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PUSH TOWS IN CANALS

BY

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The views in this article are the author's own.

Contents

1 Introduction

This publication summarizes the research carried out in the Netherlands in the 1960s into the dimensions required for the cross-section of ship canals if push tows are to navigate safely with other types of inland shipping.

The research was conducted by a working party set up by the Director-General of the Department of Water Control and Public Works (Rijkswaterstaat); in addition to the appropriate Rijkswaterstaat services, the Delft Hydraulics Laboratory, the Netherlands Ship Model Basin in Wageningen and the Department of Naval Architecture of Delft University of Technology were represented on this working party.

The necessary cross-section dimensions were determined by the space required for the different traffic situations which must be possible without danger. The traffic situation requiring the greatest amount of space — taken as the key traffic situation — involves three large vessels: one is overtaking another, while a third is sailing in the opposite direction.

At first sight it would seem that traffic problems in fairways can be approached by methods similar to those used in the case of roads, i.e. by allocating a lane of a given width to each of the vessels involved. This method has been used in some previous studies. Closer consideration shows, however, that it is unsatisfactory because in a fairway not only the vessel but also the supporting environment is in motion. As a result, the transverse movements of a vessel are more difficult to control than those of a vehicle on a highway whereas in addition, the different vessels influence one another.

As long as a single ship is sailing in the axis of a straight canal with a prismatic cross-section, it is possible to derive approximate theoretical values for at least the principal characteristic parameters of the water movement (drop of the water level and reverse flow). In this case sufficient data is also available from practical measurements and laboratory tests to determine with reasonable accuracy the deviations from the theoretical results as a consequence of the approximations used.

However, when the ship is not navigating in the canal axis and in particular when several ships are present alongside each other in the canal simultaneously, the water movement becomes too complicated for a theoretical approximation. It is therefore still impossible to obtain rules for the design of a canal cross-section by theoretical means. Satisfactory data for this purpose is also not available in literature.

Until recently this was not a serious problem because wide knowledge had been acquired through long experience of traditional inland navigation (towed barges and self-propelled ships) in which conditions (types of ship, dimensions and speeds of travel) changed only gradually (photo 1). With the introduction of push tows, this knowledge gained from experience ceased to be sufficient. Not only are the push tows considerably larger than the other types of vessel, but because of their different shape, especially of the bow, the water movement created by them has markedly different characteristics (photo 2).

It was therefore necessary to gain a better insight into this problem through model tests. Direct simulation (with free-moving model ships manoeuvring under realistic conditions) of the passing manoeuvres liable to be encountered in practice on the canal, formed an important part of the study. Before this simulation could be carried out, it was, however, necessary to obtain more detailed physical information on the phenomena, at least in qualitative terms, in specially designed series of tests.

This was useful for a meaningful interpretation of the passing tests and also necessary to determine the possible influence of scale effects. For both these reasons it was also desirable to do the most accurate possible prototype measurements. The contacts

Photo 1.   Traditional navigation changed very gradually so that until recently canal design could be based on long experience.

Photo 2. The push tow is not only considerably larger than other vessels but also different in shape, especially at the bow.

established in this connexion with the professional circles directly concerned provided valuable guidance.

A few separate series of tests concentrated on special circumstances such as side-winds, canal bends and constrictions. A further general study was made of the effects on canal banks of the water movement caused by shipping. Some specific studies were also made of the flow distribution characteristics of intake and outlet structures situated along the fairways for water management purpose. The aim was to limit as far as possible the hindrance which might be caused to shipping, and in particular push tow navigation, by such locally-generated cross-currents.

The study was conducted in the De Voorst Laboratory of the Delft Hydraulics Laboratory. The results have already been applied to the design of the widened Amsterdam-Rhine Canal, the Scheldt-Rhine Canal and the Hartel Canal (see figure 1).

The results of the study are set out in detail in reports contained in four annexes to the final report of the working party. These annexes — in Dutch — are obtainable from the correspondence address.

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2 Prototype measurements

2.1 Purpose of the study

The main purpose of the prototype measurements and tests was to obtain adequate knowledge of the complex relationship between the innumerable factors which are important in determining the conduct of barge-skippers in face of traffic situations. This information was necessary to define the structure of the model tests and to interpret the model measurement results.

The boundary conditions for the model study were also determined on the basis of prototype measurements; these conditions included dimensions, draughts, capacities, navigation speeds of the ships, traffic situations encountered and the corresponding manoeuvres: evasive action, adjusting navigation speeds, distances from other vessels and from the banks.

The prototype measurements also provided data for calibration of the model, in particular calibration of the behaviour of the ship and the helmsman under static and dynamic interference between the ship and canal. Here, the course angle in relation to the axis of the canal and the rudder angle — in particular the mean value and standard deviation as a function of time — are important parameters.

Finally, the prototype measurements together with model tests on different scales, provided important information on scale effects in nautical model tests.

2.2 Navigation habits

To gain familiarity with the navigation habits of skippers on inland canals, a number of voyages were made on board various inland waterway vessels. The experience gained in this way was of great importance for accurate manoeuvres with the model.

