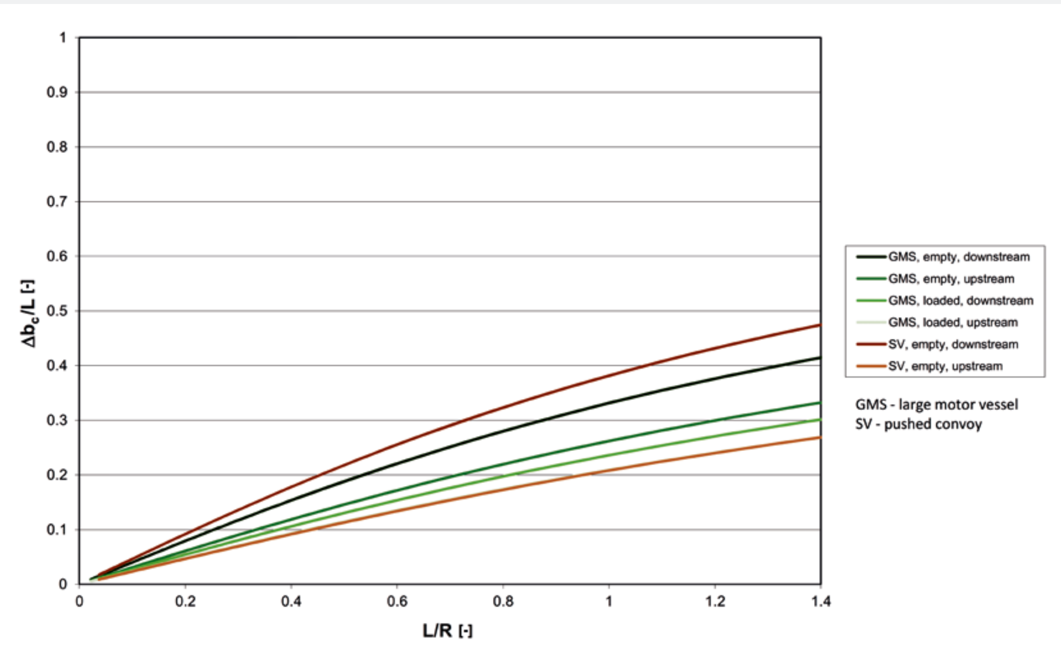


Fig. 4.1.5-12: Calculated relative additional width $\Delta b_c/L$ in bends as a function of the curvature L/R for the same boundary conditions as the examples in Figure 4.1.5-7 [BAW]

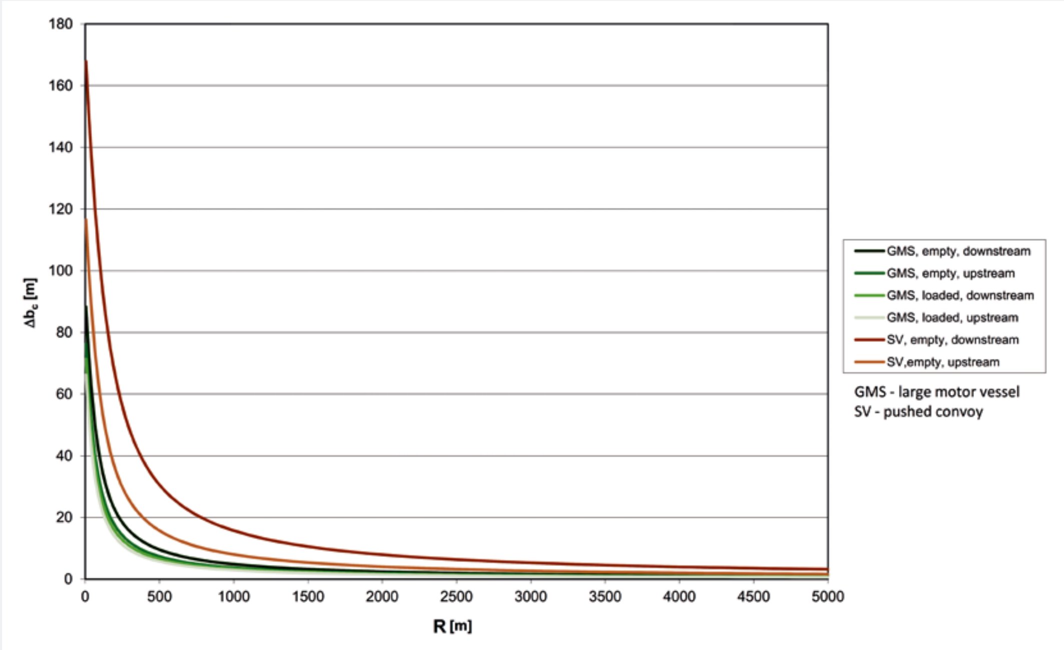


Fig. 4.1.5-13: Calculated additional width in bends Δb_c as a function of the curve radius R for the same boundary conditions as the typical examples in Figure 4.1.5-7 [BAW]

bodies. Such measures are usually considered unacceptable for this reason or because – on the Rhine, for instance, or on the stretch of the Danube River between Straubing and Vilshofen – only a certain width can be achieved in a free-flowing river in conjunction with the maximum fairway depth. Any attempts to additionally increase the fairway depth by lengthening the groynes (spur dikes), in other words by restricting the river width even more, would also have the effect of narrowing the fairway or at least increasing the flow velocities, so that the required navigational space would further increase in view of the bend navigation aspects described above.

Fig. 4.1.5-14: Field test to simulate navigation of an üGMS past the town of Lauffen (Neckar) with a unit comprised of the push boat Vogel Gryff and the MS Hanna Krieger (overall length: 139 m) [BAW]

To nevertheless enable large vessels to navigate in Germany's inland waterways – and such traffic is extremely viable from the politico-economical point of view because bigger ships are able to carry significantly more cargo with the same personnel and only a slightly higher fuel consumption – it is necessary to demonstrate that they can manage with the available navigational space. The fact that modern ships generally have very efficient rudders is helpful. Although they are larger – for example, they may be longer or wider and hence require more traffic space than conventional craft – they are able to navigate critical stretches thanks to their superior nautical qualities.

This aspect is illustrated in Figure 4.1.5-14, which shows a 139 m long, 11 m wide unit navigating past the town of Lauffen on the Neckar River (Söhngen, Qaqunda, 2011). This unit is comprised of a push boat pushing a large motor vessel typical of those used on the Neckar and was used to simulate a 135 m ship that will be approved in future. The latter vessel type has become established as the standard ship on the River Rhine in the last years. Since it is the Rhine which determines how the German fleet develops owing to its high traffic volume and transport capacity – accounting for roughly eighty percent of Germany's entire inland shipping – it is only natural that these ships should be enabled to sail on side waterways like the Neckar. If the locks, which currently represent the main obstacle to large craft, are lengthened as foreseen, such craft will also be able to navigate the Neckar. In this case an examination of their ability to cope with the confined conditions exemplified by those in the Lauffen reach in Figure 4.1.5-14 will be required. In this particular reach there will probably be no alternative to extension measures because easy and safe shipping is no longer possible here with the 135 m long vessels. Even though the bottleneck in Lauffen could "just about" be navigated under field test conditions the manoeuvre demanded extreme concentration on the part of both shipmasters.

In spite of this, the improvement measures planned on the River Neckar for the üGMS will probably not lead to a state that matches the existing safety and ease of navigation standard for the present fleet because they would be too expensive and too intrusive. In the above example, therefore, the future wave loads will be scarcely any higher than those prevailing at present, even though the ships will be navigating very close to the banks, because the ship speed will be much lower. On the other hand, significant loads will be likely from the propulsion and steering units. Amongst other things, these will include the deflected propeller wash of the main propulsion system, which occurs as a result of strong rudder actions especially with modern twin rudder systems, and the transverse thrust of a modern bow rudder.

The trend towards bigger craft – which is predicted to continue as inland navigation vessels have to maintain their competitive edge compared to other transport modes – will probably not lead to insurmountable nautical problems, i.e. no improvement measures will be necessary in most cases, but the ship-induced loads on the bed and the banks will almost certainly increase if no countermeasures are taken. From the ship dynamics perspective, this is virtually equivalent to squaring the circle. On the one hand, the requirements of the European Water Framework Directive have to be met, amongst other things by replacing conventional bank protection systems with alternative ones. On the other hand, the competitiveness of inland navigation vessels – which in many respects are a highly desirable mode of transport that reconcile ecology with economy with their low primary fuel consumption and transport costs per ton of cargo transported and kilometre – needs to be maintained, if not actively strengthened.

4.1.6 Encounters and overtaking manoeuvres in canals

A particularly critical situation from the point of view of ship dynamics is the (head-on) encounter of two ships at close quarters. Each ship produces a displacement flow field that pushes the other ship's bow sideways and pulls the stern closer. This sideways pointing flow increases along with v and T/h. The latter effect is shown in Figure 4.1.6-1. The displacement flow of a GMS was simulated by means of a source-sink distribution which "inflates" the ship to separate this effect from other influences.

If two deep-laden ships are meeting head-on at close quarters, one of them will theoretically be pushed away half the width of the "displacement ellipse" as shown in Figure 4.1.6-1.

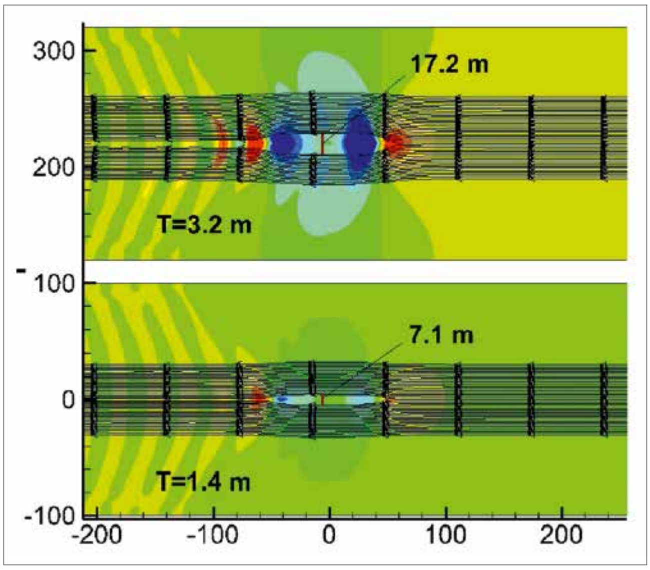


Fig. 4.1.6-1: Calculated displacement flow of a GMS in shallow water (4 m deep) for two different draughts T [BAW]

The resulting safety distance which is required between two identical ships corresponds to one width of this ellipse, in other words around 17 m for T/h = 0.8 (top) and 7 m for T/h = 0.35. The influence of T/h is evident here, though the values decrease if the ships maintain the safety distance during their encounter.

The influence of the ship-induced water level drawdown, as shown for example in Figure 4.1.1-7, must likewise be taken into account. In shallow water it is symmetrical all the way around the ship, so that no transverse forces are generated for the ship that produces the drawdown, but for the other vessel sailing close by. Therefore, the oncoming ship sails alongside the edge of this drawdown trough and is therefore accelerated towards the middle of the other ship's drawdown zone – it appears to be "attracted" to it. The influence of both the lateral displacement flow and that of the drawdown field are declining at lower T/h values. The most critical case from a ship dynamics perspective is thus a high T/h in combination with navigation close to the critical ship speed with the associated high displacement flows and drawdown.

When sailing at a moderate ship speed in shallow water, good shipmasters can pass each other safely with a net distance of approximately one beam between the two vessels. This seems to be in contradiction to the German Guidelines on Standard Cross Sections in canals. The stated safety distance is much smaller for single-lane craft (GMSs, pushed convoys), namely 2 m, despite the extremely complex sailing situation. The reason for this very low specified value is that the actual available navigational space is much broader than 2 m if the "meandering width" of both vessels is added. This width can be calculated according to the German Guidelines from the difference between the specified lane width (about 15.5 m for the trapezoidal profile) and the breadth of the vessel (11.4 m), resulting in roughly 4 m. Twice this value plus 2 m safety distance equals 10 m. Since this additional space is taken into account, the effective available additional space during the encounter is therefore approximately one beam width.

This sailing situation is especially critical because, based on model and field tests, only a limited "ship speed window" is usable under normal driving circumstances, i.e. without having to use the bow rudder. At very low vessel speeds the main rudder force is too small to counter the cross flows and transverse forces from the drawdown field unless the ship has a powerful active bow rudder. In contrast to this, if the speed is too high, the vessels will be strongly negatively affected by their own flow and drawdown fields. Hence, if one neglects meeting at very slow speed, the safe speed range for fully laden GMSs and pushed convoys in German standard canals is around 5 to 8 km/h. The cross sections for two-way traffic therefore need to exceed those for one-way traffic, not only with regard to the width but also in terms of the depth to ensure a sufficiently large speed window, and the maximum permitted ship speed must not be too low.

Figure 4.1.6-2 shows a typical encounter situation in a canal. During the final phase the ships' sterns almost make contact: the rudder pressure is much lower during this phase of a encounter manoeuvre, because in narrow cross sections the two ships' return flow fields – which support normal manoeuvring situations by increasing the propeller approach velocities – can almost cancel each other out. The propeller wash becomes relevant as a result and there may even be a flow to the rudders astern.

However, the greatest additional width during an encounter is usually needed when the two craft are parallel to each other, as shown in the middle photograph in Figure 4.1.6-2. Both ships tend to have a drift angle in this situation, causing them to sail away from the nearest bank and towards the centre of the canal. Amongst other things, this is due to the fact that their bows are initially forced apart, so that they drift towards the closer bank. In narrow canals they are also pulled towards this bank because the dynamic lowering of the water level is greater there. In order to counter this tendency, they need to sail away from the bank, though, to begin with, their sterns continue to approach the bank depending on the position of the pivot point in the front third of the ship. The ships are therefore sailing at an angle to the canal axis, as shown here. Other influences are described in Chapter 5.1.4.

During overtaking manoeuvres, each ship is exposed to the influence of the other ship's drawdown trough for a much longer time compared to encountering vessels. Accordingly, higher safety margins than those for encounters have to be accounted for. If only the main rudder are used for steering, which is usually the practice, the strong interaction forces can only be compensated by taking appropriate drift angles. Overtaking manoeuvres additionally call for the cooperation of the two shipmasters, especially when sailing in canals, because the return flow of the craft which is overtaken has to be overcome too. The overtaken ship therefore has to slow down.

It should be mentioned at this point that the ship induced impacts on the bed and the banks of the channel by the propulsion and steering devices of modern ships during encounter and overtaking manoeuvres have increased. The stability of the canal linings could be at risk as a result. This particularly applies if larger craft are to navigate in canals which are neither widened nor deepened. Action is consequently needed to counter these trends – both in relation to the ship structures, e.g. by incorporating multi-propeller drive or twin rudder systems to increase the transverse rudder forces without altering the propeller wash, and in the form of waterways engineering measures such as improved protection against revetment toe erosion.

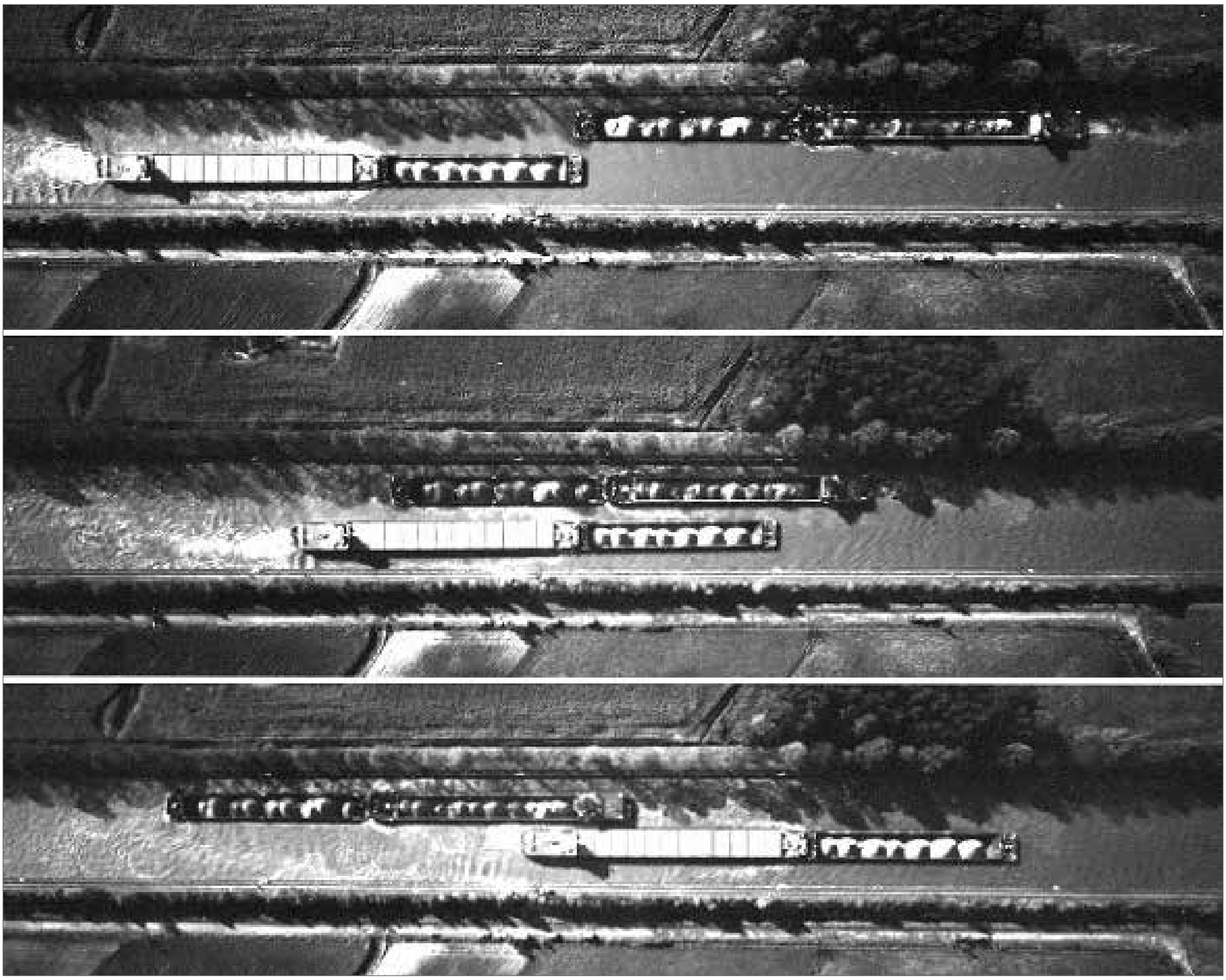


Fig. 4.1.6-2: Encounter manoeuvre of two single-lane pushed convoys (GMS plus barge, coupled one after the other) on the Dortmund-Ems Canal [BAW/DST]

4.1.7 Effects of wind

The effects of wind are a further navigational problem. Ships with a large transverse projection area exposed to wind action are particularly sensitive to these effects. This holds especially true for unladen ships and container vessels. Small draught to water depth ratios and slow cruising speed additionally increase the wind effect. In these cases the transverse wind force is considerable while the counterforce applied to the drifting underwater vessel is small and can only be produced at high ship speeds and at a large drift angle. The required traffic space is consequently enlarged (see Figure 4.1.7-1), which is one reason why the permitted ship speed must not be restricted too much. Accordingly, higher wave loads are unavoidable and have to be accepted.

Fig. 4.1.7-1: Unladen ship sailing in strong wind (blowing from the right), which is relevant in the area with low trees [BAW]

Modern inland navigation vessels can counteract transverse wind forces with powerful rudders at the bow and stern. The loads on the channel linings are increased, however, just as they are in other manoeuvring situations. Therefore conventional windbreaks such as vegetation along the banks still make sense despite the optimised design of today's craft.

4.1.8 Transverse forces at inlet and outlet structures

Cross flows in waterways can be either extended and largely homogeneous over a distance of several kilometres, or local and inhomogeneous. In the former instance they may be wind-induced or tidal drift flows in coastal waters, cross flows from the flooding of forelands during high water, the outcome of polder flooding by outlet structures or secondary flows in river bends. Local cross flows are produced, amongst other things, by outlet and intake structures, tributary mouths and canal or harbour entrances in natural waterways, vortices and circulation zones at lock approaches and groynes or in the entrance areas of locks, for example owing to filling and emptying devices of the lock chambers or the simultaneous operation of double locks or lock groups.

If a ship passes through an extended, continuous cross flow field, it adopts a defined drift angle to compensate the cross flow velocity in order to keep the aimed course. Small-scale but strong cross flow fields are generally more problematic for the safety and ease of navigation, especially if they are difficult to control by means of rudder or engine manoeuvres on account of their inhomogeneity (i.e. changes of direction), intensity (magnitude) and duration. In the past the impact of local cross flows on shipping has frequently been the object of model and field tests for this reason.

Inlet (water entering the navigation channel) and outlet (removal of water from the main channel) structures for the ser-

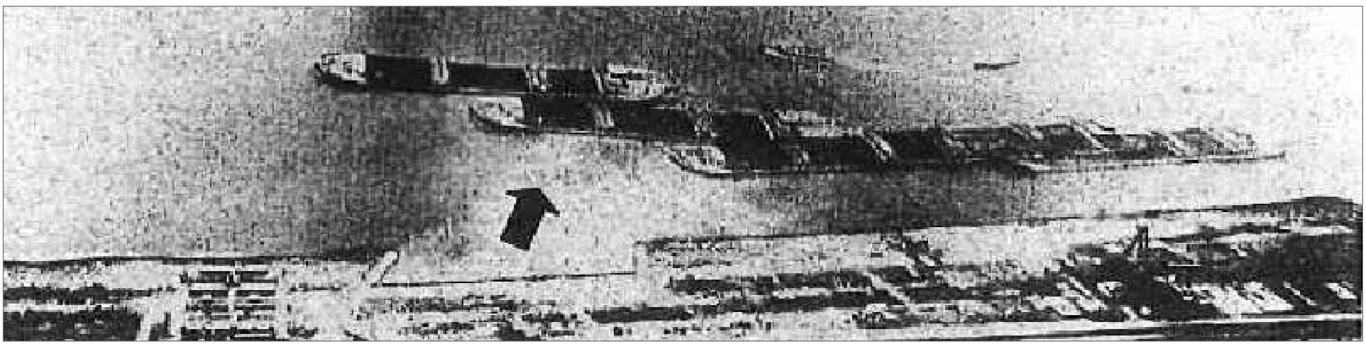


Fig. 4.1.8-1: Motion phases of a large motor vessel (MS Metz) passing an inlet structure [DVWK, 1984]

vice water required by industrial and commercial enterprises or the cooling water used by power plants are situations where cross flows can have repercussions for shipping. The transverse force and torque resulting from the cross flow velocities and the ensuing lateral shift of the ship are the criteria required for a nautical evaluation. The motion phases of a passing vessel in Figure 4.1.8-1 illustrate how severe the cross flow from an inlet structure can influence shipping.

The velocity field and the resulting cross flow velocities due to inlet and outlet structures are fundamentally different. The flow at outlet structures has relatively little turbulence. It can thus be approximated by a potential flow and causes water to flow to the outlet sides, leading to a comparatively rapid decrease in the cross flow velocity as the distance from this outlet increases. Inlet structures, on the other hand, are subject to the laws of jet propagation. The decelerated flow of the jet widens at a defined small angle and produces generally much higher cross flow velocities compared to those at an outlet structure, even at large distances from the structure. Together with turbulence effects such as flow separation as well as recirculation and mixing with the surrounding water owing to strong shear stresses at the jet boundaries, the impact of inlet structures on navigation is more severe than in the case of water removal structures. Apart from differences in the ship's exposure to transverse forces and torques, as shown in Figure 4.1.8-2, this leads to generally better conditions for shipping at outlet structures than at inlet structures. This is why the Dutch waterways extension guidelines (Richtlijnen Vaarwegen, 2011), for example, permit 1.5 times higher cross flow velocities and water quantities at outlet structures compared to inlet structures.

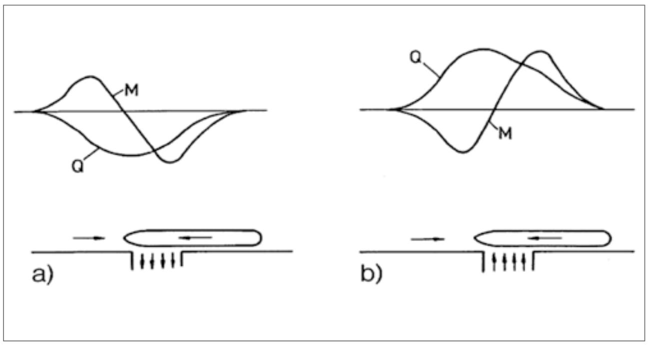


Fig. 4.1.8-2: Transverse forces Q and torques M acting on a ship as a result of a) an outlet structure and b) an inlet structure [VBW]

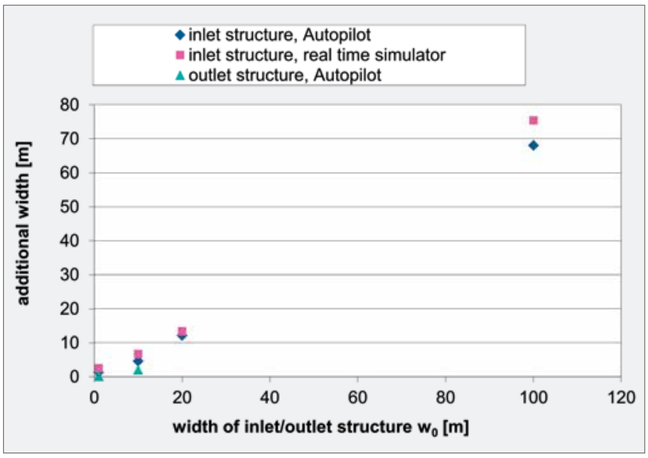


Fig. 4.1.8-3: Influence of the width of an inlet structure on the additional width (lateral displacement plus additional width due to drift angle) in the cross flow field when a 2.8 m deep-laden GMS is sailing close to the bank (distance: 4 m) for a cross flow velocity of 1 m/s (no longitudinal flow) at the inlet structure in a 4 m deep canal derived from simulator test runs (Söhngen et al. 2012) [BAW]

Constant maximum limits of permissible cross current velocities are specified in many guidelines and relevant literature to simplify navigability assessments at cross flows. A value of 0.3 m/s is often laid down for inlet structures. However, the specified limit value, which is based on tests in lay-by basins and branch canals (see Jambor, 1960), only applies to cross flow fields no wider than approximately half the ship length and assuming sufficient navigation space is available for manoeuvring.

The above-mentioned value of 0.3 m/s may thus no longer be on the safe side if the cross flow field is wider than ½ L or if the available navigable space is lower than assumed for setting the 0.3 m threshold. This may be the case if more intensive use is made of navigation channel cross sections than in the past, for instance owing to the approval of larger craft.

On the other hand, much higher cross flow velocities may be acceptable in case of narrow cross flow fields, as according to studies carried out by the BAW (Söhngen et al. 2011 and 2012) the additional traffic space utilised by shipping in the cross flow field is almost linearly proportional to the width of the inlet or outlet structure (see Figure 4.1.8-3). The maximum permitted cross flow velocity, as specified e.g. in the Dutch guidelines, therefore depends on the width of the cross flow field and can be as high as 1.5 m/s for very narrow inlet structures. Hence, since the assumptions regarding the available navigation space incorporated into this higher limit value might not be true in every single situation – as is the case with any blanket assumption about maximum cross flow velocities – it makes more sense to determine the additional traffic space due to inlet and outlet structures directly and compare it with the available navigation space for manoeuvres.

Simulator test runs carried out for a series of cross flow fields have confirmed that the additional width likewise increases almost linearly with the cross flow velocity (see Figure 4.1.8-4). Together with the proportionality to the width of the inlet or outlet structure this enables a maximum value of 5 m³/s to be specified for the permissible volume of water flowing into the navigation channel, assuming a constant water depth and a constant permissible additional width.

If a significant longitudinal flow in the canal or river is superimposed on the inlet jet, producing large-scale horizontal turbulence as shown in Figure 4.1.8-6, this flow field also increases the required navigational space (see Fig. 4.1.8-5). At outlets, on the other hand, the influence of turbulence – and hence of the longitudinal flow – is only minor and can be neglected.

As explained earlier in connection with navigation in bends, the draught-to-water depth ratio T/h also has a significant influence on the additional width in a cross flow field. With small dynamic underkeel clearances the forces may suddenly become so great that they can no longer be controlled by the shipmaster. Detailed evidence concerning the influence of cross flows is therefore recommended whenever the available navigation space is restricted, the shipping traffic makes full use of the depth conditions and the cross flow field in question is highly turbulent and possibly also inhomogeneous owing to the local geometry. This is often the case with recreational boating, especially with muscle powered craft such as rowing boats which are difficult to navigate and tend to have only a restricted field of vision, for instance because the rowers are looking in the opposite direction to the driving direction.

Critical cross flows occur not only at inlet and outlet structures but also – as explained earlier in Chapter 4.1.4 – in the approach areas of locks (especially in reaches where the lock is positioned next to a weir), at the mouths of power plant canals (downstream canal), at the mouths of side channels at river barrages, at outlet and return structures for pumping water and water management in canal reaches and double locks.

Unfavourable conditions can result in cross flows in the lay-by basin entrance areas of river and canal locks, especially when a ship is manoeuvring into these areas because its manoeuvrability is restricted by its low ship speed or a necessary stopping manoeuvre. Vessels manoeuvring out of the locks and the lay-by basins generally can use a higher engine power or have a higher speed and are therefore easier to steer, so

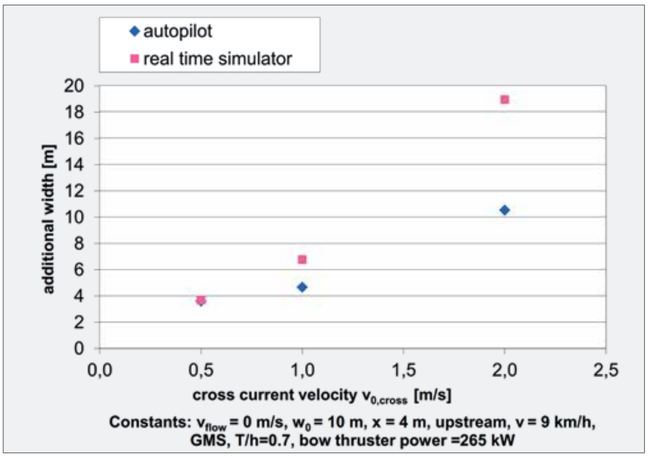


Fig. 4.1.8-4: Influence of the cross flow velocity at the inlet structure on the additional width under the same boundary conditions as in Figure 4.1.8-3 [BAW]

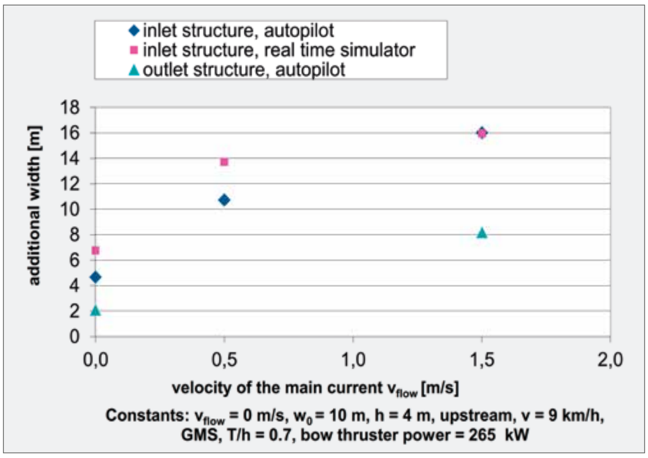


Fig. 4.1.8-5: Influence of the longitudinal flow velocity at the inlet structure on the additional width in a cross current field under the same boundary conditions as in Figure 4.1.8-3 [BAW]

that their behaviour is not affected to the same extent. At river locks, too, it is usually more difficult to enter the upper lay-by basin than the lower basin because the ships are more manoeuvrable in the downstream area as they move against the current. Jambor (1960) compares sight investigations concerning the entry conditions at canal branches from large rivers with corresponding scale model tests and derives correlations between torque moments and the magnitude of the cross flow velocity. From this he derives 0.20 m/s as a reliable measure of the cross flow velocity in the upper lay-by basin and 0.30 m/s in the lower lay-by basin (Jambor, 1960).

Cross flows caused by eddies in the entrance area of a lock when the adjacent lock chamber of a double lock is filled or emptied are a particular nuisance (see Figure 4.1.8-7). The same flow characteristics are observed at a diversion channel. Special requirements apply in the entrance area to guarantee shipping safety due to the limited room for manoeuvre and the low ship speeds. Based on studies of the maximum cross flow velocity at double locks when a vessel enters one lock chamber from the downstream area while the neighbouring lock is being emptied, Jambor (BAW, 1960) specifies the maximum permissible cross flow velocities upstream of these locks as between 5 and 7 cm/s.

There have been frequent attempts in the past to create more favourable conditions for compensating the cross flow velocities between locks by means of an extended guiding structure with openings, as indicated in Figure 4.1.8-7, yet these model tests have tended not to produce the desired success. Simultaneous filling and emptying is avoided for this reason when a ship enters a double lock.

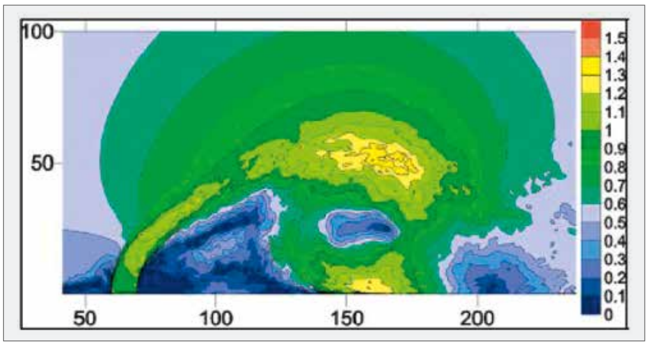


Fig. 4.1.8-6: Snapshot of the calculated flow velocities (shown are lines of identical flow velocity, the colour coding indicates the flow velocity magnitude shown on the right in m/s) in the vicinity of a 10 m wide inlet structure in a 4 m deep canal at a cross flow velocity of 1 m/s, which superimposes with a longitudinal flow in the channel (from the left, 0.5 m/s) [BAW]

Cross flows also occur when manoeuvring into or out of lock chambers without any kind of external influence. This is partially on account of the flows for which the ship itself is responsible, which were mentioned earlier in connection with safety distances. The ship-induced return flow when a vessel is navigated into a lock asymmetrically, for example along a guiding mole, forces its way from the bank towards the middle of the lay-by basin. The associated transverse thrust must be compensated, e.g. by using the bow thruster or by means of wooden rails while entering the lock chamber. Asymmetrical approach conditions are especially critical, say, if density driven flows are additionally present in tidal areas. In this case salt water flows upward into the chamber after a downstream lockage; the associated cross flows produced there can be very large.

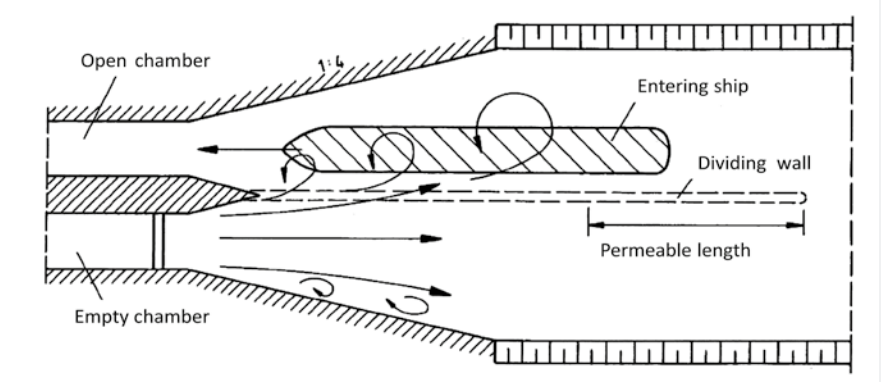


Fig. 4.1.8-7
Cross flows caused by emptying the adjacent lock chamber in the entrance area of a double lock [Partenscky, 1986]

4.1.9 Transverse thrust at groynes

Transverse thrust which occurs in the spur dike areas likewise has a significant influence on ship dynamics of inland navigation vessels. Amongst other things, it results from the disturbance of the flow field around the groyne. At the groyne head there is a strong flow towards the middle of the river whereas in the groyne field, the water mainly flows back towards the bank. This is shown in Figure 4.1.9-1, in which the main flow (greenish-grey) and the flow in the groyne field can be distinguished by the different water colours due to the turbidity of the water.

Shipmasters must counteract these cross flows in a confined navigation channel or in manoeuvring situations where the room for navigation is restricted, for example by adopting a drift angle. This is particularly advisable when sailing upstream because the ship is only moving at a slow speed over ground and therefore exposed to the cross flows for a long time. When sailing downstream, it may make more sense to accept that the ship drifts sideways in the groyne field area because the speed over ground is faster and the time for which it is exposed to the cross flows is much shorter. There is consequently less lateral shift, especially as the cross flows cancel each other out to a large extent over one groyne field.

These cross flows at groynes can be limited, though not completely avoided, by optimizing the channel control lines (connecting lines of the groyne heads). As an alternative training structure one can use longitudinal dikes instead of spur dikes. The hydraulic and morphodynamic effect is generally the same as both training structures restrict the width of the low-water bed, enabling the bed to be deepened and the water level to be retained owing to the higher flow velocities.

Fig. 4.1.9-1: Right bank of the River Rhine in the groyne field near Biblis: the water flows from the bottom of the photograph to the top [source: Google Maps]

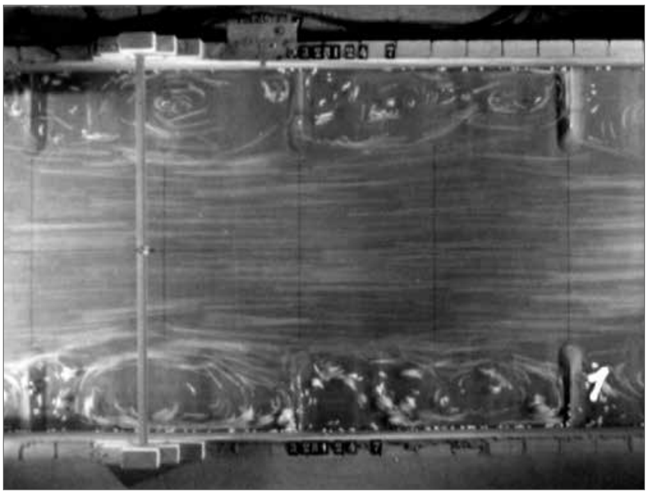


Fig. 4.1.9-2: Floating structures in model tests to determine the flow in groyne fields [Felkel, 1975]; the photographs were taken with a long exposure time and the distance between the structures is four times their length [BAW]

Despite the various advantages of this solution for avoiding cross flows and limiting the possible rise of the flood water levels, which is frequently inevitable with spur dikes, the use of longitudinal dikes to train rivers also has its drawbacks. For example, it is no longer possible to sail directly into a groyne field in an emergency situation and run the ship aground there in order to prevent an imminent collision. Above all, longitudinal dikes are generally much more expensive compared to groynes if they are to achieve the same kind of effectiveness as training structures, because they are located in deep water. The mass of building material is far greater than with groynes, where only the head extends into the deeper part of the river. Spur dikes have therefore become established as the standard regulating structure in inland waterways engineering.

Cross flows also occur in groyne areas as a result of turbulent exchange processes, caused by the considerable difference in flow velocity between the main flow and the groyne field. In other words, the cross flows vary significantly over time and because these variations are so unpredictable, shipmasters can do little to counter them (adopting a drift angle is unlikely to work). Moreover, the dimensions of these turbulent structures depend on the length of the groynes and the spacing between them. With large spacing between groynes the turbulence-induced horizontal vortices can be as large as the inland navigation vessels themselves. These vortices consequently have a major influence on the required navigational space.

They are particularly strong and unpredictable the larger the ratio of groyne spacing to groyne length as shown in Figure 4.1.9-2. A single, long drawn-out vortex which completely fills the groyne field is visible in the bottom left. The groyne field in the top right has two significant vortices while that in the bottom right has a chaotic, totally disordered vortex field. Large distances between the groynes – more than approximately 1.5 times the groyne length – should therefore be avoided where possible when new training measures are planned. They can still be found at groynes which are already in place, however.

Strong cross flows are mainly encountered at forward inclined groynes which are oriented against the main flow, even with moderate groyne distances (see Figure 4.1.9-3 on the left). Since these flows deflect the water flowing over the back of a groyne towards the middle of the river, they help to protect the banks. Backward inclined groynes, where the cross flow conditions are more favourable, are only employed where bank protection is not relevant, for example at the inner banks of narrow bends in a river transporting large amounts of sediment or in cases where the banks can be protected using supplementary methods like riprap. Transverse forces can thus never be completely avoided in groyne field areas and each ship is under a duty to maintain a suitable safety distance (see Chapter 4.2).

Like the safety distances to embankments, these distances also depend on the ship's drawdown and consequently increase with higher ship speed through the water. The reason

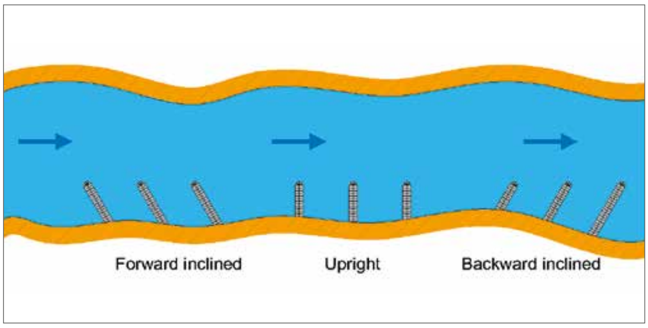


Fig. 4.1.9-3: Definition of different groyne types [BAW]

for this is that a groyne field is "drained" by the water level drawdown, especially if the groyne fields are partly silted up. This lowering of the water level produces a negative surge wave which enters the groyne field perpendicular to the flow and is reflected there before returning to the fairway. In the course of this process, water flows out of the groyne field, similar to a cross flow from the ship's perspective. The shipmaster must basically sail towards the bank in order to compensate this cross flow, as shown in Figure 4.1.9-4. The required safety distances at the groynes are accordingly high.

Fig. 4.1.9-4: Breasted-up formation sailing slowly downstream along groyne fields and encountering a GMS in model tests to determine the necessary safety distances at groynes [Neuner, 1999]

4.1.10 Cross section effects when manoeuvring into and out of lock chambers

When a vessel enters a lock chamber, whose cross section is often not considerably bigger than that of the vessel, several effects related to the ship-induced waves and currents occur. These are explained in detail in the following.

Ship-induced flush waves

Experience has shown that a ship's squat can have a considerable influence on the safety and ease of navigation – especially when leaving a lock – owing to the risk of contact with the bed, the long times needed to manoeuvre in and out and the dangerous situations that can arise if the lock is approached too fast (BAW, 2005). Model and field tests have yielded a whole series of findings in relation to these problems. The following parameters depending on the geometric constraints play a crucial role:

- Ratio of the lock sill or chamber water depth to the load draught,
- Ratio of the wetted lock cross section to the submerged ship cross section (n ratio), and
- Ratio of the actual ship speed to the critical ship speed of the vessel sailing inside the lock chamber.

A ship sailing in a navigation channel with varying cross sections as in the case of driving from the lock approach into the lock chamber induces unsteady flow processes and movements of the water level. Depending on the ship's position, varying – mainly longitudinal – flow velocities and water surface profiles as well as force effects on the hull are observed when the vessel is manoeuvring in or out of a lock. There are several fundamental differences between entry and exit manoeuvres. The conditions also differ according to whether the ship is manoeuvring in or out in the upstream or downstream area because the water depths in the chamber are not the same.

If the descent structure is a ship lift, the trough approaches and exits closely resemble the downstream conditions at locks (Söhngen, Spitzer, Stuntz, 2006). Empirical observations have confirmed that the conditions for shipping are less favourable in a lock's downstream area – regardless of whether the ship is entering or leaving – owing to the smaller cross sections, but the nautical demands are greater in the entrance area because manoeuvring is more complex.