For interpretation of the model results, it was also necessary to know what skippers considered an acceptable pattern of passing manoeuvres under practical conditions (photos 3 and 4).

Photographs 5 and 6 clearly show that dangerous situations may arise. The fact that these passing manoeuvres did not result in a collision was due to the good manoeuvrability which motor vessels generally have, unlike tow barges.

Photo 3. Push tow consisting of one barge meets a motor ship at a 'normal' distance.

Photo 4. Motor ship overtakes a single-barge push tow with normal clearance.

Photo 5.   Single-barge push tow overtaken by an unladen fast ship, with two oncoming over-taking vessels.

Photo 6.   The space on either side of the fast vessel cannot be a norm for canal design.

2.3 Traffic measurements

The traffic survey conducted in 1964 on the Amsterdam-Rhine Canal gave a clear picture of the overall traffic pattern. An analysis of the inland waterway fleet in terms of load capacity and distribution of navigation speeds shows that ships of 2,000 tons are sometimes encountered and that speeds range from less than 7 kph to more than 15 kph (see figures 2 and 3).

A more detailed analysis of the results enabled the navigation speeds to be determined at which the probability of being involved in an overtaking manoeuvre (overtaking or being overtaken) was smallest. This speed, which is between 10 and 13 kph, could be recommended for push tows (see figure 4).

2.4 Measurements with a push tow

The characteristics of a push tow consisting of 4 'Europe-I' barges (E I-barges), with a draught of 2.86 m, were measured in a section of the Amsterdam-Rhine Canal with a depth of 4.20 m and a width at the water level and bottom of 72 and 50 m respectively.

These prototype measurements concentrated on navigation at constant speed and constant distance from the banks, as these conditions could be reproduced relatively easily in the model.

The measurement results showed that the drift angle and especially the rudder angle fluctuated around a state of equilibrium (see figure 5). In general the state of equilibrium was not equal to zero.

3 Study of scale effects

3.1 Introduction

It was necessary to determine the optimum scale for the projected model study. On the one hand the model must be as large as possible in view of scale effects in the hydrodynamic phenomena. (The hydrodynamic phenomena of resistance, propulsion and rudder action may be affected by scale effects as a consequence of an excessively low Reynolds number. There may also be question of scale effects in the behaviour of a helmsman in the model, for example in perceiving the ship's movements in case the time scale is too small). On the other hand, building and operating costs make it cheaper to use a small model. Here too there is, however, a lower limit because smaller models place higher requirements on technical equipment if a given level of accuracy is to be maintained.

The scale effect study concentrated on the equilibrium rudder angle and drift angle of a push tow sailing along a canal bank and on the rudder action and resistance/ propulsion of a push tow. This study was carried out jointly by the Netherlands Ship Model Basin in Wageningen, the Naval Architecture Laboratory of Delft University of Technology and the Delft Hydraulics Laboratory.

No study was made of the scale effect in the behaviour of the model helmsman. Experience with previous model studies suggested that this scale effect will be slight, provided that the model helmsman is able to steer from the ship itself and has a line of sight corresponding to that of the helmsman of the prototype. Investigation of this problem would not have fallen within the terms of reference of the working party.

The study was conducted with a push tow of 2×2 E I-barges and a pusher tug with a power of 2×750 hp (see figure 6). Models on three scales were used, i.e. $1:40$, $1:25$ and $1:10.5$. Together with the prototype tests, a wide range of possible scales was therefore covered.

3.2 Definition of the problem

In a model the physical parameters are reproduced in such a way that certain characteristics are the same for the prototype and model; in this study they were:

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i   the Froude number $= \dfrac{v^2}{gl}$ for accurate reproduction of inertia effects;

ii   the Reynolds number $= \dfrac{vl}{\nu}$ for accurate reproduction of the influence of viscosity.

In these expressions v = speed
l = length
g = acceleration of gravity
ν = kinematic viscosity

Since g and ν are identical for the model and prototype, the following scale laws apply respectively:

i $n_v = n_l^{1/2}$

ii $n_v = n_l^{-1}$

There is of course a wide discrepancy between laws i and ii. If n_v is introduced on the basis of an identical Froude number it follows from ii that the Reynolds number will be a factor $n_l^{3/2}$ too low. This leads to differences between the model and real situation. These differences are defined as the scale effect.

A push tow sailing parallel to a canal bank without drift angle and with its rudder set centrally will be exposed to lateral forces:
— The water levels on either side of the push tow will not be the same. This leads to a difference in hydrostatic pressure.
— The water under the keel will not flow solely in the longitudinal direction. The frictional resistance therefore has a component directed athwartships (see figure 7).

The resultant of these lateral forces — referred to below as the canal bank force — is perpendicular to the ship's axis or an extension of that axis.

Two reaction forces are needed to establish equilibrium with the canal bank force. One reaction force (drift force) occurs because there is a drift angle between the push tow and its direction of travel. The other reaction force (rudder force) is caused by deflection of the rudder.

The system is clearly defined so that there is one value for the rudder angle and at the same time one value for the drift angle at which the forces on the push tow are in a state of equilibrium. These values are known as the equilibrium rudder angle and the equilibrium drift angle.