The propagation characteristics of a positive surge wave, which widens as a ship sails into a lock, are shown at various instants in time in Figure 4.1.10.-1 (see Rauwoens and Spiessens, 2008). A positive surge initially builds up at the lock entrance depending on the ship speed and the blockage ratio (n ratio). This surge propagates at a velocity which in rectangular chamber cross sections is approximately equal to the well-known wave propagation velocity in shallow water (Figure 4.1.10.-1, A).

When the surge reaches the closed end of the chamber, a total reflection occurs. The reflected wave is superimposed on the incoming wave so that the height of the surge is doubled (Fig. 4.1.10.-1, B). The wave is reflected and superimposed again and again during the complex propagation process, in which the narrowing of the cross section by the approaching ship amplifies the shock wave that is transmitted and the reflected wave is of the same type as the original wave (see Chapter 3.3.2). The surge thus continues travelling along the ship at the narrow cross section with a varying height and at a varying velocity, and a similar surge is reflected back again (Fig. 4.1.10.-1, C).

By contrast, the wider cross section astern of the ship reduces the height of the transmitted wave and results in a reflected wave of the opposite type in the opposite direction, i.e. a positive surge returns a negative surge wave and a negative surge wave a positive surge (Figure 4.1.10.-1, D). Based on this law, when the positive ship-induced surge is reflected at the closed end and reaches again the abrupt transition from the lock to the lay-by basin cross section (which is assumed to be large), the height of this transformed surge – which continues to advance in the lay-by basin – is almost zero. But the height of the negative surge wave which then travels back along the ship towards the lock chamber is identical to that of the incoming positive surge in accordance with the continuity equation.

This means that positive and negative surge waves are continually formed, superimposed and damped due to friction effects. Figure 4.1.10.-2 shows the conditions for manoeuvring into a lock from the downstream area depending on the water level. These results of model tests with a pushed convoy are presented here as an example. The tests were carried out at an identical approach speed of about 1.5 m/s or 5.4 km/h.

The graph shows that owing to the positive surges the ship speed initially decreases almost linearly with the “penetration distance” (distance between bow and the lock entrance) of the vessel in the lock chamber. The corresponding negative speed gradient increases as the water depths become smaller. This initial phase of entering the lock during which the vessel is decelerated sharply is followed by a second phase in which the ship speed is characterised by periodic variations, especially for low water depths in the chamber. These variations gradually become smaller until the ship is at a standstill.

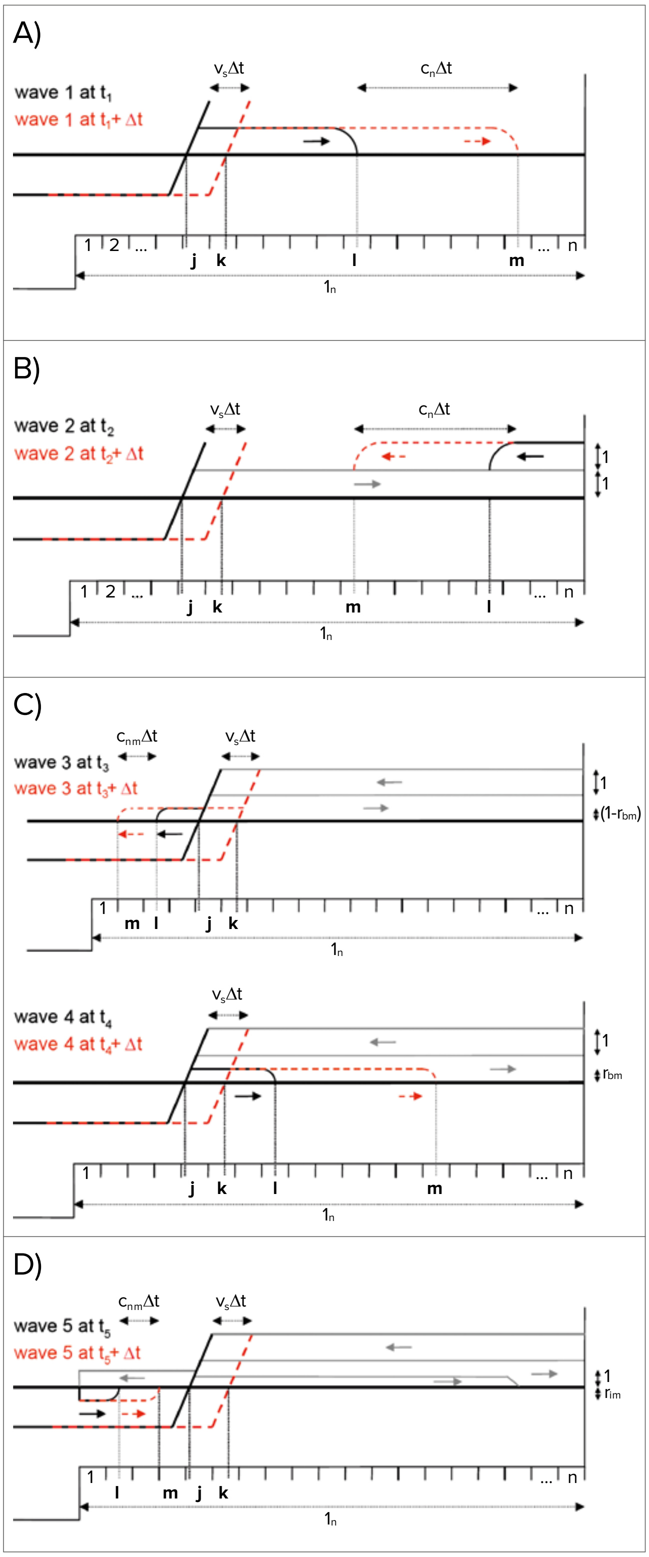


Fig. 4.1.10.-1: Propagation characteristics of a positive surge which forms as a ship sails into a lock [Rauwoens and Spiessens, 2008]

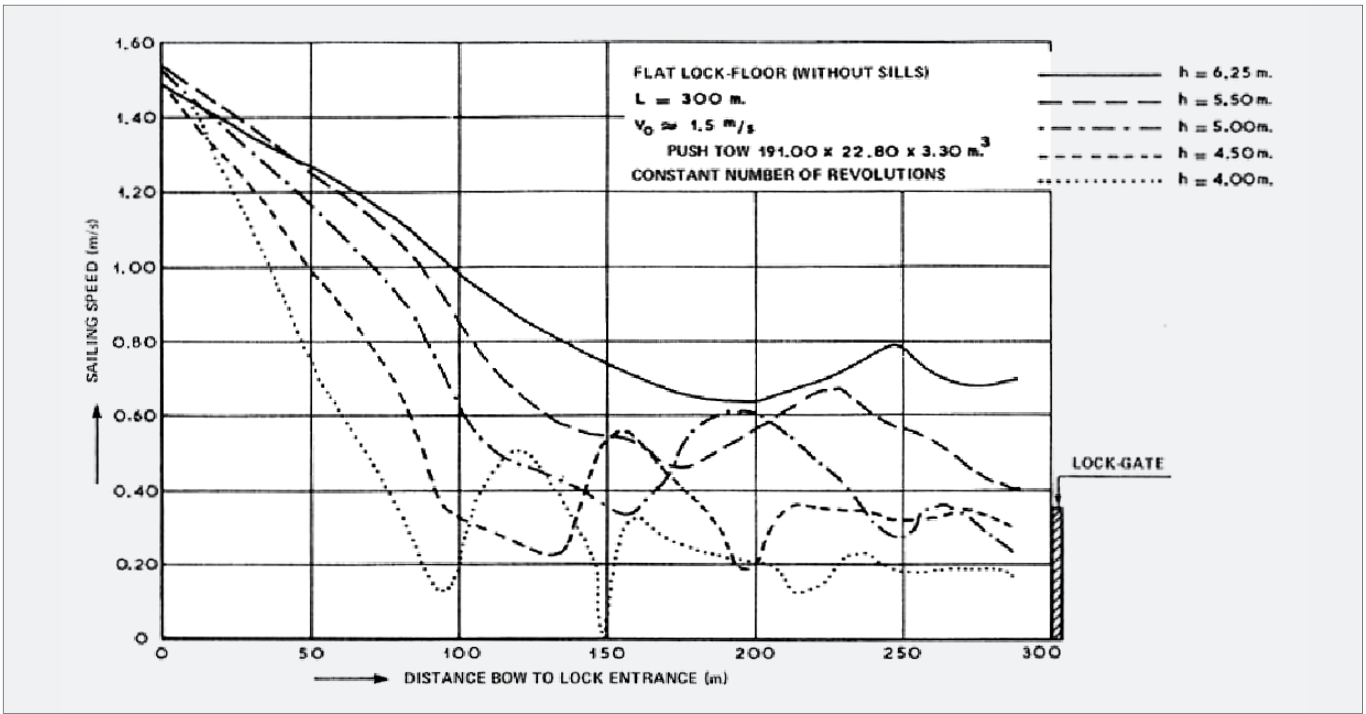


Fig. 4.1.10.-2: Change in the speed of a pushed convoy as it manoeuvres into a 24 m wide lock chamber for different water depths [Kooman, 1973]

These approach conditions which are dominated by the water depths in Figure 4.1.10.-2 apply analogously if the widths change, i.e. at smaller cross section ratios the ship's motion in the chamber becomes increasingly unsteady if the lock is approached at the normal speed and significant variations can be observed. In extreme cases the ship will come to a standstill and move backwards if the cross section ratio is very small and the approach speed too high!

Squat and dynamic underkeel clearance

Several computational approaches exist for calculating squat in narrow cross sections such as canals. But each squat formula is only valid within a strictly defined scope of application – and it works well only for a steadily driving vessel, not for extreme unsteady conditions as in case of lock approach or exit. In order to identify a generally applicable method for predicting squat under the conditions prevailing in locks, systematic model tests were carried out with different ship's hull forms, draughts, chamber widths, chamber water depths and ship sailing speeds. A multiple regression analysis based on the results of the model tests yielded a relationship for the squat ΔT referred to the chamber water depth h. According to this relationship, the relative squat ΔT/h is approximately a function of the cross section ratio n, the block coefficient C_B (ratio of the water volume displaced by the vessel and the volume of a surrounding cuboid) of the exiting ship and the depth Froude number $v/(g \cdot h)^{1/2}$ (ratio of exit speed to surge velocity in shallow water).

The squat formula derived from this for ships navigating through a lock can be represented as a set of curves on a graph (see Figure 4.1.10.-3) by plotting the squat referred to the water depth as a function of the depth Froude number. The cross section ratio n (cross section of the lock in relation to the midship cross section) appears as a parameter. The ratio of the actual ship speed v_S to the critical ship speed v_{crit} is an additional parameter in the graph. The critical ship speed is calculated according to the one-dimensional canal theory.

If a ship is sailing with the critical speed, which is the maximum possible ship speed in a steady driving situation, a corresponding limit value for the relative squat ΔT/h exists for each cross section ratio n. At a ratio n of around 2.45,

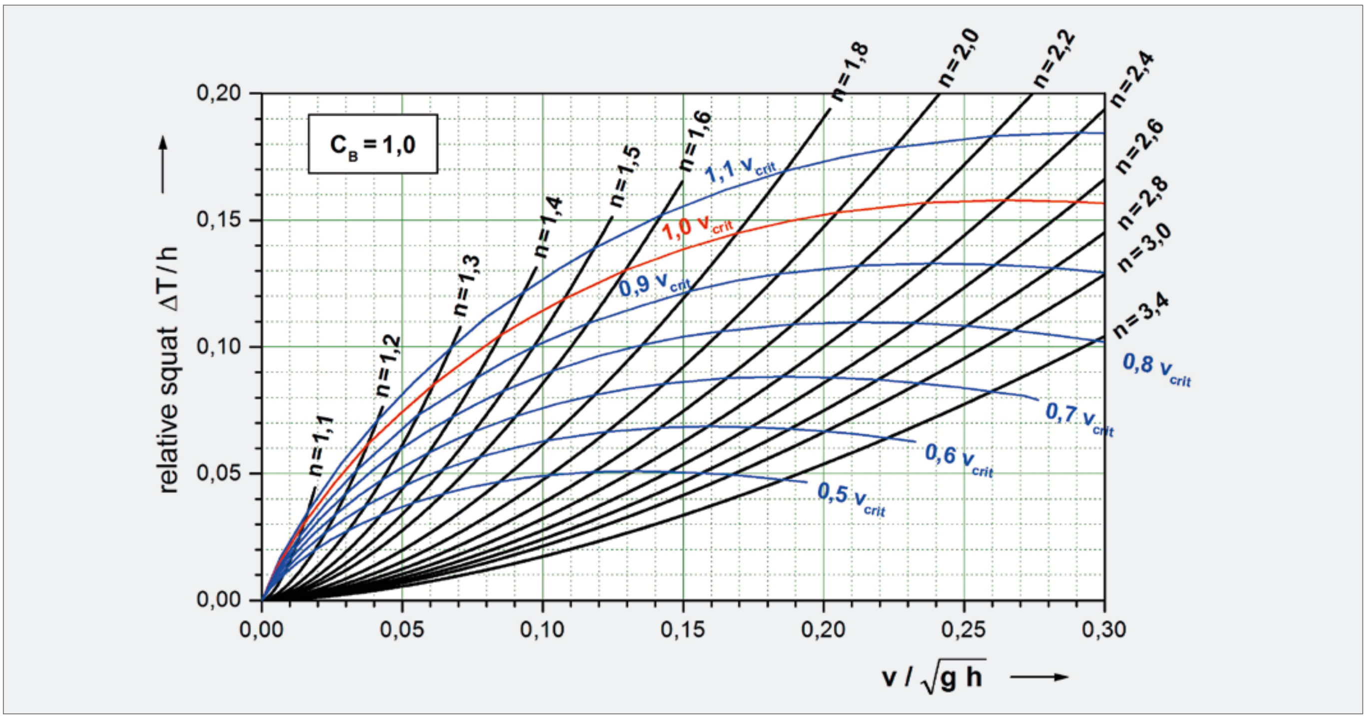


Fig. 4.1.10.-3: Graph used to determine the squat when sailing out of a lock chamber, calculated for a pushed convoy with a block coefficient C_B = 1.0 [Spitzer and Stuntz, 2005]

the curve of the ΔT/h function for $v = v_{crit}$ moreover shows an absolute maximum squat, which is equivalent to 15.8% of the water depth h. This maximum relative squat at v_{crit} thus only depends on the block coefficient. For a modern GMSs with a typical C_B value of about 0.9, it is approximately 3% higher than for ships where C_B = 1.0.

The application of the squat formula shows that in order to avoid contact with the bed at the maximum permitted load draught, it is not the widest ships that require the deepest water, but rather narrower vessels, which are closer to the above-mentioned cross section ratio n = 2.45. The reason is that narrower ships can manoeuvre out of a lock at a higher speed owing to the better cross section ratio. The breadth of the vessels navigating in the waterway must therefore also be considered in addition to the maximum load draught when determining the worst case.

According to Römisch (1993), a certain "navigation reserve" is essential to maintain manoeuvrability and prevent contact with the bed. A minimum dynamic (ship in motion) underkeel clearance of 0.20 m is recommended when manoeuvring out of a lock. The reserve for inadvertent drawdown as a result of trim and heel allows enhancing influences, particularly abrupt ship acceleration during the approach phase, to be taken into account. These factors alter the relationships determined for quasi-steady manoeuvres out of a lock into the downstream area.

High approach speeds to a lock due to the sudden narrowing of the cross section at the lock end combined with the "piston" effect can lead to a strong deceleration of the vessel and to a large trim angle, so that the squat may have a similar magnitude to when the ship manoeuvres out of the lock into the downstream area. This is even the case when the vessel manoeuvres into the lock from the upstream area owing to the bottleneck at the lock head and it may happen as well when it manoeuvres out again into the upstream area if there is a large lift height, because as the height increases – and with it the water chamber depths – the cross section ratios make higher ship speeds possible at the exit. To prevent contact with the lock sill, the minimum sill depths should therefore correspond to the required chamber water depths for manoeuvring out of the lock into the downstream area.

Times for manoeuvring in and out

The complete lockage time TC depends on the time taken to manoeuvre into the lock, close the lock gate, fill or empty the chambers, open the gate again and manoeuvre out of the lock. Detailed studies exist, particularly regarding the time to manoeuvre into a lock. They are usually limited to the downstream area because the cross section ratios there are less favourable. They show that very small cross section ratios n prolong the manoeuvring-in times disproportionately. In this case, the ease of shipping can be severely restricted while the problem of contact with the bed due to the low ship speeds and small squat depths becomes secondary.

An analysis of model and field tests of ships manoeuvring into locks and lift troughs revealed that the entry process can be divided into several characteristic phases. After approaching a lock at a given speed v_{an}, a ship is decelerated very unevenly as it sails in. In the second phase, the formation and constant reflection of the backwater at the bow as well as at the closed trough gate causes the gradient of the water surface to vary. The ship speed consequently also varies according to the approach speed and the cross section ratios, although the average overall change is only small. A limit speed which is independent of the approach speed and mainly determined by the water depth and cross section ratio n can be specified for the ship in the second phase. The third phase typically comprises the stopping manoeuvre.

An analysis of model and field tests concerned with manoeuvres into a lock from the downstream area yielded a distance-time law (BAW, 2005), which is plotted in Figure 4.1.10.-4 and can be used to estimate the time taken by a ship to sail into a lock from downstream. These manoeuvres tend to take longest in connection with low cross section ratios, small water depths, long navigational paths and long vessel lengths. The influence of the ship length is shown in Figure 4.1.10.-4 by the empirical quantity x_o, where $x_0 = 0.44 \cdot (L - 57\,m)$. The quantity x_e in the list of parameters in Figure 4.1.10.-4 denotes the distance travelled from the start of the downstream lock head until the ship comes to a standstill in the lock chamber.

It is generally true to say that, in spite of the differences between the hydrodynamic conditions when entering and exiting the lock, there are several parallels between manoeuvring in and manoeuvring out. Manoeuvres out of a lock into the downstream area can be divided into characteristic phases just like manoeuvres into it, namely a start phase with strong acceleration, an exit phase at a constant speed and a gradual acceleration as the ship is leaving the lock chamber. A speed limit like-

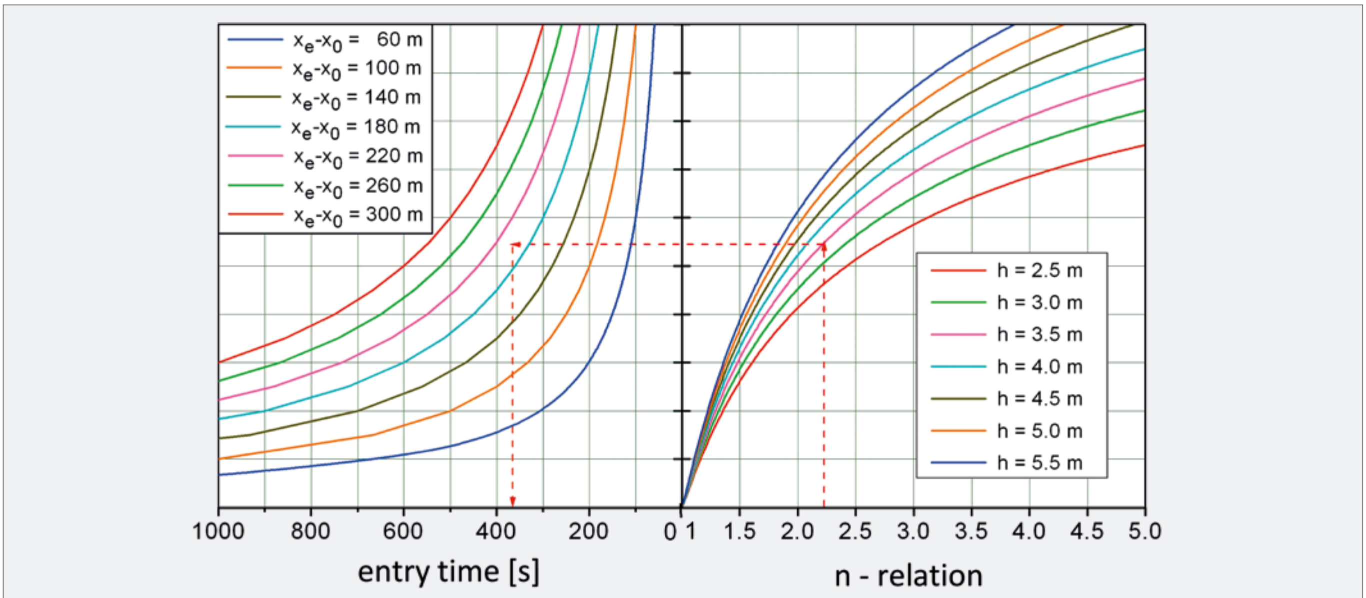


Fig. 4.1.10.-4: Graph used to determine the time taken by a ship to manoeuvre into a lock from downstream [BAW, 2005]

wise exists when manoeuvring out due to physical constraints and this is taken into account directly in the above-mentioned critical speed. According to VBD studies, in which the manoeuvring-in and manoeuvring-out times were compared, the difference between these two processes is only minor (BAW, 2005).

Safe approach speeds

It has been observed that with small dynamic underkeel clearances and constant cross section ratios the biggest risk of contact with the bed when navigating a lock is posed by the vessel manoeuvring out. There is only any danger to ships entering the lock if the approach speed is too high. If the values for the maximum squat and the permitted maximum draught and/or maximum ship speed at the exit from the lock are applied to the lock entrance situation, the conditions will be on the safe side. In addition to the risk of contact with the bed, several other factors are also important for determining the permissible approach speed.

These factors include both objective influences such as the design of the lock entrances, the manoeuvrability of the ships or the prevailing environmental conditions (wind, flow, visibility) and subjective factors like the crew's experience. Studies of ships manoeuvring into locks have also shown that the sudden, unsteady movement of a vessel at the entrance due to the formation of high waves ("piston effect") at high approach speeds and low cross section ratios can mean that the crew's assessment of the potential danger is subjectively incorrect, so that the wrong action is taken. Studies of ship behaviour when manoeuvring into a lock have been carried out by the VBD and can be used to estimate a safe approach speed (VBD, 1993 and Broß, 1994). The changes in the trim and drawdown when entering the lock were determined in the framework of these studies for 11.4 m wide vessels and pushed convoys with extreme draught ratios. It was revealed that the actual approach speed depends on various factors such as the geometry of the bow, the design of the lock entrance, the draught ratio h/T and the cross section ratio n.