It is known from the study that in a state of equilibrium the rudder is always directed towards the bank, while the equilibrium drift angle, dependent on a number of factors such as the bow shape, water depth and distance from the bank, may be either positive or negative.

The force diagrams in figure 8 show that this is due to displacement of the point at which the canal bank force acts. The equilibrium rudder angle and the equilibrium drift angle are therefore largely dependent on the forces exerted on the push tow by the surrounding water.

Since almost all the forces are caused by phenomena in which viscosity plays a part, both the rudder action and the effect of the drift angle on the interplay of forces may be influenced by scale effects. As a result there may be differences between the size of the equilibrium rudder angle and the equilibrium drift angle in the model and prototype.
Some phenomena will counteract each other, so that it is impossible to predict whether the rudder angle and drift angle in the model will be larger or smaller than in the prototype.

3.3 Measurement results

Some measurement results obtained in the study of the equilibrium rudder angle and drift angle of a push tow sailing along a canal bank are shown in figures 9 to 11.
Figures 9 and 10 compare the mean rudder angle and drift angle during the different prototype measurements with the corresponding values for a free-moving model on a scale of 1:25. Although the results coincide reasonably well, it is significant that the prototype results show a wide scatter.
Figure 11 shows the results for push tows held in a fixed position in the lateral direction, on different scales. With reference to the holding forces, the figure shows on a graph the rudder and drift angles at which the lateral forces are in equilibrium. As the measurement accuracy is 1 to 1.5 tons (prototype), the measured differences are not significant.

Possible scale effects in the state of equilibrium when sailing along a canal bank are so small in relation to the measurement accuracy and scatter of the measurement results that no scale effects could be shown in the equilibrium rudder and drift angles.

The study of the rudder action involved measurement of the transverse forces as a function of the rudder angle of push tows held in a fixed position in the lateral direction on different scales (see figure 12). Taking into account the measurement accuracy referred to earlier, there does not appear to be any scale effect here either. The study of scale effects on resistance/propulsion — expressed in terms of propeller speed — also showed that the scale effect was so small that, for a variety of reasons, it could not be quantified.

3.4 Conclusions

On the basis of these measurement results and the considerations set out in the introduction, it was decided to continue the study on a scale of 1:25. The argument that the push tow and the tow barges used in this case would then be large enough in the model to allow room for a helmsman was the determining factor.

4 Influence of the canal cross-section on the directional stability of the push tow

4.1 Introduction

In the second phase of the preparatory study a large number of tests were carried out to determine the relationship between dimensions of the canal section and their influence on the behaviour of a push tow. A systematic study of this kind had not been carried out before, although the results are very important for the adequate design of a canal used by push tows. The depth, width and slope configuration of the canal, and the propeller speed of the pusher tug, were variable boundary conditions of the model. The range of variation of these parameters is such that the results are applicable to widely differing cases.

A push tow with automatic steering was used in this study (photo 7). The steering characteristics of this automatic system can be varied in such a way that the performance of both an unskilled and ideal helmsman can for example be simulated. The use
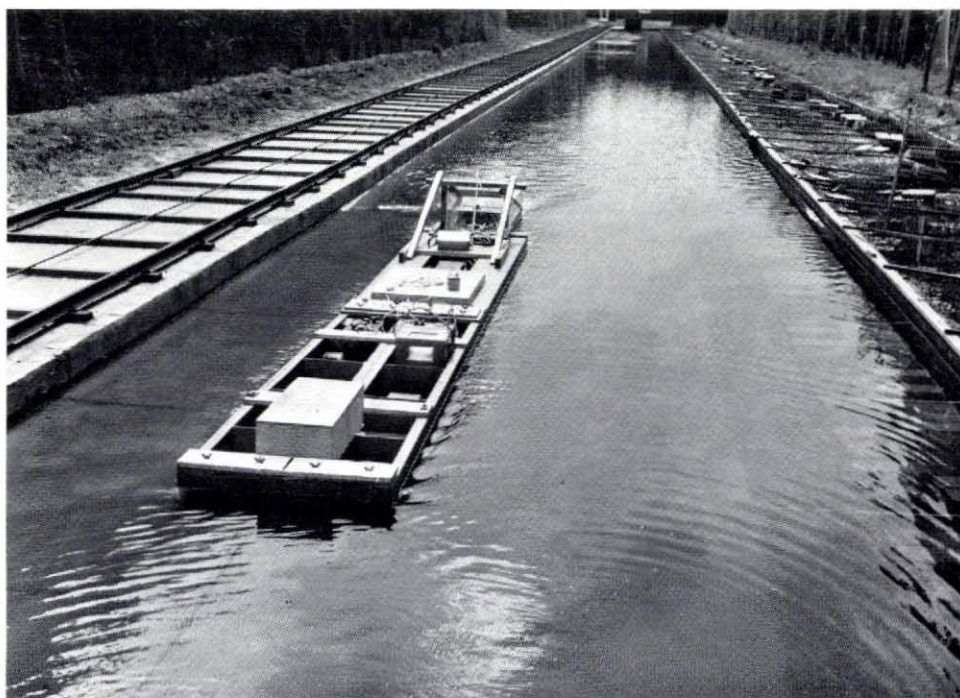
Photo 7. Automatically-steered push tow during study of directional stability in different canals, scale 1 : 25.

of an automatic system of this kind is important when the steering characteristics must be identical in all the tests of a series.