Regardless of the bow geometry, the entrance to the lock is considered by shipmasters to be safe if a suitably low ship speed is selected for approaching the lock. As an outcome of the above studies, the adherence to maximum speed limits is recommended for 11.4 m wide ships approaching a 12 m wide lock, depending on the draught and the chamber water depth. The results for the draught and cross section ratios $1.07 \leq h/T \leq 1.60$ and $1.13 \leq n \leq 1.68$ were evaluated (source: BAW), leading to the safe approach speed specified in the graph in Figure 4.1.10.-5 for the data used.

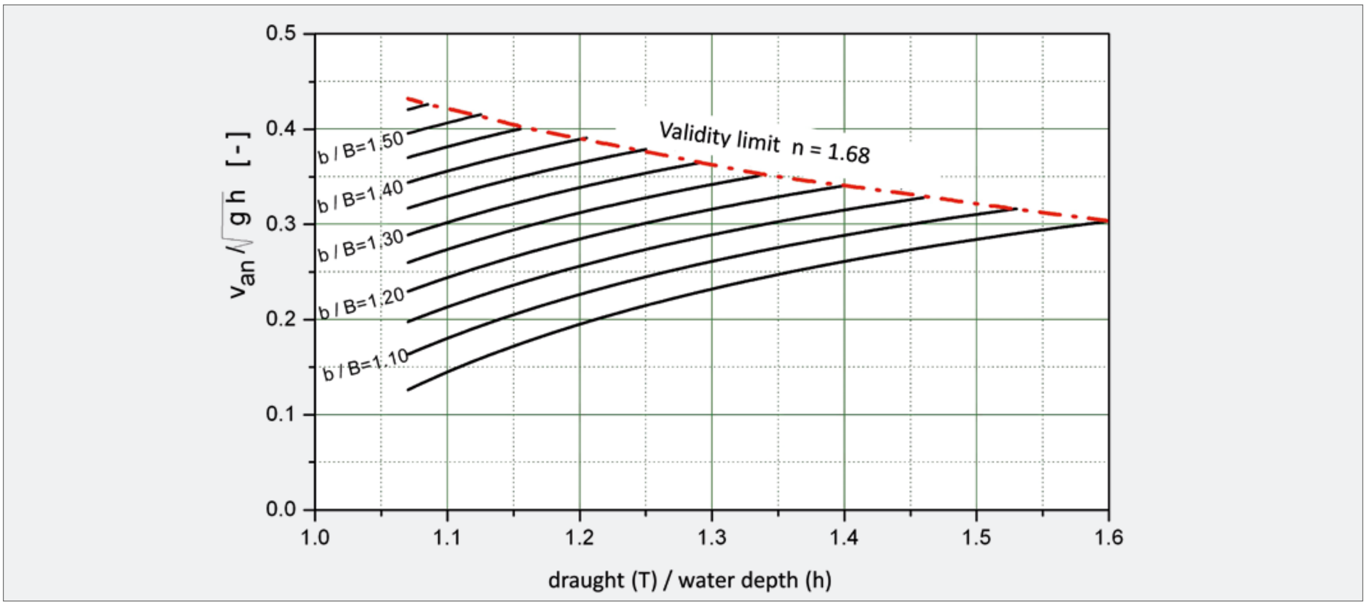


Fig. 4.1.10.-5: Permissible approach speed for safe entrance into a lock from the upstream or downstream area [BAW, 2005]

4.2 Safety distances

4.2.1 Encounters, overtaking and sailing along embankments

Safe shipping, i.e. when a ship's motion remains controllable at all times, requires minimum distances to be maintained from the bank as well as from oncoming or overtaking vessels (RILI, 2010). Since ships “meander” when sailing straight ahead, additional lane widths must be allowed depending especially on the vessel length. If a ship follows an eccentric path in a symmetrical canal or if it is sailing in an asymmetrical cross section (e.g. a canal with sloped banks on one side and sheet piles on the other side, German “RT” profile), the forces perpendicular to the ship's motion, which are produced mostly on the hull by the ship-induced waves and currents, are different on each side so that manoeuvres are necessary to counter them.

If a ship is sailing asymmetrically, the higher return flow velocities on the ship's side closer to the bank cause the water level to be lowered to a greater degree on this side, especially in the extended midship section of inland freight vessels where the return currents are most pronounced. Therefore, the vessel is pulled towards the closer bank. In contrast, the backwater-effect in front of the vessel increases due to the proximity to the bank and the bow is pushed away from the bank (“bow-out-moment”). The shipmaster counters these forces and torques by applying the rudder and adopting a drift angle. The swept area width is thus significantly larger than the ship's beam [Kuhn] and the corresponding additional width must be available between ship and bank. This will also be interpreted in the following as the necessary safety distance.

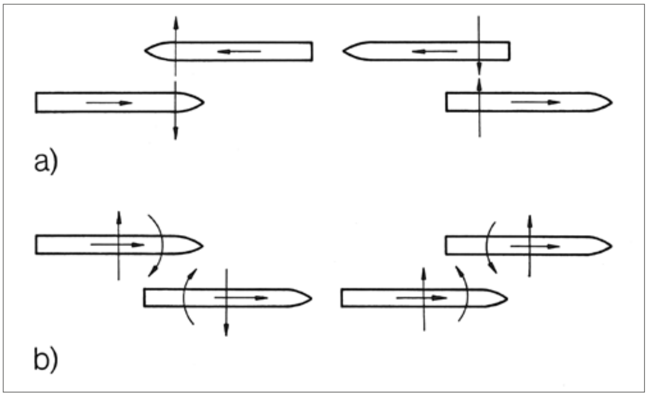


Fig. 4.2.1-1: Interaction between two ships a) during an encounter and b) during an overtaking manoeuvre [Kuhn, 1985]

Ships encountering or overtaking one another are obliged to sail asymmetrically. The two opposing return flows and wave fields are superimposed in addition to the above-mentioned forces when sailing alone. The forces and moments exerted on the two ships are indicated in Figure 4.2.1-1. As soon as they start to pass one another, the fore bodies are forced apart by the bow waves and the ship-induced sideways currents while at the end of the manoeuvre the afterbodies are moved closer together owing to the suction effect.

The influence on the ships' behaviour is much stronger during overtaking manoeuvres than when two ships pass each other because the two different return flows are superimposed and the manoeuvre lasts much longer than during an encounter. Extensive rudder manoeuvres are required by both ships during overtaking to stay on course. The vessels are initially turned towards each other but at the same time forced apart. The most dangerous phase occurs at the end of the overtaking manoeuvre, when the ships are turned towards each other, see Fig. 4.2.1-1. Both ships need to reduce their speed here, which means this manoeuvre takes a relatively long time.

It has already been explained earlier in Chapter 4.1.6 that the necessary safety distances are mainly determined by the ship-induced flow and wave fields (Söhngen, Dettmann, Neuner, 2007). Additionally, the development of the water and pressure levels induced by a large motor vessel (length 105 m, width 11 m and draught 2.8 m) sailing in two canals of different widths will be considered in the following in more detail, see Figure 4.2.1-2.

The ship sails 20 m from the bank in the middle of the narrow canal (b = 40 m) but follows a very eccentric path at the same distance from the bank in the wide channel (b = 200 m). The water depth is 4 m in both cases. The ship speed was then adjusted in the calculations to ensure that the average drawdown is roughly the same in the midship area of both ships, mirroring the typical situation of "sailing according to the wave pattern". The ship in the wide canal consequently sails faster than the one in the narrow canal. The bow and stern waves due to the local flow field, which are superim-

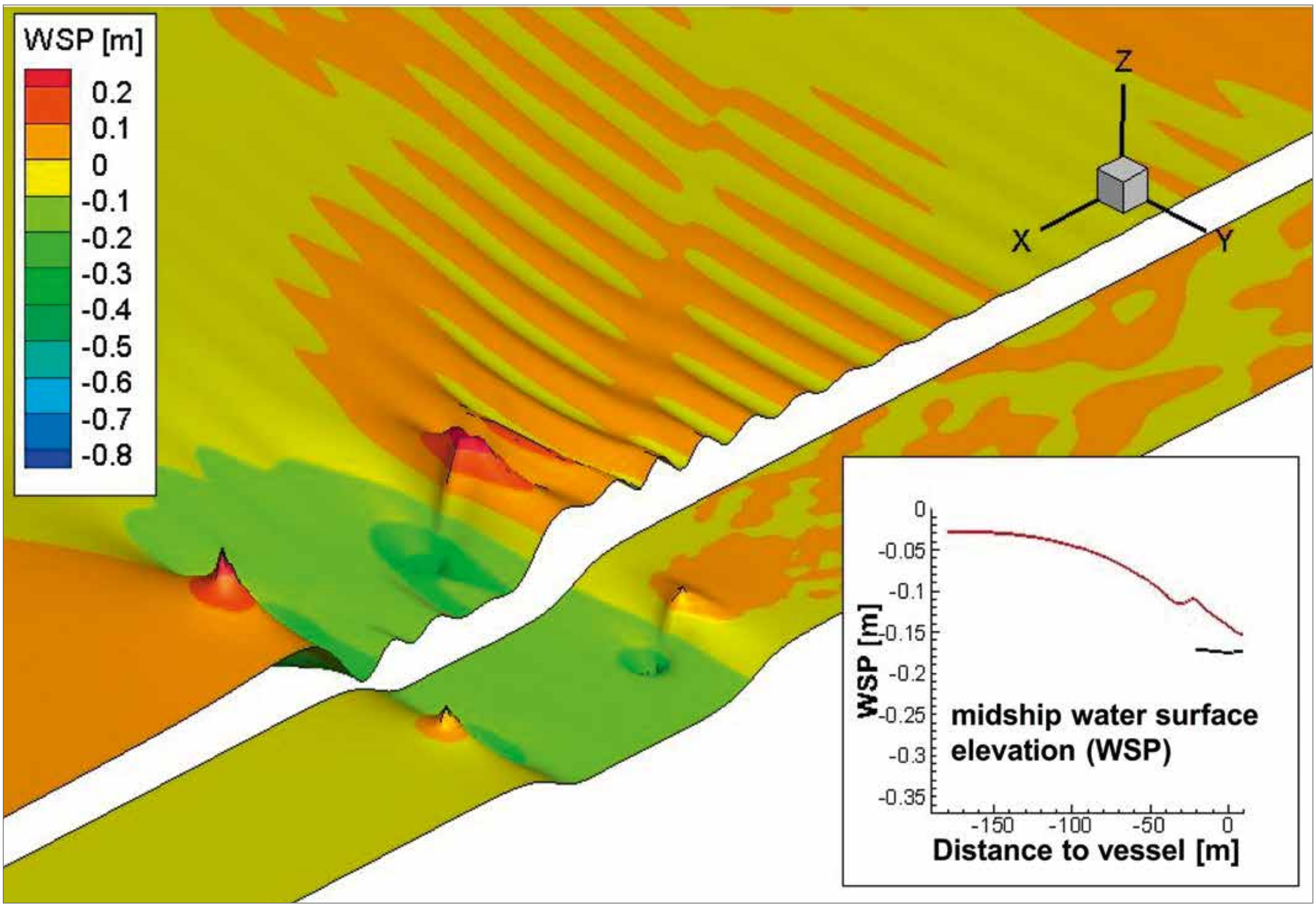


Fig. 4.2.1-2: Ship-induced water surface levels (WSP) and pressure heads (underneath the ship), shown as a in the survey map and cross profile induced by a GMS sailing at different speeds but with the same drawdown in the midship area in rectangular waterways with a width of 40 m and 200 m [BAW]

posed on the average drawdown field, are accordingly large. To illustrate this phenomenon more clearly, the wave heights shown in Figure 4.2.1-2 are exaggerated, so that the secondary waves are more pronounced.

If a second vessel crosses the drawdown field of the first vessel shown in Figure 4.2.1-2 during an encounter or overtaking manoeuvre at close quarters, the higher bow and stern waves in the wide channel would have a much greater impact on the second ship than would be the case in the small canal with the result that e.g. the second ship's bow section is strongly forced away while passing the bow of the first vessel in a wide channel. Added to this is the flow, which is induced in the bow area by the local displacement of the ship as explained earlier in Chapter 4.1.6. This flow is likewise directed towards the second ship, forcing it away. The purpose of the safety distance between the two vessels is, for example, to limit these forces in the bow area besides those in the midship area.

These force effects are lower in the narrow canal because the ship is sailing slower than in the wide canal, yet the drawdown is normally identical. The local bow and stern waves are therefore lower and the displacement-induced cross flows smaller than in shallow water. This is one reason why a smaller safety distance between the ships is sufficient in the narrow canal compared to a wide river.

Another reason is the large transverse gradient of the water surface in shallow water when sailing close to the bank. This

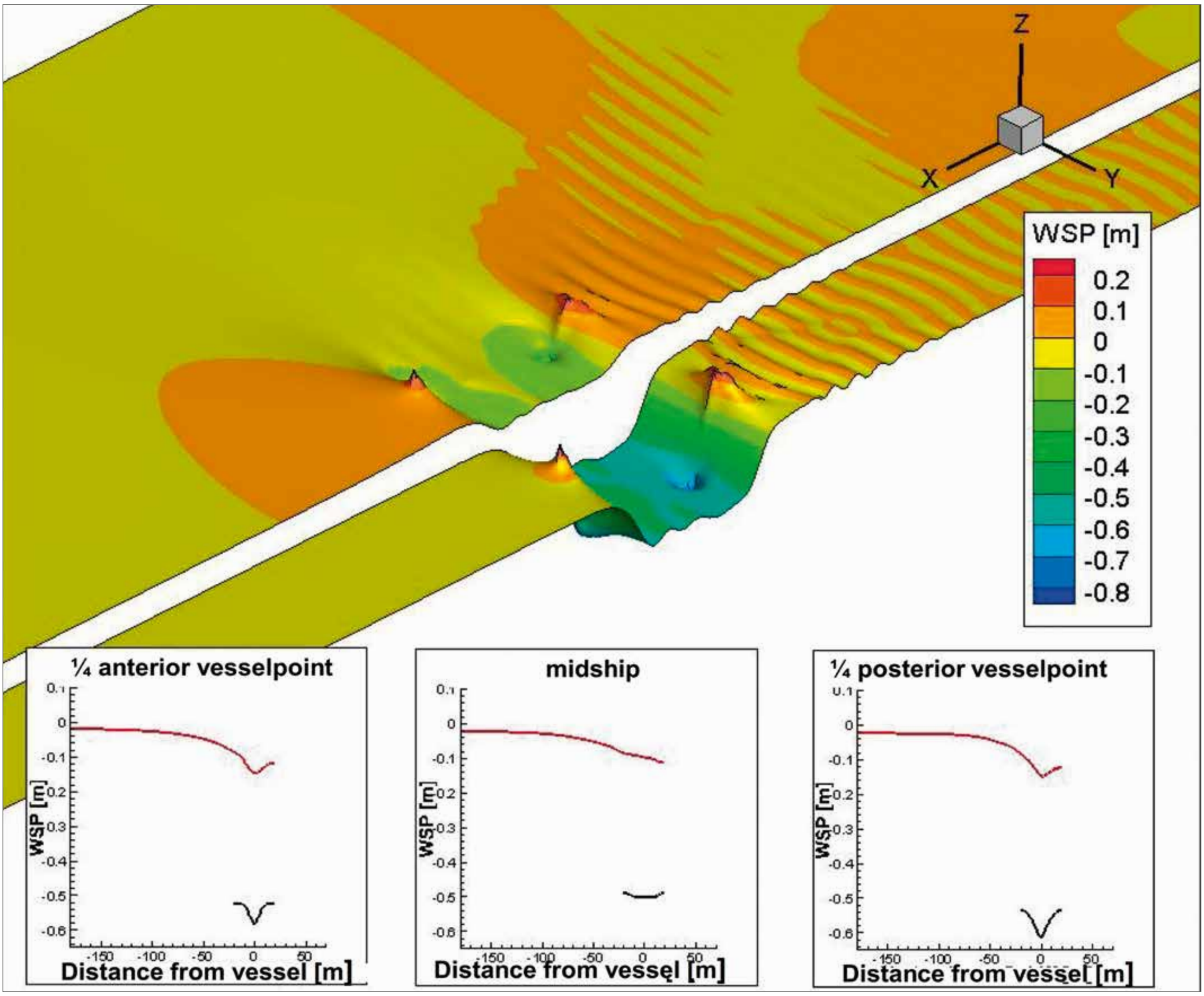


Fig. 4.2.1-3: Wave pattern (water surface height besides the vessel, pressure height underneath the ship) shown from a bird's eye view and corresponding cross profile, induced by a GMS sailing at a speed of approximately 10 km/h in rectangular channels of different widths (40 m and 200 m) [BAW]

is visible in the bottom right of Figures 4.1.1-7 and 4.2.1-2 (red line). The difference between the water levels on the starboard and port sides of the passing ship is correspondingly large, as is the suction force between the two vessels. In a narrow canal, on the other hand, this suction force is much lower as shown in Figure 4.1.1-7, where the ship follows an eccentric path ten metres from the bank both in shallow water and in a narrow canal. The water surface gradient in the narrow canal is much smaller than in shallow water, which explains the smaller suction forces between the two ships.

Consequently, smaller safety distances are sufficient in the narrow canal; the largest distances are required during the phase when the two vessels are approximately level with one another.

These considerations show that the safety distances for standard canal cross sections, for example, cannot be simply transferred to a wide canal or a wide river because – assuming an identical average drawdown of about 0.3 metres, which is the value used in the diagram and corresponds to

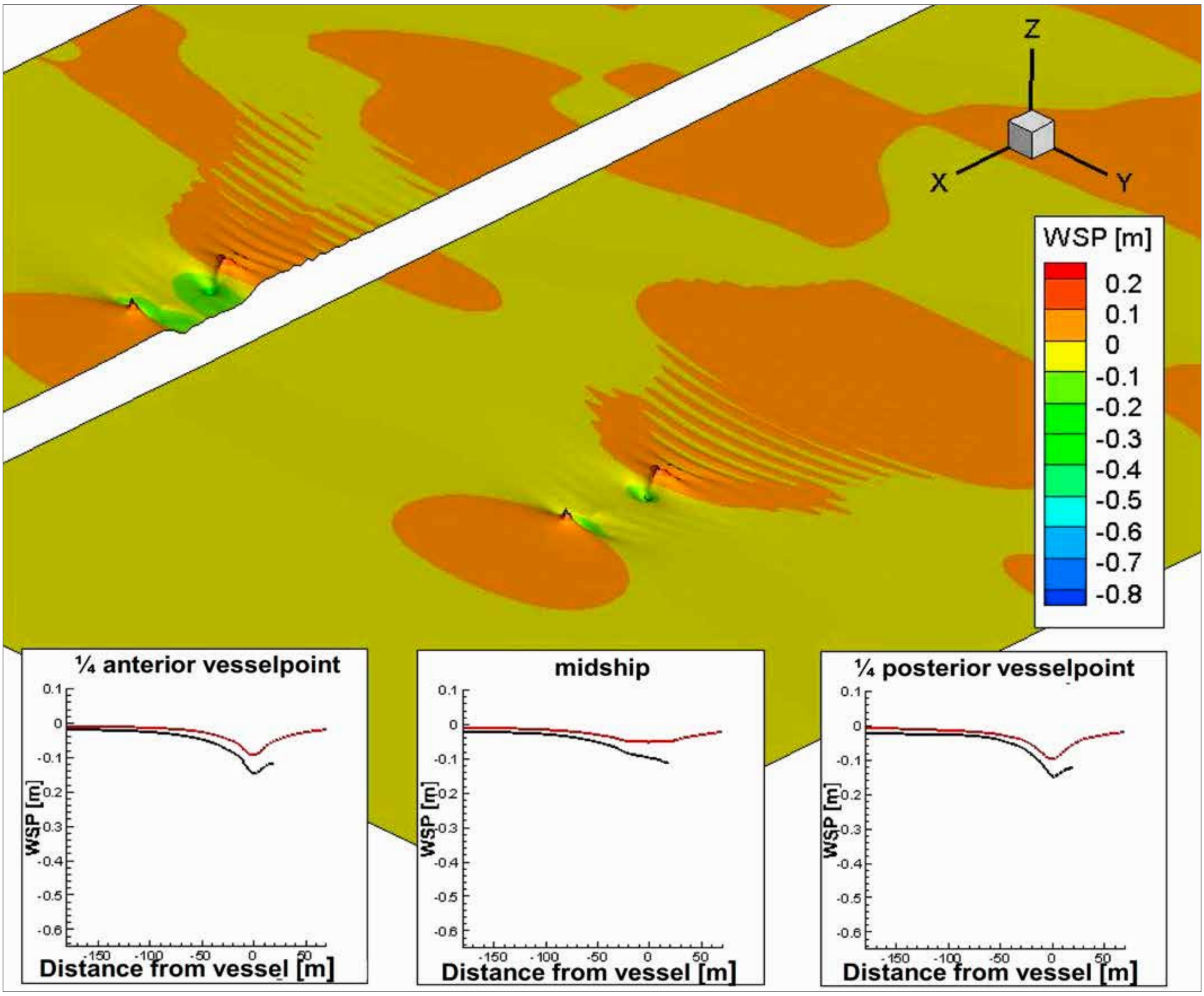


Fig. 4.2.1-4: Same as Figure 4.2.1-3 – comparison of a 200 m and 400 m wide channel [BAW]

normal sailing – the bow and stern waves are much higher in shallow water than in the canal, the lateral gradient of the drawdown trough is by far larger, because the relative eccentricity is greater and because the absolute ship speed is higher. As a result, necessary safety distances from the bank are generally smaller in a canal than in shallow water.

However, all safety distances can be significantly influenced by the choice of ship speed as they depend on the displacement-induced flows. According to Figure 4.1.6-1, these flows have an almost linear relationship with v as well as with the water level differences due to drawdown – and thus also with the size of the drawdown itself, which in turn is closely linked to the ship speed through the water. In particular, this speed must be adapted to the cross section of the channel.