Initially the comparison parameters used in this study were derived from the average rudder angle and the average drift angle of a push tow encountered when the push tow sails close to the axis of the canal. The relevant literature suggests that these parameters are the most commonly used in studies of this kind. These parameters do, however, have the drawback of disregarding the non-steady phenomena which are particularly important during navigation. It is precisely the extent to which the ship and its rudder fluctuate periodically around their mean position which gives an indication of steerability.

In the remainder of the study, the parameters were therefore adapted more accurately to the dynamic behaviour of the ship.

4.2 Measurement results

The mean rudder and drift angles were determined from observations on a free-moving push tow on a scale of 1:25. The number of voyages (at least 4) and the length of each voyage (approx. 4 km for the prototype) were large enough to determine the mean value accurately. These averages were determined for a number of different distances between the push tow and the canal axis.

Figures 13 and 14 indicate as examples the results for rectangular canal sections with a width of 100 m and water depths varying from 3.80 to 7.40 m. These results show that direct comparison of the cross-sections was not possible. The absolute values of the rudder angle and drift angle were small in all cases and always permissible. In addition, the rudder angle characteristic appeared to be much the same in all canal sections, regardless of the variations in the section shape. Only the drift angle characteristic showed noticeable variations, depending on the canal section (see figure 14).

The reasoning followed in the interpretation is therefore based on the characteristic of the drift angle at an increasing distance from the canal axis. The drift angle is a consequence of the canal bank suction acting on the push tow. A steep gradient in the drift angle characteristic therefore signifies strong local variations in the interplay of forces, which may be experienced as an obstacle by the helmsmen. In this way it was possible to formulate a number of requirements with which a canal section must comply.

As the study progressed, emphasis was also placed on the extent to which the rudder and drift angles fluctuate around their state of equilibrium during navigation. In figure 15, the behaviour of the automatic pilot in the model is compared with the behaviour of a skilled helmsman during one of the prototype measurements. It is to

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be expected that the differences observed between the model and prototype will have only a slight influence on the results of the study.

The standard deviations of the rudder angle and drift angle appear to be comparatively low under practically all conditions They did therefore not appear to be a sufficiently sensitive parameter for the influence of the canal section on the directional stability of the push tow. As an example, figure 16 gives an impression of the measurement results.

4.3 Conclusions

Together with the previous study, the tests led to the following conclusions:

— The canal water depth must not be less than about 5 m, corresponding to 1.5 times the draught of the largest vessel.
— The shape of the underwater slopes has no noticeable influence on the directional stability of the push tow.
— If the water depth immediately in front of the canal bank is not less than 1.1 times the draught of the largest vessel, the navigable width and the directional stability are no smaller than in a completely rectangular canal section.

5   Overtaking manoeuvres

5.1   Introduction

The principal aim of the model study of push tow navigation in canals is to determine the cross-section of canals intended partly for push tow navigation. The cross-sections were studied under two conditions:

— A push tow navigates singly on the canal (see chapter 4).
— A push tow and other ships pass each other.

In the first study the cross-sections were compared with the aid of a parameter derived from the rudder angle or drift angle encountered when the push tow sails in succession through canals with different cross-sections.

A similar method of study was used in designing the North Sea Canal (Delft Hydraulics Laboratory report M 726), the North Sea-Baltic Canal (Hansa No. 36/38, 2-9-'52), the Panama Canal (Lea, C.A. and Bowers, C.E.; Panama Canal, Ship Performance in Restricted Channels; Proc. ASCE 1948) and the Suez Canal.

In busy canals it must be possible for two ships of the largest permissible dimensions to sail past each other in opposite directions; if the traffic density makes it desirable even more than two traffic lanes may be needed for sufficient space for oncoming vessels during an overtaking manoeuvre. The traffic situation which is considered decisive for a particular canal will depend on the desired capacity of that canal.

The study was based on a traffic density which makes it desirable to have sufficient space for oncoming vessels during an overtaking manoeuvre (three navigation lanes). In addition, it must be possible for the ships to travel sufficiently fast to make economic use of their engine power. This means for example that a push tow should not have to reduce its speed to less than approx. 10 kph.

The distribution of vessel types makes it unnecessary to allow for all conceivable combinations. When the daily traffic in both directions is estimated at 5 to 10 push tows for example and 150 to 200 other vessels, allowing also for the high level of uniformity in the dimensions and speed of push tows, overtaking of two push tows can be ruled out. The probability that the three traffic lanes will be used simultaneously by two push tows and a normal tow can also be considered very low.