Figures 4.2.1-3 and 4.2.1-4 illustrate the impact of a laterally limited navigation channel. The ship shown here is sailing in three waterways of different widths (width 40 m: ship sailing in the middle, width 200 m: ship path 20 m away from the bank and width 400 m: centric ship course) at a constant speed of 10 km/h. Whereas the drawdown is roughly 40 cm in the narrow canal, it is less than 15 cm in the wide canal. Despite this difference in drawdown, the transverse water level gradient is again the dominating factor concerning lateral forces acting on a second ship when it crosses the drawdown field of the first vessel. It is clear from these diagrams how the necessary safety distances are determined by the ship-induced wave field and its transformation close to the bank, so that it is not possible to specify one numeric value which fits every situation. The values selected for a particular design project must therefore be adapted to the individual circumstances.

The above-mentioned aspects are summarised in Table 4.2.1-5. It also indicates the order of magnitude of safety distances required for safe navigation in the different channel cross sections and at the different ship speeds considered here.

4.2.2 Navigation at groynes

Cargo vessels keep a respectable distance when passing groyne heads if the navigation channel width and the traffic situation allow this (see Figure 4.2.2-1). This is necessary on account of the cross flows, which are dependent on the flow field prevailing in the river and induced by the ship itself as a result of the drawdown - they were explained earlier in Chapter 4.1.9 and have been estimated in BAW studies.

In particular, the influence of river flow and horizontal turbulence was examined by scale model tests. The lateral displacements of floats were analysed statistically to find a relation between these sideways movements and the groyne arrangement and geometry, the hydraulic conditions and the distance between the floats and the groyne heads. The corresponding cross flow velocities derived from these data were combined with formulae for extra widths applicable when vessels sail in

Scaling parameter			Physical cause and approximate ship-to-ship or ship-to-bank safety distances for vertical banks
Width	Ship speed	Traffic situation	
Wide river	High cruising speed	One-way traffic, encounters and overtaking	Significant deformation of the primary wave field close to the ship and at the bank when sailing close to the bank (approx. 1 beam)
– " –	Moderate cruising speed	– " –	Limited deformation because the ship speed is lower (approx. 2/3 beam)
Narrow river, canal	– " –	– " –	Smaller deformation of the primary wave field because the eccentricity of the ship's course is smaller than in wider channels (approx. 1/3 beam)
– " –	Cautious speed	One-way traffic and encounters	Further reduced wave heights because the ship speed is lower (according to German guidelines for standard canal cross sections: 2 m ship-to-ship, 4 m ship-to-bank)
– " –	Slow speed	– " –	Bank forces are not relevant. Shipmasters must be able to find their way nevertheless, therefore reduction up to visibility distance (approx. 2 m)

Table 4.2.1-5 Scaling parameters; physical causes and order of magnitude of safety distances [BAW]

Fig. 4.2.2-1: Inland navigation vessel sailing upstream past a groyne field on the Rhine near Dormagen (the water flows from the bottom of the photograph to the top) [source: Google Maps]

cross flow fields, which were obtained from a parameter study on the additional width required by inland navigation vessels owing to cross flows (Söhngen et al. 2012), see also Chapter 4.1.9. The cross flow component due to the drawdown, which induces a surge running into the groyne field, can be calculated theoretically and be superimposed on the cross flow component due to the river flow and turbulences [BAW].

The result is the additional width needed by inland navigation vessels passing spur dikes, which is interpreted as a safety distance. The approaches were compared with model tests carried out by TU Munich regarding horizontal safety distances (Neuner, 1999).

The higher the flow velocity, the larger the safety distance because the former determines both the stationary cross flow components and the contributions due to turbulence. With a large ratio of groyne spacing to groyne length, the influence of the flow is particularly great. This influence can basically be countered by sailing faster. In this case, however, the cross flows due to drawdown also increase, so the safety distances which are necessary under boundary conditions relevant in practice – for vessels navigating both upstream and downstream as well as for large rivers where, based on BAW measurements, ships typically sail at a speed of 12 to 15 km/h – range from 7 m (GMS, upstream, v = 12 km/h, v_{flow} = 1 m/s) to 21 m (pushed convoy, downstream,

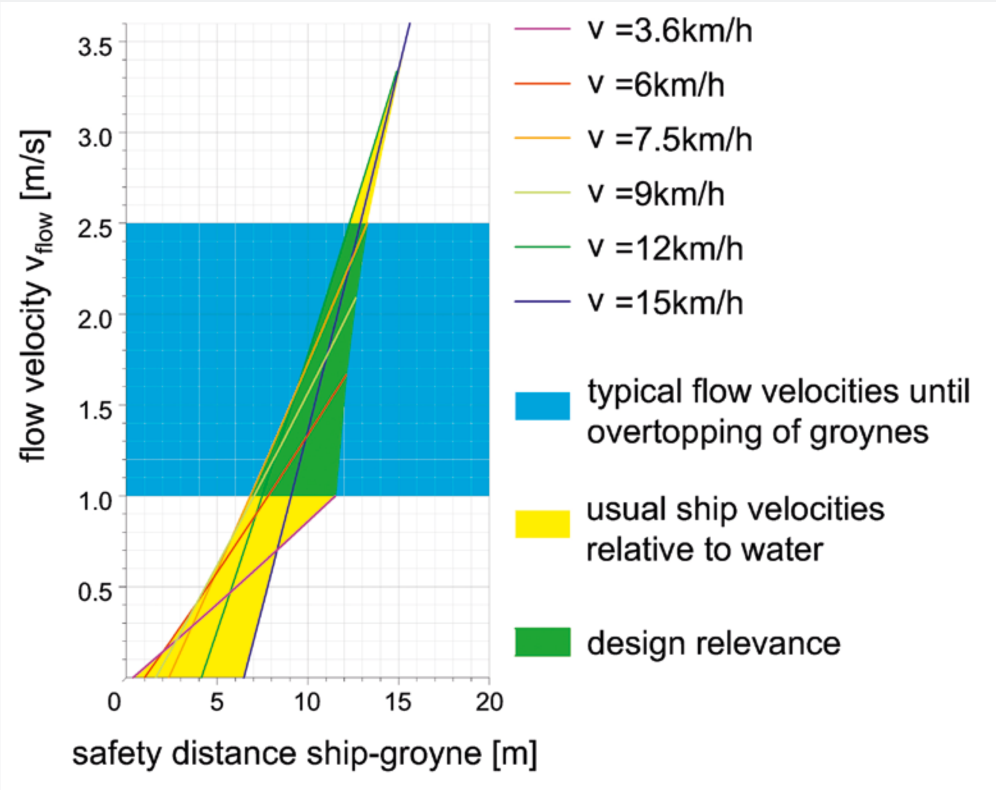


Fig. 4.2.2-2:
Safety distance to groyne heads of an upstream sailing GMS (length 110 m, beam 11.4 m, T/h = 0.75), calculated for long, wide groyne fields (groyne length 100 m, distance between groynes 200 m, navigation channel width 200 m, river width 300 m) on the Rhine at mean water level (water depth approx. 4 m) as a function of the flow velocity and the ship speed through the water v [BAW]

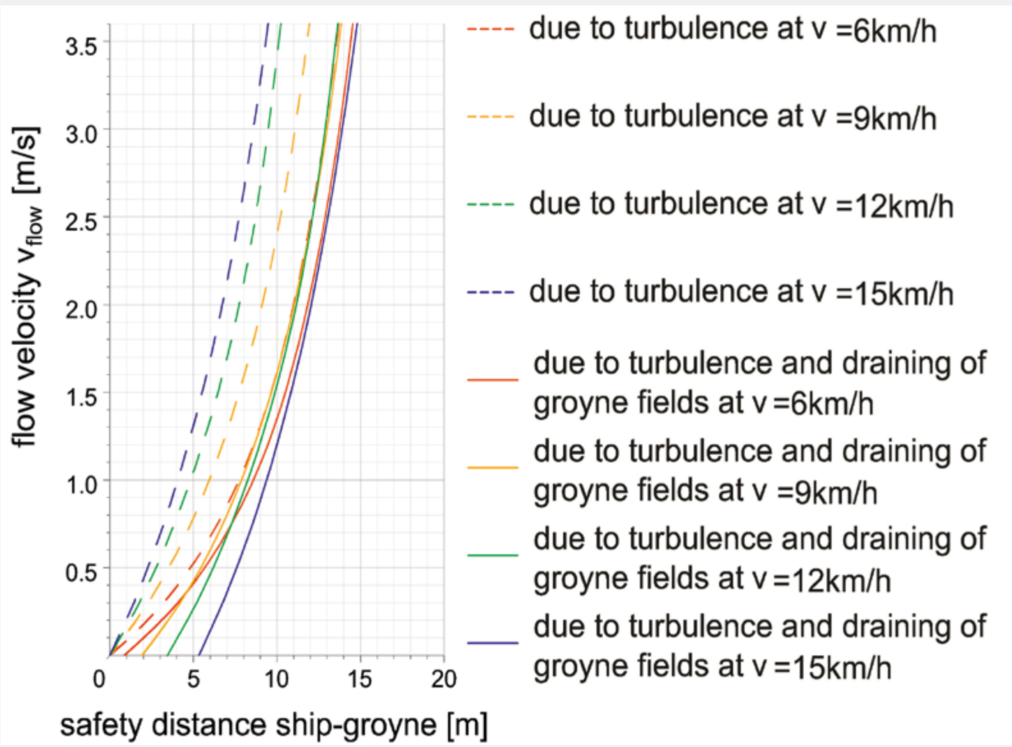


Fig. 4.2.2-3:

Same boundary conditions as in Figure 4.2.2-2 but with a GMS sailing downstream; the curves on the left represent the safety distances due to flow and turbulence while the curves of the same colour on the right describe the corresponding values applicable when the groynes are drained [BAW] v = 12 km/h, v_{flow} = 2.5 m/s) on the Rhine at mean water level. If the optimal ship speed is chosen not too fast to restrict the drawdown-related cross flows and not too slow to restrict the impact time , these values will be between 7 and 17 m, in other words the "one beam" rule of thumb that is derived from experience is confirmed.

The results of these calculations are shown in Figures 4.2.2-2 to 4.2.2-4. They apply to reaches regulated by groynes on one river side only, a ratio of navigation channel width to overall river width of about 0.6 and both, GMSs and pushed convoys. The practically relevant flow velocity ranges are represented in blue, the ship speeds in yellow and the combination of both influences in green. The influence of groyne overflow, which causes the cross flow velocities to decrease, was ignored to ensure that solid results were obtained concerning safety distances. Lower values as considered in the figures need to be assumed for lower water levels or smaller distances between groynes.

Figure 4.2.2-3 shows the safety distances for a GMS sailing downstream. It differentiates between the safety distances due to flow and turbulence (dashed curves) and the distances derived from all influencing parameters (solid curves). If the ship speed is related to the flow velocity, in other words if it corresponds to e.g. approximately 1.7 times this velocity in the downstream direction as explained in Chapter 4.1.5, the former are more or less independent of the flow velocity. A value of 8 m, rounded to the nearest full metre, applies to all ship speeds presented here. In normal sailing situations a dependence on the ship speed only exists due to "draining".

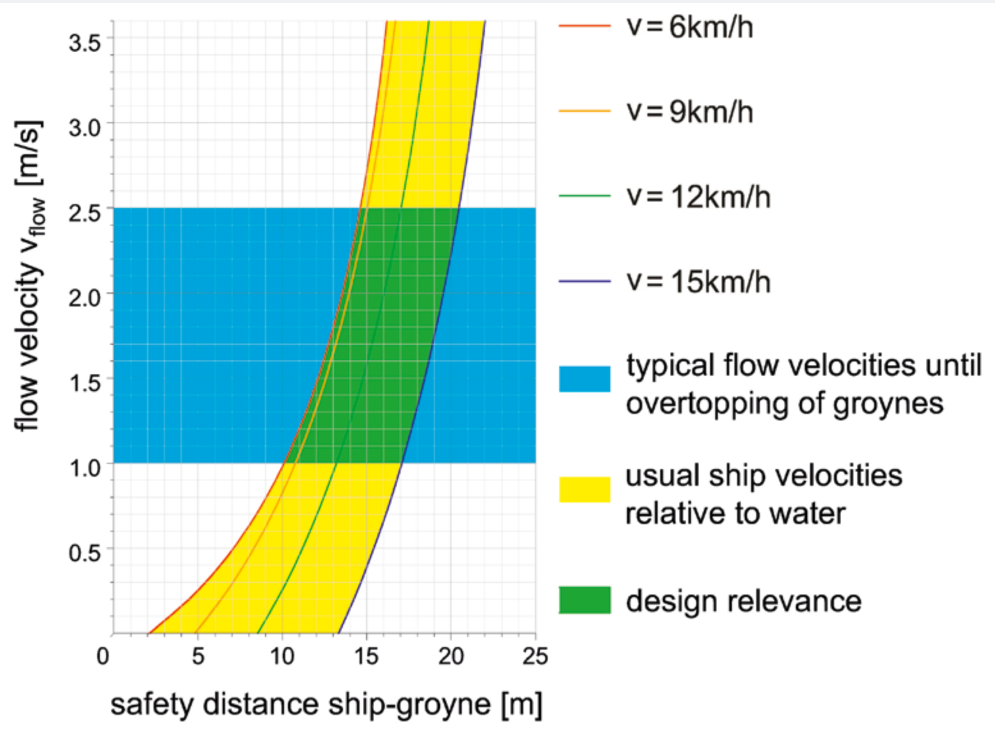


Fig. 4.2.2-4:
Pushed convoy sailing downstream (length 185 m, width 11.4 m) under the same conditions as in Figure 4.2.2-2 [BAW]

5 Manoeuvring of Ships

While the previous chapters dealt with the scientific principles underlying the motion of vessels in shallow water, Chapter 5 provides practical and nautical explanations regarding the handling of ships under different operating conditions.

5.1 Handling of ships

The operation of vessels comprises acquiring and performing transportation tasks, monitoring and guaranteeing the safe operating conditions of the vessel and the safety of the cargo, managing, supervising and training the staff as well as the economic efficiency of shipping and ensuring the manoeuvring of the vessel in the waterway. According to the purpose of this paper, the focus is in the following on the behaviour of ships during sailing and manoeuvring, i.e. the operative navigation.

5.1.1 Maintaining course without external influences

Chapter 4.1.3 discussed the physical influences acting on the vessel and the individual influence of how the ship is handled (human factor) on the required navigational space. When ships sail alone centrically in a deep and wide canal without any flow and without cross-wind, this can be defined as “sailing without external influences”. The steering options customary in this situation and the motion patterns of the vessel are presented in this chapter. The assumption is that the ship sails in the centre of the canal so as to achieve an energetically favourable operating point at which the flow around the hull is symmetrical and hydromechanical influences are kept to a minimum. In spite of this, the vessel never moves precisely straight ahead, instead it “meanders” along an ideal course as explained earlier in Chapter 4.1.3. In the following, two means for keeping the ship on course are distinguished, apart from using emergency control systems: the “non-follow-up” control mode and the “follow-up” control mode.

Steering in non-follow-up mode is the traditional way of piloting a vessel. This means, if there are deviations from the intended course, the helmsman moves the steering lever in order to counteract the deviation, and the rudder follows today in most cases due to actuation by a hydraulic system in the direction of the lever. If visibility is good and fairway marking sufficient, the drift off course may be visually noticed or read off the rate-of-turn indicator as well as the heading line on an installed electronic screen chart. If visibility is reduced and there is no direct view, navigation is performed using the rate-of-turn indicator and radar image interpretation, and, where necessary, the installed electronic chart as navigational aid.

If, for example, the desired course is straight ahead and the centreline is off-course (for example to starboard, i.e. to the right looking in the direction of travel), the control lever of the main rudder is moved to counter the observed deviation (i.e. for the present example steering to the left port rudder). After the rudder has moved and stopped in the adjusted position (rudder turning time is usually 6°/s), the vessel slows down in its rotary motion, stops and turns in the opposite direction.

In order to keep the speed of rotation to a minimum and avoid a situation where the centreline swings over the desired course, the steering lever and thus the rudder have to be returned to 0 degree at an early stage. In the process of this course correction, the vessel experiences a lateral shift (to starboard in the present example) off its original course without any additional external influences. This adjustment process will continue in the opposite direction or, if the amount of rudder has been insufficient for correcting the course, in the same direction.

Modern vessels can be steered in the follow-up-mode. It is an automated adjustment mode, using a rate-of-turn regulator and is also called “autopilot”. In this mode, the intended turn rate to port or starboard is set by the helmsman manually. Then the rudder is controlled automatically, so that the vessel will oscillate around the set turn rate. If the set turn rate is 0, the ship is kept on the current heading with the unavoidable oscillating (“meandering”) motion. In this mode, like in the non-follow-up mode, lateral shifts may occur which are not automatically corrected unless the rate of turn is adjusted.

Both steering modes may cause lateral shifts which, depending on visibility conditions, can be visually estimated, interpreted using radar images if the shift amounts to more than about 10 m, or detected by means of the electronic chart.

The follow-up mode takes some burden off the shipmaster since only the position of the ship in the fairway needs to be controlled, whereas in non-follow-up mode course deviations need to be observed and adjusted all the time. Rudder actions (number of rudder movements per minute) are much more frequent in the follow-up mode than in the non-follow-up mode and tend to cause higher wear and tear on the steering gear system. Generally, shipmasters will try to steer their course using small rudder angles and the least possible number of rudder movements, because each use of the rudder will reduce the thrust available for making headway thus reducing the vessel's speed.

With the help of high-quality rate-of-turn regulators ships can even navigate in locks, but their essential role is to relief stress and enable the navigator to sail the ship without interruption for the maximum allowed time of 14 hours. Thus the shipmaster can dedicate more attention to general operational navigation tasks.

5.1.2 Keeping course despite external influences

Where the ship comes close to a bank, the symmetrical flow around the hull is disturbed and hydrodynamic forces act on the ship, which tends to accelerate it towards the bank, see also Chapter 4.2.1. To prevent that the ship is "pulled towards the bank" the amount of rudder required for keeping course is greater than it would be if the ship was sailing along the centre of the channel. If the ship is sailing too close to the bank, both the amount of rudder and the drive power have to be reduced (reduced speed) in order to return to the centre of the canal. If the stern has swung out too far towards the bank, only a large amount of rudder and an increase in power can help. When the speed is too high, even a large amount of rudder will not suffice because the increased pull effect exceeds the transverse rudder force. As a consequence, the ship's bow is thrown off the near bank and carried over to the other side, where it is likely to strike the opposite bank.

On trained or impounded rivers a distinction is made between sailing upstream, against the flow, or downstream, with the flow. Vessels proceeding upstream try to sail the navigation channel where the flow and water depth allow an optimum speed. Vessels moving downstream try to make effective use of the flow to attain a high speed over ground with the minimum possible propulsion power.

Sailing steadily straight ahead in the strict sense of the word is something that does not really occur when sailing on still waters and even less on rivers. This is due to the fact that firstly rivers consist of a sequence of bends, as a rule, with hardly any straight stretches. Secondly, the direction and magnitude of flow velocity always changes across the cross section and in flow direction even on stretches that are virtually straight, and thirdly, the ship is not always able to keep a course in parallel with the resulting flow or the bank. The shipmaster can detect the resulting flow neither visually nor by means of technical aids.

When visibility is good, the action of the flow on the ship can be detected directly. When visibility is reduced, it has to be derived from the ship's behaviour with the help of navigation equipment (e.g. radar) or navigational aids (e.g. electronic river chart), for example in cases where the ship goes significantly off the set course or is offset laterally.

An evaluation of the ship motions is required before corresponding steering actions for compensating the lateral offset or correcting the course can be carried out. The ship's navigational space needed is therefore always larger on a river than on still water bodies. Shipmasters well familiar with the course of the river can respond in a more timely and more farsighted manner to the action of the flow, require less space and are able to sail at higher speeds than a shipmaster with little local knowledge.

5.1.3 Bend navigation

When approaching or while negotiating a bend, shipmasters need to anticipate a range of different nautical situations. Based on previous experience, shipmasters will make their predictions regarding the motion behaviour of the vessel taking the local water-level-dependent flow conditions into account. In line with these predictions they manoeuvre the ship ahead of the bend into a starting position either more to the left or the right bank. In addition, they tend to slow down the vessel.

Fig. 5.1-1: Sailing downstream on the River Neckar [DST]

If the view of the bend is restricted, the shipmaster must be ready to expect an encounter immediately after the bend and take the additional space required by the oncoming ship into account. For example, if the bend is preceded by a bridge, neither the geometry of the bend nor possibly oncoming vessels can be detected by radar image interpretation, especially at night time and when visibility is poor.

The signal waves emitted by the radar are reflected by the bridge and do not show any actual echoes for behind the bridge. With the help of an electronic river chart, the shape of the bend can be visualized, but not the oncoming vessels. Where bends are difficult to navigate, shipmasters usually use VHF ship-to-ship radio communication to inform each other on vessel positions. The accuracy of the position description depends on the shipmaster's level of knowledge of the route and the nautical equipment of the ship.

The introduction of AIS transponders will help shipmasters to locate the positioning of oncoming vessels with much more certainty, because the information received from other vessels can be displayed on the electronic river chart. Provided the position information received from the other ship over VHF corresponds to the real position, the shipmaster approaching the bend brings the ship into the starting position judged as being the most appropriate one for negotiating the bend safely, taking into account the available space including any possible positioning inaccuracies of oncoming vessels.

Once a ship has started navigating the bend, possibilities for course corrections from the ideal line are limited, particularly when moving downstream, because the width of the fairway is limited, for example on tributaries to the Rhine and on canals. Also, the extra width needed to counteract centrifugal forces by taking an adequate drift angle must be accounted for, especially if the fairway width is small, see Chapter 4.1.5.