The preliminary study showed that the traffic situation which creates the greatest difficulties is that in which a large ship with poor steering characteristics is overtaken by another large ship. For this reason, the decisive situation was chosen as that in which a normal tow is overtaken by a push tow with 2 × 2 wide barges, while a motor vessel is sailing in the opposite direction (see figure 6). Speeds of 7 kph for the normal tow, 10 kph for the push tow and 15 kph for the motor vessel were chosen. The aim of the study was to allow the manoeuvre to take place without difficulty under these conditions, naturally on the assumption that the skippers complied with the requirements of good seamanship, in particular by reducing speed where necessary, and allowing each other enough room. At the speeds indicated, the overtaking manoeuvre takes 13 to 14 minutes and continues over a distance of about 2.1 km. If there is no room for oncoming traffic, the overtaking manoeuvre can only be begun if the closest oncoming vessel is more than 5.5 km away. This shows that three lane navigation is necessary when traffic is dense.

The manoeuvring tests were based on the closest possible approximation to the real characteristics of shipping. For this purpose, the tests were designed and carried out in close contact with canal ship operators (photos 10 to 15).

The model tests were carried out with free-moving ships. During an overtaking manoeuvre the successive positions of the ships were recorded photographically (photo 16). A parameter was then derived to assess the safety of the decisive traffic situation; this parameter is characteristic of the relevant canal section. It is also necessary to determine what values the parameter must have for the canal to be sufficiently safe.

The traffic situations in the model can also be assessed visually to determine their safety.
An expert eye-witness will obtain a good impression during observation of the ship movements, to the extent that safety diminishes as the ships are closer together.
A film was therefore made of passing manoeuvres in the principal canal sections (see photos 8 and 9). Safety in different canal sections can then be compared without relying excessively on the memory of observers. At the same time persons who were not able to follow the progress of the tests from day to day can gain an impression through this film of the course of the manoeuvres and the differences in the canal section dimensions.

5.2   Simulation of prototype collisions

A number of prototype collisions were simulated in the model in order to investigate whether a situation which in practice appeared to lead to collisions because of a high
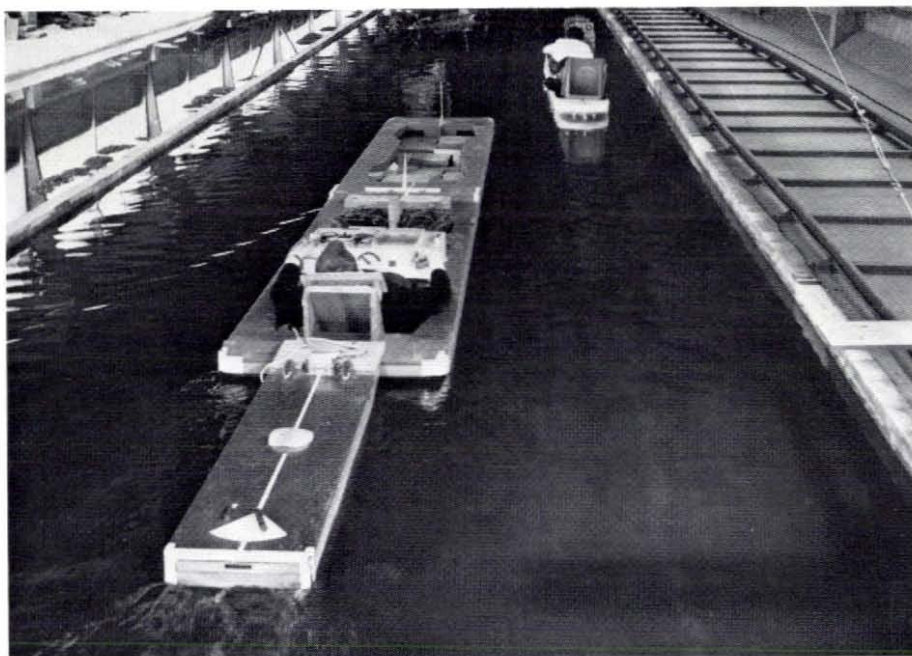
Photo 8.
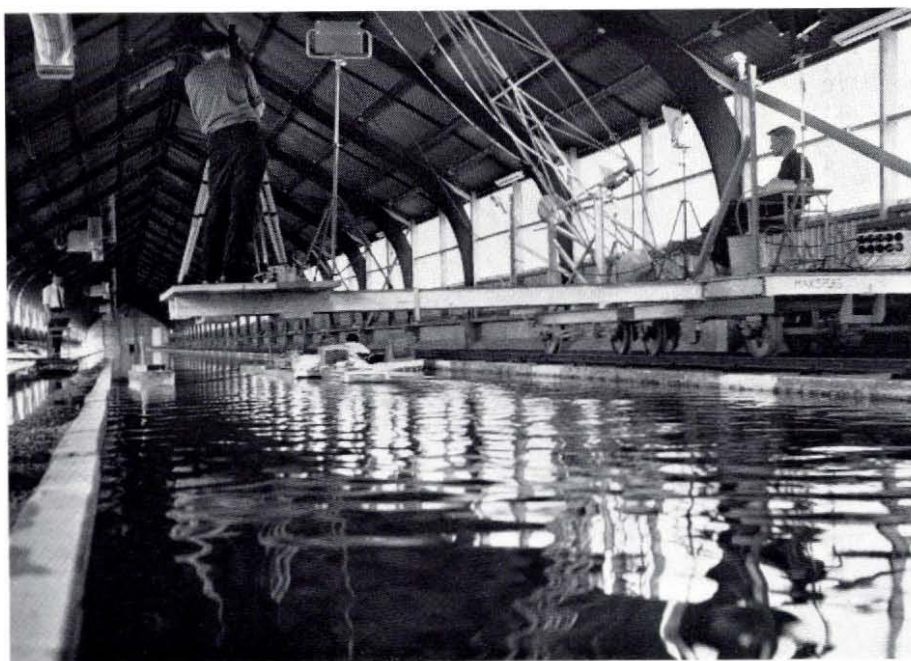
Photo 9. Decisive traffic situation in the model. Passing manoeuvres are filmed from the instrument trolley travelling behind the tow.

speed of travel or an insufficiently wide passing distance, also made an unsafe impression in the model. These tests were repeated several times in the model and the phenomena were found to be reproducable to a high degree; they also coincided with the prototype observations.

An example of a collision later on simulated in the model is described in the minutes of the Netherlands Water Police (see figure 17).

5.3 Phenomena during overtaking

As already indicated the behaviour of the tow barge is the most critical in the decisive traffic situation. The push tow and oncoming vessels maintain their course well without deviating significantly from it and remain practically straight in the canal. The tow barge cannot, however, hold its course when it is overtaken by the push tow. The forces which push the tow barge off course are mainly due to the water movement prevailing around the push tow.

In front of the push tow a slight increase in water level occurs and the reverse flow, generated by the push tow, has curved flow lines there. Because of this phenomenon a force acts on the tow barge sideways of the bow of the push tow; this force is exerted towards the starboard bank and affects the rear of the tow barge first. The latter then slews over towards the bank while the forward part of the barge moves away from the bank. As the push tow continues its overtaking manoeuvre, the repelling force is displaced towards the bow of the tow barge. In this situation, the tow barge is angled in relation to the bank but still moves roughly parallel to it. Meanwhile the rear part of the tow barge drops into the lower water area which begins just behind the bow of the push tow. As a result the barge train is slowed down considerably.

When the whole tow barge is alongside the push tow the latter has little influence on it. The tow barge then has a short time to adjust its position before the most critical part of the overtaking manoeuvre begins. The water-level drop is quickly made up again to the rear of the push tow barges, so that the tow barge is accelerated. This phenomenon continues until the push tow has overtaken completely. The towing motor vessel must then try to keep the tow line taut by increasing its speed. If this is not possible, the tow barge will close up on it and will be less easy to steer because the tow line will no longer draw the bow in the correct direction.

At the same time the tow barge will be exposed to a strong suction force towards the push tow. This lateral force is also a consequence of the reverse flow directed towards the psuh tow at the rear of the push tow barges and to a lesser extent at the rear of the pusher tug. This suction force also acts first on the rear of the tow barge which therefore slews over towards the bank. If this angle is large enough the tow barge will not be drawn far off course but will move parallel to the bank.

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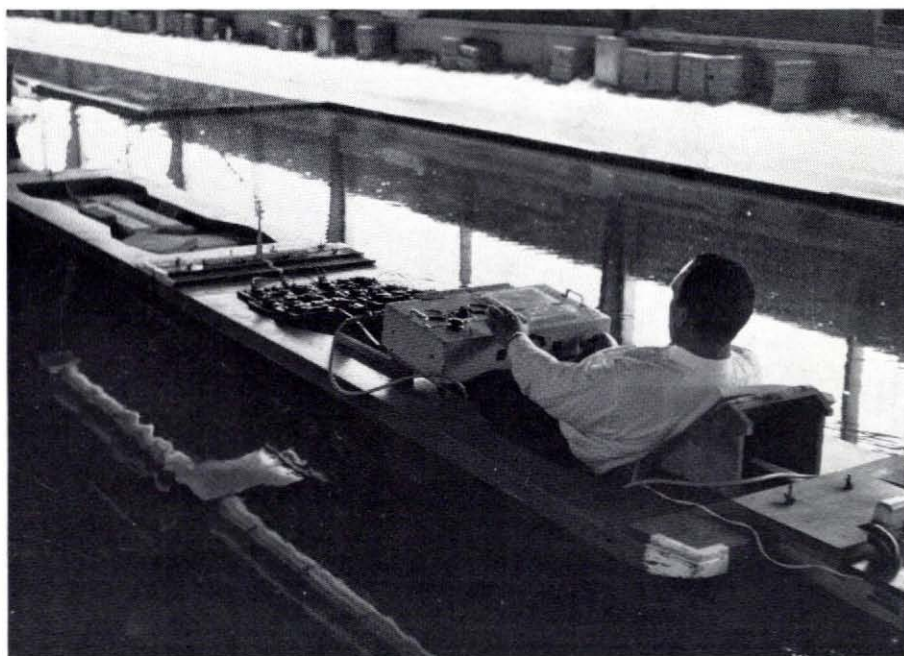
Photo 10.

Photo 11. Steering the model push tow compared with prototype. There is no room for the model helmsman in the pusher tug.