When sailing narrow bends, bow rudders or thrusters are normally used to support steering. Passive bow rudders produce very efficient crosswise forces if the vessel is sailing at high

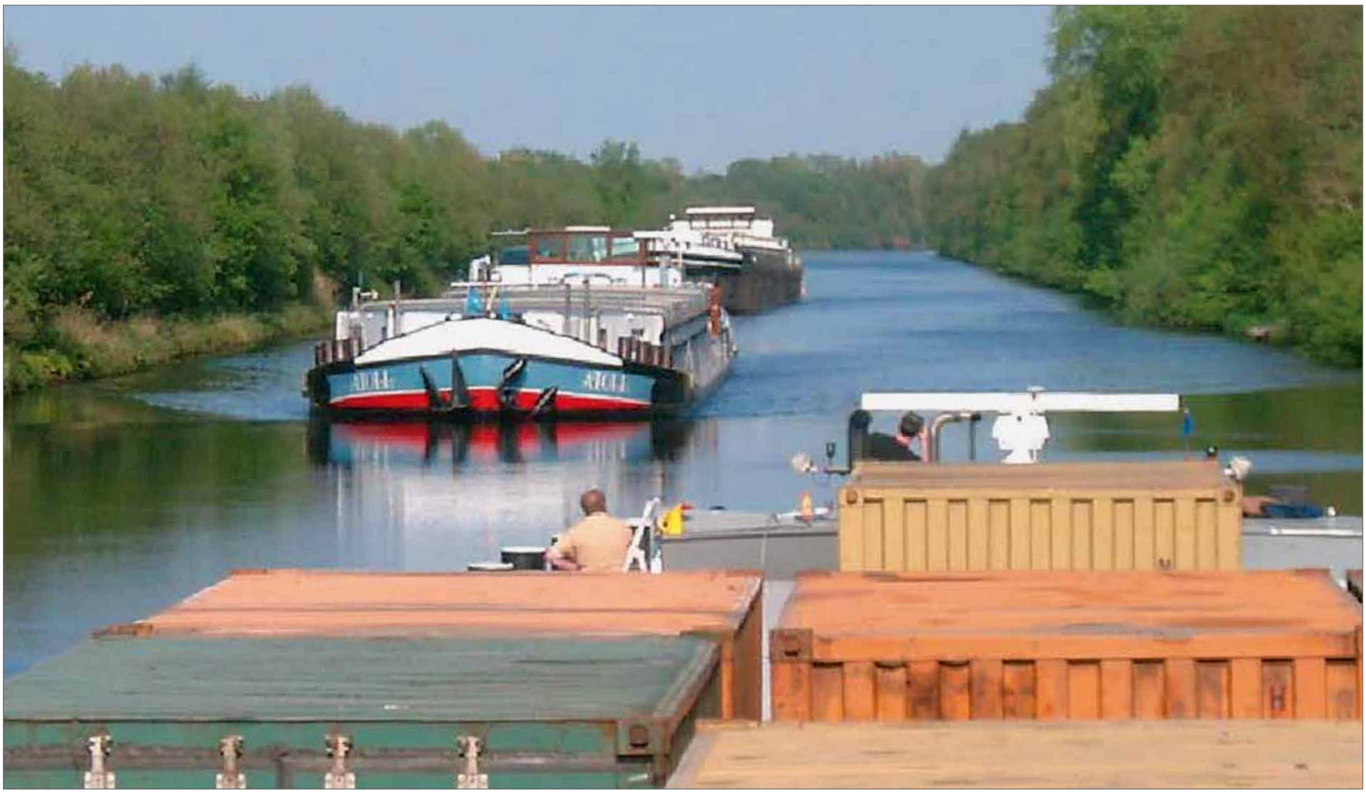


Fig. 5.1-2: Encounter of the test vessel with two other Europe ships at Coastal Canal km 16.9 [BAW]

speeds like, for example, the unladen push-tow units sailing downstream the Lower Rhine River. In contrast, the efficiency of active bow thrusters decreases if the speed relative to water is too high, so they are mostly used with low speeds.

In principle, the motion pattern in bend navigation is similar to that of course keeping despite external influences. However, shipmasters are required to have excellent knowledge of the route and a sound judgment of the motion behaviour to be expected from their own ship and from other vessels.

5.1.4 Encounter manoeuvres

When ships pass each other on a canal (vessels with the largest permitted dimensions for canals with standard dimensions) very often they cannot avoid sailing close to the bank. The relative proportions of the ship's beam and the fairway width are similar to the relative proportions of a lorry and the width of a lane on a federal highway without the shouldering. In contrast to vessels on rivers or canals, lorries are not at risk to collide when driving towards each other at the allowed speed on a two-way highway. By contrast, when two ships meet in a confined waterway, they will almost inevitably collide and/or strike the bank if the encounter occurs at the allowed maximum speed under similar width conditions as two lorries on the road, because the flows and waves caused by the ships can hardly be controlled. Therefore, the ships have to reduce their speeds.

One reason for this is that during the encounter of the two ships two opposing wave and flow fields superimpose. At the beginning of the encounter, the ships run into each other's drawdown trough so that both of them will accelerate. On leaving the water level depression, their speeds decrease again. The superimposed flow fields, especially sailing close to the banks, will draw the ships towards each other.

If, for example, two fully laden (T = 2.8 m) large motor vessels pass each other in a German standard trapezoidal canal profile (water surface width of 55 m, water depth 4 m, drawdown at critical speed about 0.8 m), the maximum achievable ship speed of about 9.5 km/h when sailing alone falls to a critical speed of about 8 km/h during an encounter. Hence, if the selected ship speed at the beginning of the encounter manoeuvre is too high, the ship will reach the critical ship speed range during the manoeuvre. In this situation there is an acute risk that the ship touches the ground or the embankment even if the clearances to bed and bank appeared to be sufficient at first. On the other hand, by reducing the speed to just 6 km/h (still a safe speed for navigability) the water level drawdown is reduced to approximately 0.2 m, so that the influence of the drawdown on the encounter manoeuvre is minimal.

The mutual interaction of forces between ships or convoys that pass each other is caused by their associated flow fields which are characterised by the displacement current and the wave formation around the individual ships as explained, for example, in Chapters 4.1.1 and 4.2.1 in more detail. In relation to the moving vessels, the ship's own flow field is steady-state unless the speed or navigation channel cross sections change.

Where two motor vessels pass each other on a canal (usually port-to-port), it is sufficient to apply a bit of starboard rudder (initiating a right turn) at a distance of 3 - 5 ship lengths before the bow-bow-position in order to first move out of the centre of the channel. The bow waves of both ships and the current directed laterally away from the bow caused by displacement will result in a strong water "cushion" that helps prevent them from coming too close.

When the two ship bows are level, the waves and sideways cross currents force the bows apart, while the suction effect occurring just after the moment of the bow-bow-position draws them together. In this position, the suction effect tends to be stronger than the bow wave, so that both vessels are forced to move with their bows towards the suction side of the other ship, i.e. usually to port. Since the distance between the two ships may get rather small without any corrective steering, the course is supported by applying starboard rudder.

It should be noted that when both ships are in parallel position, their induced flow fields are opposed and will partly cancel each other out locally, causing also a local deformation of the superimposed drawdown troughs, so that in this parallel position both ships will show a tendency to repel each other along the entire broadside.

Half way through the encounter, the ships' sterns will be drawn together due to the mutual suction effect and the additional suction effect of both propellers (see Figure 4.1.6-2). Both ships thus move to port with their sterns and to starboard with their bows. If port rudder is applied (initiating a left turn), the two ships regain the centre of the canal. Immediately after the encounter, the stern waves force the sterns apart.

As a rule, laden ships moving in a canal or a navigation channel limited in width and/or depth should slow down before meeting another ship so as to reduce the forces caused by drawdown and return flow. They should also have rudder and/or manoeuvring power available during and immediately after the encounter to be able to steer their course. If necessary, a short-term increase of drive power is possible to increase rudder forces, in order to control the hydrodynamic effects on the ship. Furthermore, at reduced speed the transverse bow thruster can be used to better keep a steady course.

Encounters occur rather frequently or even regularly on our waterways. They are a great challenge for shipmasters, especially when fairways are restricted. To ensure the safety and ease of navigation, waterways usually comply with the specified standard dimensions which may be exceeded or undercut in the individual case. In addition to the conditions influencing navigation and ship dynamics, other factors to be observed are:

- Fleet structure
- Traffic volume
- Geography
- Wind and visibility, etc.

5.1.5 Overtaking

Overtaking is one of the most challenging manoeuvres in ship navigation. Both the ship overtaking and the ship that is being overtaken must adjust their speeds and courses in order to perform a successful overtaking manoeuvre. If an encounter requires an elevated level of attentiveness, overtaking requires even more consideration, attentiveness and nautical skills to avoid the ships touching each other.

For performing the manoeuvre, the overtaking vessel first of all needs enough excess speed, i.e. a sufficient speed difference (approx. 2.0 km/h up to 3.0 km/h) between the ships is required. Furthermore, the vessel speed with regard to the water depth and the navigation channel width should not be too high to avoid the critical ship speed range.

These boundary conditions require that the ship to be overtaken reduces its speed while maintaining manoeuvrability. Depending on the navigation area and the traffic situation, both ships may be forced to slow down, for example in canals, in order to avoid the critical ship speed range which is reduced due to the two ships' unfavourable blockage ratio, while the speed difference between the two must still be maintained.

Both ships are supposed to set the course such that there is a maximum possible distance between them. If the navigation channel is relatively wide (such as, for example, on the Rhine) the speed difference for overtaking may be smaller, if the ships are able to keep a larger lateral distance.

If an overtaking ship – usually moving on the port side of the vessel to be overtaken – comes up to the stern of the other ship with its bow, the bow of the overtaking ship and the stern of the ship that is being overtaken will attract each other, because the suction effects from the depressions caused by the ships and superimposed on each other, plus the additional drawdown from the propeller of the ship that is being overtaken, are stronger than, for example, the pressure created by the bow or stern waves of both ships (see Chapter 4.2.1 and explanations for Figure 4.2.1-2). It is therefore better if the courses of the ship being overtaken and the vessel overtaking are inclined to port (driving to the left) immediately before the overtaking manoeuvre. As a result of the hydromechanical forces acting on both ships, their courses will then approximate the initial one.

Once the two vessels have paralleled and are positioned next to each other, the drawdown increases due to parallel and increased return currents of both vessels (double blockage ratio in case of two identical vessels). Their superimposed drawdown troughs show the greatest depth between the two ships

Fig. 5.1.-3: Overtaking while moving upstream on the Danube [DST]

so that, for reasons of hydromechanics, the hulls are attracted to each other along their entire lengths.

In order to compensate for this motion, the ships must choose a course which makes their bows drift apart. The overtaking ship thus should steer to port, the ship that is being overtaken to starboard. If the rudder “dosing” is at its optimum, the motions caused by hydromechanics on the one hand and by rudder action on the other, cancel each other out and the overtaking ship passes the other vessel at almost constant distance in this phase of the manoeuvre.

Immediately before the two aft-ships are level, the overtaking vessel reduces its drive power in order to reduce the suction effect acting on the other ship and steers starboard to prevent its stern from drifting over to starboard side too far. For the same reason, the ship being overtaken steers to port. Having passed the other aft-ship, the overtaking ship can/must increase drive power again.

Once the stern of the overtaking ship is on the level with the other ship’s bow, the latter will be attracted to the overtaking ship. Therefore, the vessel being overtaken must apply starboard rudder (with the main rudder or/and port rudder in case of a passive bow rudder or bow thruster) as early as possible so as to turn its bow away from the overtaking vessel. By no means the overtaking ship must cut back into the course of the ship being overtaken too early since that would result in the other ship being pulled in its wake and may collide with its stern.

The probability of colliding is much higher during overtaking manoeuvres than during encounters. The essential reason for this is that the manoeuvre itself takes rather long. Hence, the forces resulting from the flow characteristics and the water level drawdown between the ships can act on both ships for a much longer time than in an encountering situation. Nevertheless, the potential damage in the event of a collision during an encounter is much higher than in the event of a collision while overtaking.

5.1.6 Stopping

In accordance with the applicable version of the Vessel Inspection Regulation (German "Schiffsuntersuchungsordnung"), vessels longer than 86 m must be able to stop within a defined distance in order to mitigate or avert dangerous situations. Thanks to, for example, the wide navigation channel of the Rhine, vessels shorter than 86 m are able to turn and avoid stopping. Facing downstream, ships longer than 86 m must, however, be able to stop in relation to the ground which means that ships must be able to run astern with a speed equal to the river’s flow velocity in order to stop in relation to the bank.

The downstream stopping manoeuvre on rivers can be described as a sequence of three phases. The first phase begins with the reversal of rotation of the propeller and ends when full reverse thrust is reached. First the engine revolutions are reduced until the propeller speed is zero (standstill). Some ships use propeller shaft brakes to accelerate this operation and reduce the required stopping distance. After that, the rotation direction is reversed, often by means of a gearbox, and the new propeller speed is adjusted. This process takes about 8 to 15 seconds. In older engine systems (slow running propulsion engines), this process may last longer than 60 seconds, because the engine speed has to be reduced first and the engine switched off. By means of a camshaft shift the engine has to be restarted rotating in the opposite direction before the propeller speed can be increased again.

The second phase ends with the standstill of the vessel in relation to the surrounding water body. The third phase ends with the ship stopping in relation to the ground. Correspondingly, the ship will be running backward through the water from the beginning of the third phase. Due to this third phase, which must be considered in the case of flowing waters, the downstream stopping distance in relation to ground is much longer than on still waters at the same ship speed over ground. When stopping on still waters, the third phase is not relevant because the vessel comes to a stop also in relation to the ground at the end of the second phase.

During these phases of the stopping manoeuvre, which may take several minutes depending on the vessel size or load, in fixed pitch propeller systems the main rudder is not effective in keeping the vessel on course, because the surrounding flow approaches the rudder in an uncontrolled way and no predictable directed transverse rudder force is generated. Thus the rudder will not produce a controllable steering effect as is the case under normal sailing conditions when running ahead, while the rotating propeller, nevertheless, produces significant transverse forces on the ship which need to be accounted for in the stopping manoeuvre.

With a drive system that features one propeller, when running straight ahead usually right-hand rotating propellers are used. Viewing the propeller from stern to bow, a right-hand rotating propeller is defined as a propeller turning in clockwise direction. The steering effect of a propeller when running straight ahead is not relevant because the transverse rudder forces are greater by far, so that an effect on the actual heading will not be noticed unless the rudder is in neutral position (geometrical zero position). When accelerating from standstill with neutral rudder position, ships with a clockwise rotating propeller head to port; in a steady drive they tend to head to starboard. With an anti-clockwise rotating propeller, the conditions reverse. Thus, in ships with a two-propeller drive, the steering effects cancel each other out, because one clockwise rotating and one anti-clockwise rotating propeller is used.

The propeller's direction of rotation determines the direction of the steering effect. Propeller transverse forces are generated by the different approaching directions and approaching velocities of the propeller. These depend on the geometry of the aft-ship, the eccentricity of the thrust centre and the different thrust deduction values on the port vs. the starboard side.

When going astern, there are also transverse forces produced by the rotating propeller that act on the vessel as mentioned earlier. These forces are even stronger than with a forward driving vessel, because the water jet formed by the propeller hits the aft body of the vessel from astern, while the jet is directed backwards away from the vessel's hull in a normal driving situation, i.e. when going ahead. A propeller rotating clockwise for going ahead turns anti-clockwise when the ship goes astern. This means that the water which is accelerated by the propeller hits the aft body pointed towards the port side. Correspondingly the aft-ship tends to move to port side and the ship heads to starboard. From the beginning of the stopping manoeuvre for which the propeller direction has been reversed, the propeller transverse forces dominate, because the rudder cannot produce any directional transverse forces until the ship is making sternway. In a ship with a two-propeller drive with counter-rotating propellers, the propeller transverse forces neutralise each other so that a course deviation is avoided.

Due to the reverse movement of the ship through the water the main rudder is not approached by a directional flow until the end of the third phase (when a flow velocity of approx. 5.0 km/h is reached), and then little but still generally insufficient rudder transverse forces can be used for keeping course.

A ship with a fixed pitch propeller begins the stopping manoeuvre by adjusting the propeller speed to "astern" and the rudder to amidships. The rudder in mid-ship position favours the flow to the propeller more than an angled position does, where part of the rudder area is blocked.

The ship (single-propeller drive) is deflected from the original course to starboard as a consequence of the steering effect of the propeller, or rather, the aft-ship turns to port side. This drift is corrected when the propeller direction of rotation is adjusted from "astern" to "ahead" and the rudder is turned hard to port. Once the ship is back on course, the stopping manoeuvre can be continued. Due to these course corrections stopping takes more time and the stopping distance becomes longer. To be able to keep a ship on course without these corrective actions, transverse thrusters are used.

Single sailing motor vessels (without pushing a barge) can use either a bow thruster or a stern thruster to compensate for the crosswise propeller forces during stopping. Most push boats have a bow thruster or a flanking rudder, which is located forward of the propellers, to be able to produce transverse forces to better keep a steady course going astern.

In ships with two fixed pitch propellers the counter-rotating direction of the propellers helps to keep a steady course. Faster stopping by stopping both drives and bringing the rudder to midship position is possible without major course deviations.

Ships with a variable pitch propeller do not need to reverse the shafts' rotation direction. The first phase of the stopping

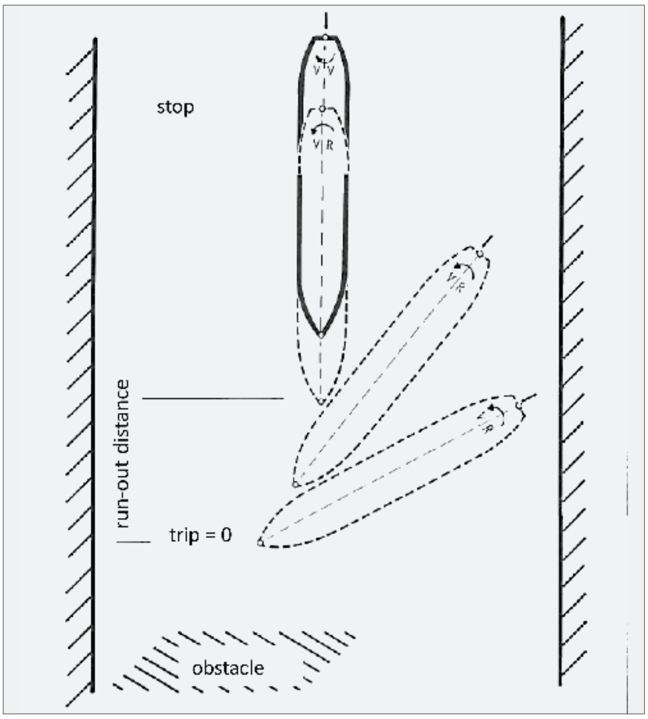


Fig. 5.1-4: Emergency stopping to avoid collision or other accident [v_r=rotating speed going astern; v_v = going ahead] [VBW]

manoeuvre takes less time and stopping distances are shorter. If manoeuvring with the main rudder system is restricted, transverse thrusters are additionally used for the stopping manoeuvre, just like in the case of vessels equipped with a fixed pitch propeller. In the case of a variable pitch propeller, the direction of rotation of the propeller is not reversed, so that in the case of a clockwise-rotating propeller the ship's course will veer off to port side from the beginning of the stopping manoeuvre. In the case of an emergency stopping manoeuvre, the ship's bow is required to turn to starboard so that variable pitch propeller systems (single propeller drives) are most likely to feature anti-clockwise rotating propellers.

Vessels driven and steered by a rudder propeller or a cycloidal propeller remain manoeuvrable also without transverse thrusters during a stopping manoeuvre. Owing to the fully controllable drives, the vessel can be kept on a steady course and stopping distances are shorter.

Stopping is one of the emergency manoeuvres used to avoid a collision (see Figure 5.1-4). The potential dangers of the manoeuvre have to be judged very thoroughly, particularly with regard to the question as to whether the available navigation channel width and length is sufficient for the required navigational space while the ship is temporarily not steerable. If this is the case, for example when a ship's propeller rotates clockwise when making headway (see Figure 5.1-4), the drift-off movement of the ship which is due to the non-compensation of the propeller's direction of rotation during stopping can be tolerated in the worst case. However, if there is insufficient width and an evasive action manoeuvre is not possible even with the full available manoeuvring capacity for averting an imminent collision, a stern anchor can be used when moving downstream which slows down the ship and thus prevents the stern from swinging out. The speed over ground must not be too high, however, to avoid excessive stress on the anchor chain.

5.1.7 Turning

According to the applicable version of the Vessel Inspection Regulation, vessels shorter than 86 m must be capable of turning. In order to perform a turning manoeuvre, the vessel is slowed down, sometimes up to a stop over ground.

This requires good judgment of the space needed for the manoeuvre, and river flow must be taken into account, too. The aft-ship needs sufficient room to swing out safely without striking the bank. In the case of ships with a fixed pitch propeller, turning is favoured by moving the aft-ship in the direction of rotation of the propeller (clockwise-rotation going ahead corresponds to evasion of the stern to the starboard side). There is no preferred turning direction for ships with two fixed pitch propellers since the two propellers are usually counter-rotating. This also applies to ships equipped with rudder propellers or cycloidal propellers.

A ship with two propellers has an advantage over a single-propeller ship in that it can apply an additional rudder torque with the help of the counter-rotating propellers, so that turning manoeuvres can even be carried out without rudder action. Such a manoeuvre is, however, rather slow.