When the rear of the push tow has just passed the tow barge after overtaking, it is still possible that the bow of the tow barge will be drawn over so strongly that the tow barge veers off course and slews over to port in the canal. A collision with the push tow is no longer possible at this stage but the tow barge may collide with an oncoming vessel. In practice, it is also possible in this situation for the tow barge to collide with another ship overtaking it after the push tow did. This course of events in an overtaking manoeuvre, like the occurrence of a collision, must naturally be regarded as impermissible.

The phenomena described above can be illustrated by an example. This concerns the behaviour of the rearmost tow barge in a train of two barges and a motor vessel which is overtaken by a wide push tow. The canal is treated in this case as a two-lane fairway so that the push tow can move well over to port. This overtaking manoeuvre was measured 16 times in all.

The test in which the tow barge requires the greatest amount of space is illustrated completely in figure 18. This figure also defines the concepts of 'navigation lane width' and 'space adjacent to the navigation lane'. The navigation lane width is the width between two lines in between which are enclosed all the different successive positions. The traffic lane width is the width of a canal lane.

All the measurements in this series showed much the same characteristics. It is therefore reasonable to combine the observations into a mean value to enable the speeds and accelerations to be derived with greater accuracy by differentiation (see figure 19).

Although the phenomena followed the same pattern in all the tests as a function of time, the values reached in the different tests may differ considerably. This is illustrated on the basis of the measurement results for a trapezoidal canal section with a water depth of 5 m and bottom and surface widths of 115 and 155 m respectively (see figures 20 to 29). Figures 20 to 23 show that the model helmsmen of the tow barge and push tow did not 'learn' during the series of 55 tests. Good and less good voyages occurred at both the beginning and end of the test series. Because of their experience of steering model ships the maximum performance of the model helmsmen had already been reached before the beginning of the measurements. The learning effect thus did not interfere with the measurement results.

In the 3rd and 30th voyages the distance between the tow barge and push tow was negative (see figure 22). This means that after passing the rear of the push tow, the tow barge moved over partly behind the push tow. In voyage 3 this resulted in a collision with the push tow owing to the fact that on this voyage the tow barge had a very broad navigation lane width (see figure 20); the cause was not an excessive distance from the canal bank (see figure 21) or between the push tow and the canal axis (see figure 23).

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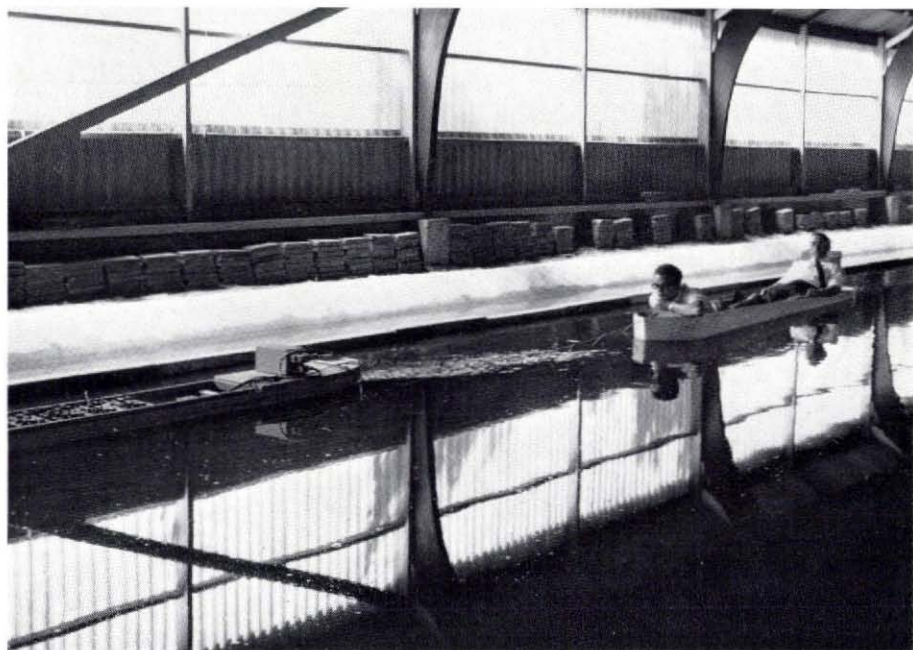
Photo 12.

Photo 13. Steering a model tow barge compared with the prototype. Instead of a tug, a RHK ship is used in the model steered by the person at the front. The person at the back steers the tow barge.

The model helmsman of the push tow is generally able to navigate in the centre of the canal with a good measure of accuracy. His instructions were to keep the starboard side of the push tow in line with the canal axis. He had no visible means of guidance. The ends of the model were hidden for this purpose by black plastic foil. The only guidance was provided by the line of the canal banks.

Whenever the push tow was too far over on the starboard side of the canal according to the personal impression of the tow barge skipper, the helmsman of the push tow was 'reprimanded'. This may explain why, after the 3rd and 30th voyages, a number of voyages were navigated too far over on the port side (see figure 23).