If a turning manoeuvre is to be performed close to a bank, just a slight rudder angle is set and the ship will make the turn in a large circle while running ahead. The stern will only drift

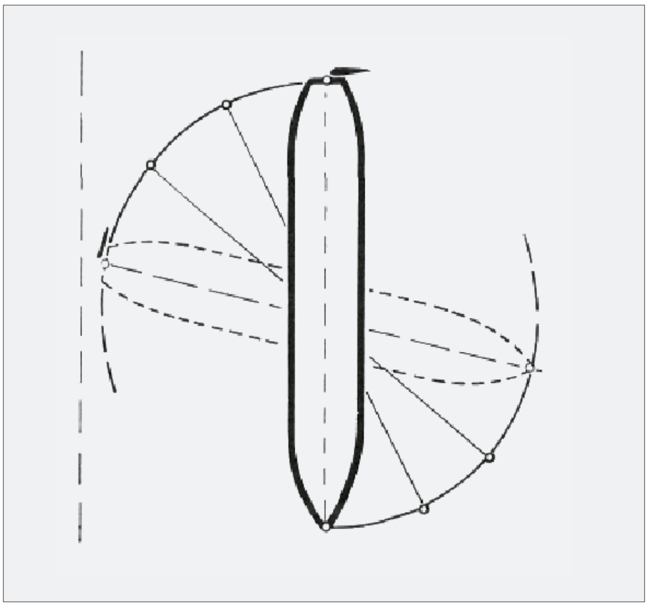


Fig. 5.1-5: Turning at rest with full rudder to port [VBW]

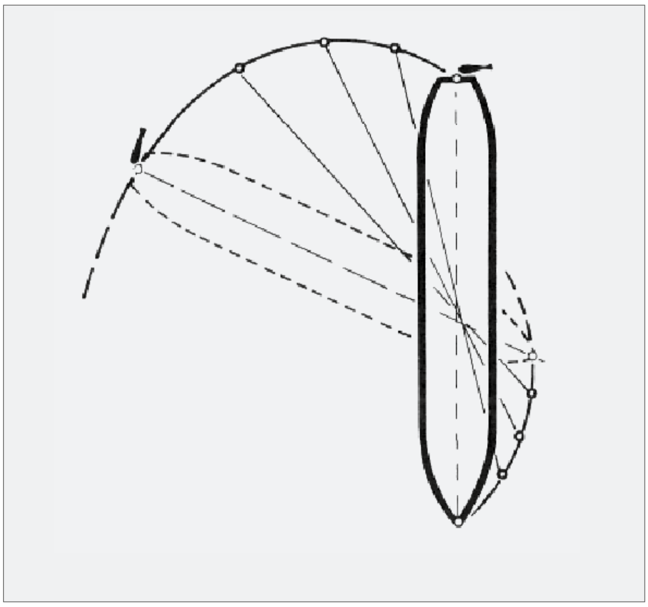


Fig. 5.1-6: Turning at rest with high-performance rudder to port (the propeller wash is deflected so strongly that it draws the stern rearwards) [VBW]

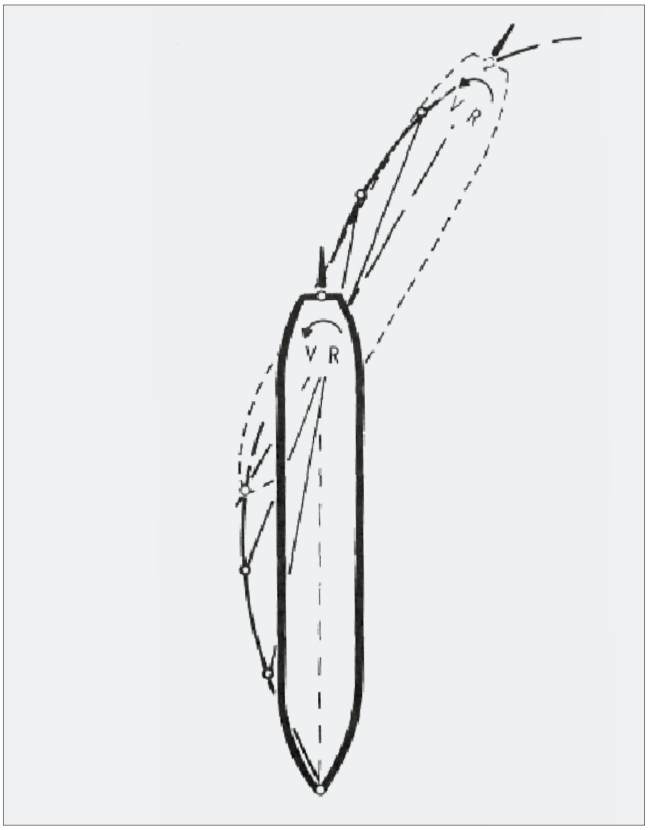


Fig. 5.1-7: Turning while going astern without rudder action (turn is initiated by the propeller swirl) [VBW]

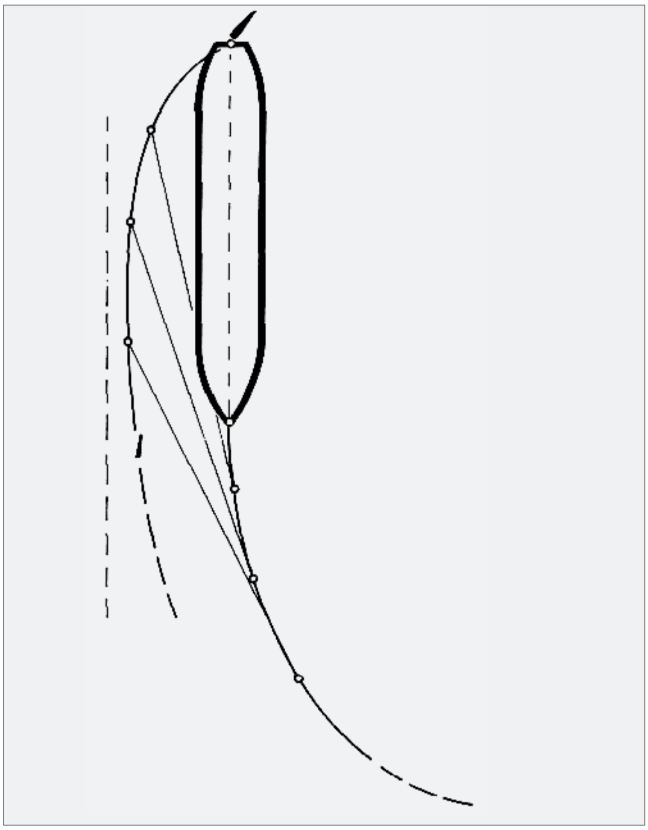


Fig. 5.1-8: Turning at rest with small rudder angle [VBW]

a little over the intended course before the manoeuvre. The smaller the rudder angle, the smaller is the drift of the stern and the larger is the turning circle. The distance to the bank may be small.

If the rudder is turned out full with the propeller rotating for running ahead, the vessel will turn in the narrowest turning circle (Fig. 5.1-5). The stern will swing out relatively far and if the rudder system is well-designed, the ship is able to turn in a very small circle, virtually turning on the spot. Before the manoeuvre, the distance to the bank must be large enough.

Some ships are capable of generating such a strong rudder action due to the type and design of the rudder system that although their engines are running in forward they turn backwards in a large circle when the rudder is put hard over (Fig. 5.1-2).

When going astern with the rudder amidships, depending on the type of vessel, the steering effect of the propeller without rudder action may initiate a turn, exclusively however, towards the side of the actual direction of rotation of the propeller going astern (clockwise to starboard – anticlockwise to port), see Fig. 5.1-7. The rudder angle has hardly any influence on the situation, but with the rudder amidships, the flow to the propeller is better and the ship is more inclined to turn over starboard.

5.1.8 Going astern

In ships with a fixed pitch propeller or a variable pitch propeller, the steering effect of the propeller predominates when the ship goes slowly astern. A clockwise rotating propeller (which rotates anti-clockwise when the ship is going astern) and an anti-clockwise rotating variable pitch propeller (which rotates also anti-clockwise when the ship is going astern) tend to push the stern of the ship to port, see Fig. 5.1-7. Going straight ahead tends to be impossible for vessels without additional rudders such as bow thrusters. What is important in addition is that the rudder fails to have significant effect when the ship is picking up speed, because there is no specific direction from which the flow approaches the rudder. When speed is picked up running astern, the rudder effect becomes stronger again depending on the velocity of the flow approaching

Fig. 5.1-9: Entry into a lock [DST)

the rudder. Today, modern inland navigation vessels tend to use transverse thrusters when going astern so as to facilitate course-keeping. If the vessel is equipped with a 4-channel bow thruster or a pump jet, it is possible to push and steer the vessel by means of these active rudders only. In this case the vessel is controllable as in a normal sailing situation while going astern.

Ships with two fixed pitch propellers or two variable pitch propellers are capable of steering a course by adjusting the propeller speeds or the propeller pitch. However, as a rule, transverse thrusters are used to better keep a steady course.

Push-tow units consisting of a pusher and one or several barges use flanking rudders or transverse thrusters when going astern. Some modern barges are equipped with passive bow thrusters which also contribute to keeping a steady course. Ships equipped with rudder propellers and cycloidal propellers are capable of keeping a steady course going astern without using a transverse thruster.

If there is cross-wind and under particular flow conditions, all vessel types use transverse thrusters to keep a steady course when going astern.

Fig. 5.1-10: Leaving a lock [DST]

Fig. 5.1-11: Navigating a vessel into a lock [DST]

5.1.9 Approaching and leaving a lock

The approach to a lock can amount to a critical handling situation, particularly if the navigation channel in the outer lock harbour is deeper than the water depth above the lock sill. For example, the deep-laden ship approaches the lock gate at safe speed, i.e. the minimum speed at which navigability is ensured without using the transverse thruster, using only the main rudder. This means the ship would be sailing through the lock-approach channel approaching the lock entrance at a speed of approx. 5.0 km/h up to 7.0 km/h, and it is generally not possible to adjust a lower speed if the ship uses the main thruster only. Disengaging the propulsion system with the aim of reducing the speed after a certain run-out time would result in the ship “drifting along”, a state which is prohibited according to shipping police rules, because the vessel is no longer manoeuvrable. This speed of 5.0 to 7.0 km/h may be too high if the cross section of the lock harbour changes considerably at the lock sill. As a consequence of a sudden change in the flow around the bow area, the bow might squat so deep that the bottom of the hull touches the ground at the lock sill. In the event that the approach and entry into the lock are expected to be critically difficult, ships approaching locks must reduce speed significantly. For this purpose, the thrust direction of the bow thruster can be set to “ahead” at an early stage to reduce the speed and simultaneously maintain manoeuvrability by means of the main rudder system. Apart from that it is possible to bring the vessel to a complete stop in the lock-approach area to then re-accelerate carefully so as to ensure sufficient rudder effect while keeping the speed of approach low.

Even if the depth between the top of the lock sill and the water surface is sufficient so that it is not to be expected that the ship will touch ground, a relatively high speed on entering the lock causes considerable water level fluctuations inside the lock, see also Chapter 4.1.10 for more details. They will stop or even push backwards the ship before it can accelerate ahead again. For a single vessel entering an empty lock this is a situation that can be mastered by the shipmaster, but if the vessel approaches the closed lock gate and is accelerated again by the water level fluctuations, it is faced with the danger of a collision with the lock gate. This is the reason why closed lock gates feature impact protection devices. If there are several vessels in the lock they may be moved around due to the water level fluctuations, their mooring ropes may break and they may collide with each other or with the lock structure.

On leaving the lock, vessels should accelerate at low propulsion power. Moving off at high power causes water level fluctuations which accelerate the ship even more. If the vessel is alone in the lock, the impact is limited and controllable. However, if several ships are in the lock, they, too, are accelerated due to the water level fluctuations, after their mooring ropes have broken. Even if their propulsion systems are off, their speed may be higher than that of the vessel that caused the water level fluctuations. The vessels collide with each other.

The restricted width of the lock structure requires precise navigation and a timely response to any influences that could make the ship deviate from its course. Thanks to low ship speeds in the lock chamber, modern ships which are, for example, equipped with bow or even stern thrusters, can master the situation without using the fender beams. When locks are extremely narrow, fender beams can be used to adjust the ship's positioning and keep it off the bank.

The proportions of a ship in relation to a lock can be compared to those of a car that is to be parked in a very narrow garage. The car's width would be 1.70 m, the driveway to the garage would be 1.78 m wide, and the garage 30 m long. These numbers illustrate the restricted width of a lock chamber. Just like when parking a car in a garage, shipmasters try to perform the manoeuvre without touching the lock structure or its gates or installations.

5.2 Navigation by telematics

In the past landmarks along waterways (churches, towers, groups of trees, building types), the natural course of the river with its varying water depths and flows, fairway markings such as buoys or beacons, warnings or notices etc. were used to be the most important navigation and orientation aids for shipmasters to steer a steady course. The advent of radar technology in the 1950s allowed ships to continue moving ahead despite fog, snow or generally restricted visibility. However, navigating by radar only, without being able to see at all, was not possible unless the shipmaster was an experienced navigator and, in addition, had excellent knowledge of the route, so that he/she was able to interpret the radar image and make prudent decisions in steering the course. Since the fairway in the river was not directly visible on the radar image, shipmasters had to find it from experience and local knowledge, and with the aid of visible waterway markings.

In the early 90s, electronic river charts were introduced as navigation aids for inland navigation vessels. The positioning of a ship was indicated on a display screen with an electronic nautical chart making use of a positioning system (GPS, global positioning system). Over the course of time, the accuracy of the charts and the precision of positioning systems were further developed and refined. However, the electronic chart, which now also indicated the course of the fairway, only showed the position of one's own ship other vessels were not shown. The actual traffic situation could only be judged based on the interpretation of radar images.

Today, positioning, electronic charts and radar signals are overlaid so that the nautical traffic situation is shown on a display screen. Furthermore, additional nautical information can be shown, such as specific ship parameters that are identified with the help of Inland AIS (Automatic Identification System) based on the other ships' radar echoes, and which can be accounted for in ship handling.

To make sure that everybody uses nautical information aids in the same way, the systems have been standardized and requirements regarding their use have been specified, for example by the CCNR (Central Commission for the Navigation of the Rhine) using RIS (River Information Services), and they are approved by the shipping police.

The increasing use of information technology in ship handling takes some of the burden of route knowledge off the shipmaster, since the position of the ship can be seen on the electronic river chart and can be communicated via radio. The use of IT measurably improves traffic safety, particularly when visibility is restricted, and provides reliable aids to shipmasters when navigating river stretches they are less familiar with. However, it can be observed in practice that even when visibility is good shipmasters tend to sail exclusively within the fairway where the water depth is guaranteed by the authorities, even if, for example, sufficient water levels enable the use of a broader width of the navigation channel particularly to allow for overtaking and encounter manoeuvres.

6 Developments and outlook

Thanks to the growing scientific knowledge particularly in the fields of nautical science and ship dynamics the navigability of existing waterway cross sections for larger ships can be verified in much more detail. The development of simulators for inland waterways, for example at the BAW and the DST or the vocational college (in German: "Binnenschifferberufs-kolleg") in Duisburg, has been a success. These simulators are now increasingly used to verify channel cross sections which were originally designed for smaller vessels in order to enable an even more targeted analysis and approval of the use of certain ship types on specific waterways. An extended management of waterways and ship operation seems to be possible in the future, in addition to an increased use of telematic equipment on ships and the associated land-based infrastructure.

The volume of goods traffic in Europe is continuously rising as is the need to ensure that goods are transported in the most cost-efficient and economic manner, meeting increasingly demanding ecological requirements. It is imperative, therefore, to maintain the waterway infrastructure for the existing traffic relations and to extend waterways which were less frequented in the past in order to meet future demand and enable their use for water-borne transport - even if only ship units adapted to local conditions are used in the initial phase. This is why it is important to use existing resources efficiently to ensure that the future transport demand is met and the prospects for the transport industry are in line with transport market growth.

The ship-waterway system is also influenced by rising fuel and operating costs. There is an increasing focus on investments in the energy-optimization of engines, efficiency increases for rudder and steering devices and new bow and stern geometries designed for optimum flow and operation conditions. Apart from these design-related investments in the ship and its equipment, there is a growing potential for optimizing the actual ship operation and handling of the ship in motion. The sailing vessel has to adapt to the flow as well as to the conditions in locks and ports. This leads to different optimal ship

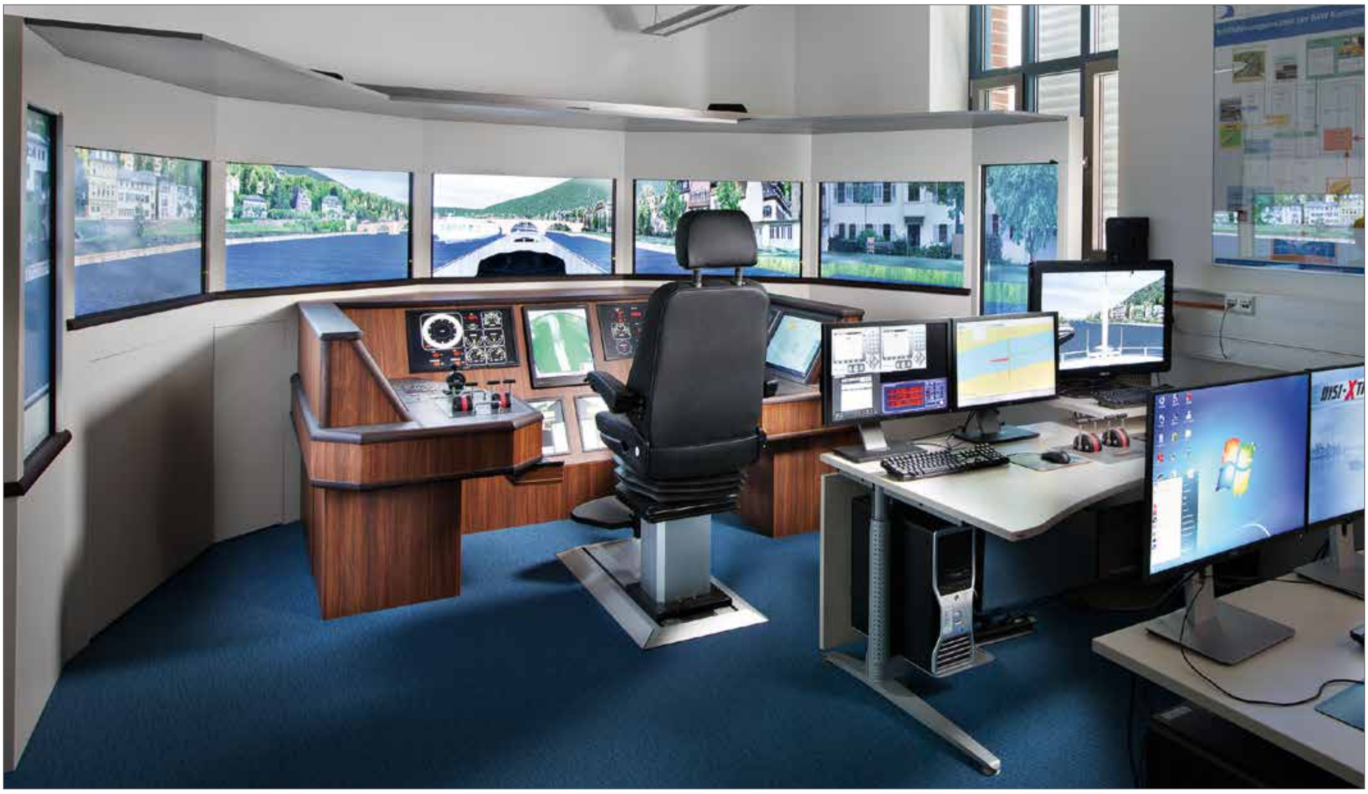


Fig. 6.-1: Ship handling simulator for inland vessels [BAW]

speeds and manoeuvres (for example in situations such as overtaking, sailing at low speed), which, in turn, may result in previously unknown interactions affecting ship dynamics.

Overall, these trends mean that innovations and new developments in the ship-waterway system are still possible. The increasingly deep insights into the ship dynamics in inland navigation are always updated and will offer a considerable potential for development and decision-making to waterway users on the one hand and operators and planners on the other.

The pressure to make better use of waterways and to sail them in more strategic ways is likely to increase due to rising fuel prices and the impact of climate change – especially in view of lengthened or more severe low water periods or longer periods in which HSW is exceeded. It is likely, therefore, that powerful navigation systems will be available in the future. Depending on the type of ship, its cargo and the arrival time window at the terminal port, the shipmaster will get advice on which course makes sense in a particular place to make optimal use of depth or flow conditions and which ship speed is recommended for the respective place, particularly with the aim of saving fuel.

Such advanced "driver" assistance systems could also assume steering functions in the future. Available track guidance systems have proven their capability in shallow water navigation, for example on the River Rhine, and are now gradually extended to incorporate traffic recognition functions and evasion manoeuvre functions. AIS data which are soon to be extensively available will be helpful in this respect.

However, this – just as a generally optimal ship control – will not be possible unless sufficiently precise and regularly updated information is available, especially about depth and flow conditions in the navigation channel. Such information should be retrievable from the ECDIS charts, for example.

The ship-waterway system will continue this development in the next ten to twenty years. From a current perspective, the Western European fleet of ships is likely to continue to grow by about 1 to 1.5% per year (its long-term average growth rate) regarding cargo volume. Although the transport market is presently characterized by a high share of bulk goods and a still growing number of container transports, there is also a growing trend again towards smaller lots and hence also smaller ship sizes. It remains to be seen whether this will be an economically sustainable alternative leading to a tendency to use smaller ships again.

At present, the trend towards bigger ships seems to be unbroken. Thus it is evident that the current dimensions of waterways – particularly impounded rivers and canals – do not grow as fast as the vessels of more recent design which are nowadays available. Thus, while the majority of the modern large motor vessels are designed with maximum load draughts ranging from 3.20 to 3.60 m, the highly frequented impounded rivers and canals can only accommodate load draughts between 2.7 and 3.0 m. Experts currently verify whether the enlargement of fairway widths and depths on existing waterways with a high traffic frequency (for example the Wesel-Datteln Canal) would be viable from the point of view of the economy, and whether a lasting generation of extended waterways can be established. Meanwhile, a growing number of transports take place on smaller and less developed waterways using inland navigation vessels of a size greater than that for which the waterways were originally designed. The usability standards differ - and will continue to do so - across the German network of navigable waterways. If the overall system is to be well interlinked and economically feasible, the priority axes for waterborne transport must be extended based on standardized channel cross sections.

Waterborne transport will be highly relevant for the ecology still in the future. Road and rail transport is often near the limits of their capacity because of the unbroken growth of the European transport market. Especially in urban agglomerations the ecological and economic advantages of inland navigation vessels become evident.

The aspects discussed in this brochure show that not only the boundary conditions for inland navigation but also the ship's behaviour in conjunction with its propulsion and steering devices are subject to continuous development. This paper provides an insight into current knowledge about ship dynamics in inland navigation and their interdependencies with the infrastructure of waterways. It is advisable to ensure that the interdependencies are updated on a regular basis.

7 Glossary

Achievable ship speed
The speed a vessel sailing at medium load draughts can technically achieve with the chosen or installed engine power under prevailing depth and cross sectional conditions and while avoiding the critical ship speed range.

Bow wave
The flow approaching the vessel will build up directly in front of the bow (stagnation point), causing e.g. secondary waves on both sides of the vessel.

Canal
An artificial waterway which was built for shipping and water supply purposes and whose water level is controlled by weirs, descent structures (locks, ship lifts) and pumping stations.

Critical ship speed
It defines a sailing situation in which the transition from subcritical to supercritical flow begins. A breaking stern wave is a sign of this transition. As a rule, it is impossible for cargo vessels to exceed the critical ship speed so that in fact the critical ship speed is the upper limit of the ship speeds that can be achieved by large displacement vessels. In practice, vessels do normally not sail faster than approximately 90% of this value because if this speed is exceeded, the power demand increases sharply.

Cross section ratio
The ratio n of the cross sectional area A_K of a waterway at a particular water level (which affects the return flow) to the cross-sectional area A_S of the submerged part of a vessel ($n = A_K/A_S$). Internationally the reciprocal of n is generally used to characterize the amount of cross section occupied by the vessel. It is referred to as blockage ratio.

Cross section relevant for the return flow
This refers to the part of the discharge cross section in which the return flow field induced by the ship appears. It is also called “cross section affecting ship dynamics” or “effective cross section”, and it determines, together with the submerged ship cross section area, the critical ship speed.

Deadweight ton (DWT)
Maximum possible cargo load for the ship in tons (1000 kg)

Discharge
The volume of discharge per time unit, e.g. m^3/s

Discharge cross section
Cross sectional area perpendicular to the main direction of flow.

Downstream water
Reach of water immediately downstream of a barrage.

Draught (also load draught)
The distance between the deepest point of a vessel at rest (relative to the water) and the plane of the water surface.

Drawdown
The water level drawdown in the vicinity of a vessel which is caused by the ship-induced displacement flow and return currents. The flows around sailing vessels result in a lowering of the water surface.

Driving dynamics of inland vessels
Discipline concerned with the movements of the ship in the navigation channel and the impact of such movements e.g. on the channel bed and banks.

Dynamic draught (draught while sailing)
Draught (ship at rest) plus squat (ship in motion).

Dynamic underkeel clearance
Refers to the net distance between the bottom of the ship hull in motion and the bed of the waterway. It is formally calculated as the difference between water depth at the ship and the dynamic draught (load draught plus squat).

Equivalent low water level (GlW)
Low water level used to define the fairway depth. It has a specified probability of occurrence based on long-term water level observations.

Equivalent low water level for the Danube
The low water level fixed for the Danube; on 89% of the ice-free days in a year the water level is either equal to or below this fixed water level. RNW is applicable to the reach of the River Danube between Regensburg and the state border.

Fairway
The part of the navigation channel used for ship traffic, which has specified widths and depths and whose maintenance is envisaged.

Fairway depth
The fairway depth is defined as the depth to be maintained with reference to a specific water level (for example, GIW on the Rhine and Elbe or RNW on the Danube) by measures which are both possible and reasonable.

Fender
Elastic object that is used for protecting a ship against the impact of a collision with a structure or another ship.

GMS
Large (self propelled) motor vessel (CEMT – class Va)

Groyne (spur dike)
A transverse structure used for river training (water level increase and/or degradation of the river bed for a greater fairway depth).

Highest Navigable Water Level (HSW)
Upper critical water level up to which shipping is permitted on the waterway.

Load draught
The draught of a vessel according to its load.

Lock sill
Sill on the lock gate serving as a stop for the closed lock gate.

Longitudinal groynes (longitudinal dikes)
Longitudinal structures in a river installed to elevate the water level, guide the flow and bring about a deepening of the fairway.

Manoeuvring situation
Navigation at a low ship speed for the purposes of manoeuvring. The advance ratio of the propeller is close to zero, helping to gain maximum thrust of the main propeller and the active bow rudder (e.g. for starting, stopping, turning).

Mean water level (MW)
The arithmetic mean of water levels measured over a long period of time (generally at least one year).

Mean load draught
The average load draughts as they are observed in practice. Especially in long routes they are smaller than the geometrically possible (potential) load draughts, and sometimes even smaller than the standard load draughts, due to the uncertainty of the water level forecast.

Mean low water level (MNW)
The mean low water level derived from observations made over a sufficiently long period of time.

Minimum dynamic underkeel clearance
The proverbial "few inches of water under the keel". It factors in uncertainties in accounting for the squat or water surface heights, for example, which may be subject to temporary changes due to, amongst other things, positive or negative surges from lock operation or backwater due to wind effects. The minimum dynamic underkeel clearance thus is a safety reserve to compensate for uncertainties that cannot be avoided. In reaches with a rocky bed a higher value should be chosen than in reaches with a gravel or sand bed, due to the risk of grounding and potential damage.

Navigation channel
That part of the waterway which is normally used for ship traffic according to local conditions. In most cases the navigation channel is larger than the fairway.

Negative surge
A temporal lowering of the water level induced by a ship or a structure and progressing roughly at the rate of the wave celerity, e.g. negative surge due to lock operation or water withdrawal.

Planning speed
The speed at which a vessel (recreational craft) begins to slide and ride up on its own bow wave.

Port side
The left-hand side of a ship, when looking from stern to bow.

Port side rudder
Rudder angle, forcing the ship to turn to the port side in a normal headway operation (left turn when looking in sailing direction). More generally: when the trailing edge of the main (stern) rudder points to the port side or the trailing edge of a passive bow rudder points to starboard as well as when the working direction of a bow thruster points to starbord (exiting jet in starboard direction).

Positive surge
A temporal elevation of the water level progressing roughly at the rate of the wave celerity, which is induced by a ship or a structure, e.g. surge due to backwater, lock operation, flooding.

Potential load draught
The load draught that would be technically achievable in the context of the water depth conditions, mandatory minimum ship speeds and squat, if the shipmaster knew exactly the depth conditions prevailing in the fairway, i.e. for example, if the water level in a particular reach which determines the load draught does not change over time and can thus be assessed in a reliable way. The knowledge of the potential load draughts in all reaches along a route is the basis of the standard load draught.

Primary wave (primary wave system)
A result of the interactions between the moving ship and the waterway, which in turn are induced by the ship-induced flow around the ship's hull due to displacement. The lowering of the water level on either side of the ship and the backwater at the stern and the bow are part of the displacement flow. The primary wave travels forward with the ship and declines as it moves away from the ship's hull.

Pushed convoy (see also Push-tow unit)
Consists of a motor vessel plus barge(s) (lighter(s)).

Push-tow unit (see also pushed convoy)
Consists of of a motor vessel or a push boat plus barge(s) (lighter(s)).

Return flow
The water that flows in the opposite direction to the ship. The return flow is caused by the ship's displacement effect (pistion effect) and the drawdown.

Running (or rolling) wave
Transversal stern waves travelling along a bank and breaking at a certain moment; they are particularly high when a vessel approaches its critical speed.

Secondary waves
Ship-induced waves of short length caused by sudden pressure increases in the bow and stern areas and which lead to the well-known wedge-shape of the waves forming around sailing ships. Secondary waves define the hull speed of a planing vessel.

Shallow water
A navigation channel with limited water depth, but without navigationally relevant lateral borders (banks are farther away from the vessel axis than about one ship length). In contrast to deep water, shallow water influences the ship-induced wave field. Laterally moving waves can decrease unhindered (e.g. in wide, free-flowing rivers).

Sill depth
Distance between the lock sill and the water surface. It limits the usable depth while entering or leaving a lock chamber.

Slope supply flow
The depression caused by drawdown is refilled from astern by a running wave at a sloping bank.

Squat
The sinking effect of the vessel in motion, generally measured at the least favourable point of the vessel.

Standard load draught

Shipmasters as a rule have sufficient experience to know which load draught is permitted or geometrically possible in a particular reach of a waterway at a specific gauge height (see also potential load draught) in this reach. The difference between this possible draught and the gauge height is a well-known constant for each gauge. At each relevant gauge alongside the planned route, the shipmaster determines the corresponding load draught allowed (taking account of the possibility of changes in the water level) and uses the lowest value of all the gauges to obtain the standard load draught.

Starboard

The right-hand side of a ship, when looking from stern to the bow.

Starboard rudder

Rudder angle or generally rudder action (including bow thruster usage, forcing the ship to turn to the starbord side in a normal headway operation (right turn when looking in sailing direction). More generally: when the trailing edge of the main (stern) rudder points to the starbord side or the trailing edge of a passive bow rudder points to port as well when as the working direction of a bow thruster points to port (exiting jet in port direction).

Stern waves (transverse)

Type of wave occurring at the stern of a ship and caused by the primary and the secondary wave systems, the wave crest being perpendicular to the ship's direction of travel. Transverse stern waves caused by primary and secondary wave systems may be superimposed on each other.

Stretch (route)

The reach between the ports of departure and the terminal ports usually navigated by a ship.

Trim

Inclination of the longitudinal axis of a vessel in relation to the horizontal.

Underkeel clearance

The distance between the deepest point of a vessel at rest and the bed of the waterway.

Upstream water

Reach of water immediately upstream of a barrage.

Wake

Flow in the keel water behind the stern of the sailing vessel.

Water depth

Vertical distance between a point on the water surface and the channel bed.

8 References

BAW (2005): Untersuchungen zu den Ein- und Ausfahrbedingungen in das Schiffshebewerk Lüneburg – Naturuntersuchungen und Prognoserechnungen. BAW-Gutachten Nr. 3.04.10044.01, Karlsruhe, September 2005.

Kuhn; Rudolf (1985): Binnenverkehrswasserbau. Berlin, Verlag Ernst & Sohn, 1985.

Römisch (1993): Der ‚Squat' im begrenzten Fahrwasser – Betrachtung aus hydrodynamischer Sicht. Ship & Offshore, 45. Jg., Ausgabe 10, 1993.

VBD (1993): Einfluss der Bugformen von Binnenfahrzeugen auf das Einfahrverhalten in Schleusen. Versuchsanstalt für Binnenschiffbau e.V., Duisburg, Bericht Nr. 1338, Februar 1993.

Broß, H. (1994): Einfluss der Bugformen von Binnenfahrzeugen auf das Einfahrverhalten in Schleusen. Binnenschifffahrt – ZfB, Heft 13, Juli 1994.

Partenscky, H.-W. (1986): Binnenverkehrswasserbau – Schleusenanlagen. Springer-Verlag, Berlin, 1986.

Neuner, H. (1999): Untersuchungen zu den horizontalen Sicherheitsabständen in einem mit Buhnen geregelten Flussabschnitt. Dissertation, Universität München, 1999.

Felkel K. (1975): Modellversuche mit Buhnen in einer Rinne mit fester Sohle. Wasserwirtschaft, 1975.

Söhngen, B.; Wiitte, H.-H. (1999): Flussbau und Fahrwasserbedingungen am Beispiel des Donauausbaus Straubing-Vilshofen. Tagungsband: HTG Kongress, Magdeburg, September 1999.

Söhngen, B. (1999): Fahrdynamische Modelluntersuchungen. BAWMitteilungen Nr. 80, 1999.

GBB (2004): Grundlagen zur Bemessung von Böschungs- und Sohlensicherung an Binnenwasserstraßen. BAWMitteilungen Nr. 87, 2004.

English Version: Principles for the Design of Bank and Bottom Protection for Inland Waterways. BAW Newsletter No. 88, 2005.

Söhngen, B.; Kayser, J. (2005): Neue Bemessungsgrundlagen für erforderliche Steingrößen und Deckwerkdicken zum Schutz vor Wellen- und Strömungsbelastungen von Binnenschiffen. Tagungsband: HTG Kongress, Bremen, September 2005.

Söhngen, B.; Spitzer, D.; Stuntz, N. (2006): Field investigations and numerical calculations concerning modern vessels entering and exiting the Lüneburg ship lift. Conference Proceedings: 31st Internationalen Navigation Congress, Estoril, Portugal, May 2006.

Söhngen, B.; Dettmann, T.; Neuner, H. (2007): Modelluntersuchungen zur Ermittlung der erforderlichen horizontalen Sicherheitsabstände von Binnenschiffen zu Uferböschungen. BAWMitteilungen Nr. 90, 2007.

Söhngen, B. et al. (2008): Considerations to reduce the environmental impact of vessels. Publication: PIANC Report no. 99, 2008 (co-author).

Aberle, J.; Söhngen, B. (2008): Analysis of propeller jet induced scours. Conference Proceedings: International Conference on Fluvial Hydraulics, "River Flow 2008", Izmir, Turkey, September 2008.

Söhngen, B.; Kayser, J. (2010): Design of bank and bottom protection – new design principles for the necessary riprap stone sizes and revetment thicknesses for protection against wave and current attack caused by inland vessels. Publication: PIANC Magazine „On Course", No. 140, August 2010.

Söhngen, B.; Pohl, M.; Gesing, C. (2010): Bemessung von losen Schüttsteinen gegen schiffsinduzierte Strömungen und Wellen. Tagungsband: Dresdner Wasserbaukolloquium, Dresden, März 2010.

Söhngen, B.; Wassermann, S.; Schmidt, A. (2011): Untersuchung einer Fahrrinne in der Fahrrinne für Teilstrecken des Mittelrhein als eine der möglichen Anpassungsmaßnahmen auf den Klimawandel. Tagungsband: Duisburger Kolloquium für Schiffstechnik/Meerestechnik, Institut für Schiffstechnologie und Transport Systeme, Universität Duisburg, Mai 2010 (veröffentlicht 2011).

Söhngen, B.; Qaqunda, R. (2011): Untersuchungen zur Befahrbarkeit des Neckar mit 135 m langen Schiffen in der Streckenfahrt. Wasserwirtschaft, Heft 6/2011.

Söhngen, B.; Maedel, N.; Hahne, L.; Verdugo, I.; Iribarren, J. (2011): Smart Rivers Conference, New Orleans, Louisiana, USA, September 2011. (Paper held by Wurms, S. on behalf of the authors.) Publication: Homepage of the Smart Rivers 2011 Conference (http://smart11.pianc.us/ag_techprog.cfm) and PIANC Magazine „On Course", January 2012.

Spitzer D.; Söhngen, B.; Aberle J.; Geisenhainer P. (2012): Belastung der Gewässersohle durch Propellerstrahlen – Teil 1: Untersuchungen bis zum 2. Weltkrieg. KW – Korrespondenz Wasserwirtschaft, 4/2012.

Spitzer D.; Söhngen, B.; Aberle J.; Geisenhainer P. (2012): Belastung der Gewässersohle durch Propellerstrahlen – Teil 2: Untersuchungen nach dem 2. Weltkrieg. KW – Korrespondenz Wasserwirtschaft, 6/2012.

Doychev, S.; Söhngen, B. (2013): Impact of ship size on induced waves and currents in confined waters. Conference Proceedings: 3rd International Conference on ship manoeuvring in shallow and confined waters, Royal Institute of Naval Architects, Flanders Hydraulic Research and Ghent University, September 2013.

Maynord, S. T. (1990): Velocities Induced by Commercial Navigation. US Army, Corps of Engineers, Waterways Experiment Station, Technical Report HL-90-15, September 1990.

Maynord, S. T. (2000): Physical Forces near Commercial Tows, Upper Mississippi River Illinois Waterway System. Navigation Study, US Army Corps of Engineers, ENV-Report 19, Vicksburg MS, März 2000.

Maynord, S. T. (2005): Wave height from Planing and Semiplaning Boats. US Army Corps of Engineers, River Research, Appl. 21:1-17, Wiley InterScience, 2005, www.interscience.wiley.com.

Schokking, L. A.; Janssen, P. C.; Verhagen, H. J. (2003): Bowthruster-induced damage. PIANC Bull. No. 114, October 2003.

DST (2006): Model tests to determine ship-induced loads on banks. Report 1794, DST – Development Centre for Ship Technology and Transport Systems, November 2006.

Hofman, M.; Kozarski, V. (1999): Shallow water resistance charts for preliminary vessel design. Int. Shipbuild. Progr., 47, No. 449, 1999.

RILI (2010): Deutsche Richtlinien zu Regelquerschnitten in Binnenwasserstraßen. Bundesministerium für Verkehr, Bau und Stadtentwicklung (erschienen 2011).

Richtlijnen Vaarwegen (20119. Rijkswaterstaat, The Netherlands, 2011.

Oumeraci, H. (1988): Funktionelle Hafenplanung unter Berücksichtigung der Schiffsbewegungen infolge Wellenunruhe im Hafen. Mitteilungen des Franzius-Instituts, Universität Hannover, Heft 66, 1988.

Haffke, K. (1983): Zur hydrodynamischen Belastung vertäuter Schiffe durch vorbeifahrende Schiffe. Dissertation, Technische Universität Braunschweig, 1983.

Kooman, C. (1973): Navigation locks for push tows. Rijkswaterstaat Communications, No. 16, The Hague, 1973.

Jambor, F. (1960): Lage und Gestaltung der Schleusen und ihrer Zufahrten. BAWMitteilungen Nr. 15, 1960.

BAW (1960): Querströmungen im unteren Schleusenvorhafen bei Schleusenentleerungen von Doppelschleusen im Neckar. Bericht, Bundesanstalt für Wasserbau, Karlsruhe, Januar 1960.

Rauwoens, S.; Spiessens, K. (2008): Gedrag van een schip in een sluis. MSc Thesis, Universiteit Gent, Faculteit Ingenieurswetenschappen, 2008.

Spitzer, D.; Stuntz, N. (2005): Naturuntersuchungen zur Einfahrt von GMS in das SHW Lüneburg und Modellierung von Schiffsbewegungen und schiffserzeugten Wellen. Tagungsband BAW Kolloquium „Schiffsinduzierte Belastungen und mögliche Verkehre im beschränkten Fahrwasser", Juni 2005.

9 List of abbreviations

BAW	Bundesanstalt für Wasserbau (Federal Waterways Engineering and Research Institute)
BB	Backbord (port)
BfS	Official notices to skippers
BMVBS / BMVI	Bundesministerium für Verkehr, Bau und Stadtentwicklung / Bundesministeriums für Verkehr und digitale Infrastruktur (Federal Ministry of Transport, Building and Urban Development / Federal Ministry of Transport and Digital Infrastructure)
DEK	Dortmund-Ems-Kanal (Dortmund-Ems Canal)
DST	Entwicklungszentrum für Schiffstechnik und Transportsysteme e. V. Duisburg, former VBD (Development Centre for Ship Technology and Transport Systems)
E	Einzelfahrer (self-propelled vessel)
ECDIS	Electronic Chart Display and Information System
ENC	Electronic Navigation Chart
ES	Europaschiff (Europe Ship)
ESK	Elbe-Seitenkanal (Elbe Lateral Canal)
GlW	Gleichwertiger Wasserstand (equivalent low water level)
GMS	Großmotorgüterschiff (large motor vessel)
HOW	Havel-Oder-Wasserstraße (Havel-Oder Waterway)
HSW	Höchster schiffbarer Wasserstand (highest navigable water level)
HTG	Hafentechnische Gesellschaft e.V. (German Port Technology Association)
HW I	Hochwassermarke I (flood level mark I)
HW II	Hochwassermarke II (flood level mark II)
KK	Küstenkanal (Coastal Canal)
MDK	Main-Donau-Kanal (Main-Danube Canal)
MLK	Mittellandkanal (Midland Canal)
MW	Mittelwasser (mean water level)
NfB	Nachrichten für die Binnenschifffahrt (official news relating to inland navigation)
NIF	Nautischer Informationsfunk (Nautical radio information service)
NW	Niedrigwasser (low water level)
RHK	Rhein-Herne-Kanal (Rhine-Herne Canal)
RORO	Roll-on / Roll-off
SKS	Stichkanal Salzgitter (Salzgitter Branch Canal)
SL	Schubleichter (pushed barge/lighter)
StB	Steuerbord (starboard)
STG	Schiffbautechnische Gesellschaft e.V. (The German Society for Maritime Technology)
TEU	Twenty Foot Equivalent Unit (container size)
üGMS	Extra-long large motor vessel with a permitted beam exceeding 11.45 m and/or length exceeding 110 m
UHW	Untere-Havel-Wasserstraße (Lower Havel Waterway)
VBW	Verein für europäische Binnenschifffahrt und Wasserstraßen e. V. (Association for European Inland Navigation and Waterways)
WDK	Wesel-Datteln-Kanal (Wesel-Datteln Canal)

10 Nomenclature

Designation	Unit	Explanation
a_b	m	Groyne spacing
A_K	m²	Cross section of the water body
A_S	m²	Midship cross section
b	m	Water surface width
b_q	m	Width of the cross flow field
B	m	Beam
c	m/s	Wave celerity
C_B	–	Block coefficient
g	m/s²	Gravitational constant
h	m	Water depth
H_{Bug}	m	Bow wave height
H_{Heck}	m	Stern wave height
H_{Sec}	m	Secondary wave height
k_{sk}	m	Roughness height of the channel
KF	m	Underkeel clearance
l_b	m	Groyne length
L	m	Ship length
M	N·m	Torque
$n_{äqui}$	–	n-ratio, based on equivalent canal profile
n	–	Coverage ratio (A_K/A_S)
P_D	kW	Propulsion power, drive power (shaft power)
Q	N	Transverse force
R	m	Curve radius
T	m	Draught
TT	t	Deadweight tons
u	m	Distance from the bank
u_{max}	m/s	Maximum slope supply flow velocity
v_{an}	m/s	Approach speed
v_{krit} or v_{crit}	m/s	Critical ship speed
v_q	m/s	Cross flow velocity
v_{rueck} or v_{return}	m/s	Return flow velocity
v	m/s	Ship speed relative to water (through water)
v_{ag}	m/s	Ship speed above ground
v_{Str} or v_{flow}	m/s	Flow velocity
WSP	m	Water surface, water level

Driving Dynamics of Inland Vessels

Vessel Behaviour on European Inland Waterways and Waterway Infrastructure with special respect to German Waterways

- *Inland Navigation Vessels and Navigation*
- *Infrastructure*
- *Ships in Motion*
- *Manoeuvring of Ships*
- *Developments and Outlook*

BAW

Federal Waterways Engineering and Research Institute
Bundesanstalt für Wasserbau
Kussmaulstrasse 17, 76187 Karlsruhe
www.baw.de

VBW

Association for European Inland Navigation and Waterways
Verein für europäische Binnenschiffahrt und Wasserstraßen e.V.
Haus Rhein, Dammstrasse 15 - 17, 47119 Duisburg
www.vbw-ev.de

ISBN 978-3-939230-48-9 (Print)
ISBN 978-3-939230-49-6 (Online)
Printed in Germany

BAW
Bundesanstalt für Wasserbau
Federal Waterways Engineering and Research Institute