The last three voyages of the push tow were made much (average about 10 m) too far over to the starboard side of the canal. This may have been caused by a lack of concentration on the part of the helmsman of the push tow as a result of fatigue or reduced motivation. In these 3 voyages the distance between the tow barge and the push tow was no less than 12 m so that the tow barge skippers had little reason to correct the behaviour of the push tow helmsman.

In order to investigate whether the distance between the push tow and the canal axis influences the navigation lane width of the tow barge these values are compared in figure 24. There seems to be no influence.

It is also important to know whether the navigation lane width of the tow barge is dependent on the distance between the latter and the bank (and push tow). For this purpose figure 25 shows for each voyage the largest and smallest distance observed between the tow barge and the bank (measured at the plane of the keel) expressed against the navigation lane width. For small navigation lane widths (< 36 m) the minimum distance is 10 to 20 m. With a large width (> 36 m) the tow barge always (7 cases) comes within less than 10 m of the bank. In 4 cases the distance was even less than 5 m. It may therefore be concluded that the traffic lane required for the tow barge need not be any greater than the navigation lane width which is still conidsered permissible.

The above observations show that the scatter in the measurement results is considerable; this cannot be ascribed to a dispersion of the material boundary conditions. The sole cause must lie in the uncertain behaviour of the model helmsmen. Since the model helmsmen had the intention of steering the best possible course in each passing test, they gained the impression that the progress of the passing manoeuvre was determined by chance. By analysing in greater detail the frequency distribution of the scatter in the results, it is possible to determine the probability of the tow barge and push tow moving out of their traffic lanes.
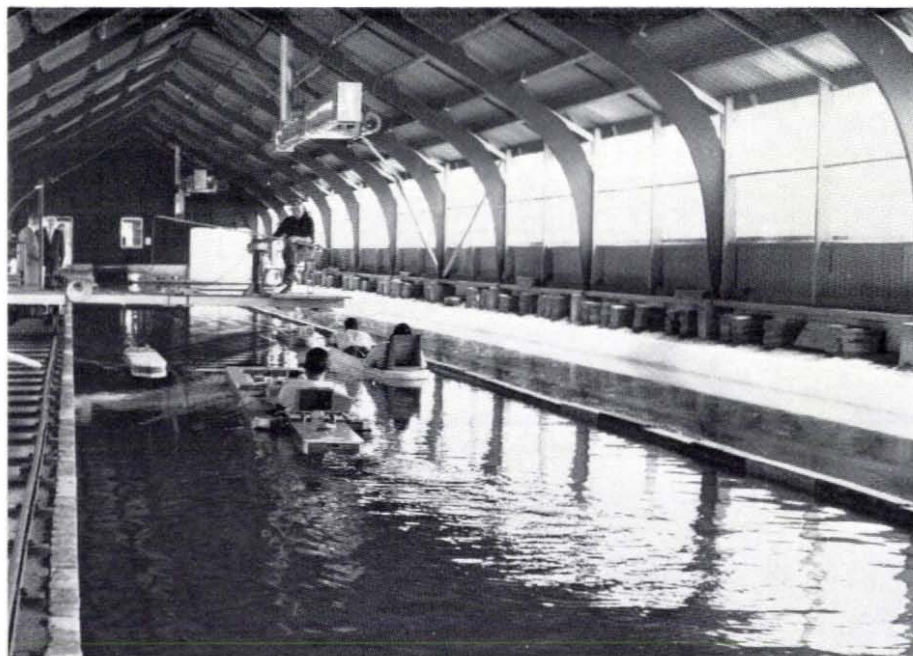
Photo 14.

Photo 15.   Model passing manoeuvre. The push tow and tow barge were steered by experienced skippers who determined the respective distances intuitively.

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The cumulative frequency distribution of the traffic lane widths used by the push tow and tow barge is shown in figure 26. The measurement results contained in figures 20 and 23 are used again here. The navigation lane width of the push tow was assumed to be 1.1 times the width of the push tow during the overtaking manoeuvre. During the relatively short measuring period this value was not exceeded. The traffic lane width of the tow barge was assumed to be identical to the navigation lane width (see figure 20). The data obtained from a number of similar passing tests in other canals was also available for the tow barge. This data is shown in figure 26.

It appeared that the relative cumulative frequency distributions can be represented in an approximation by parallel straight lines with a logarithmic distribution and a normal frequency distribution along the co-ordinate axes respectively. This means that all the frequency distributions have much the same standard deviation.

With the aid of figure 26 it is now easy to determine the relationship between the traffic lane width and the frequency with which this width is exceeded. In the canal considered above where the tow barge can use the entire starboard half of the canal (traffic lane width 66.30 m), the frequency of exceedance is about 1%. This also indicates the probability of collisions. Allowance must, however, be made for a scale effect in the manner of steering the model, so that the probability of collisions in the prototype may differ from the probability of collisions in the model. A detailed consideration of the scale effects will be found in chapter 3.

For completeness, the relative cumulative frequency distributions are shown in figures 27 and 28 for the smallest distance between the tow barge and the push tow and bank.

Finally, figure 29 shows the relative cumulative frequency distributions for the overtaking length and the time required by the push tow to overtake the entire barge train (tow barge drawn by motor vessel). This figure also shows the time which elapses until the push tow has just passed the tow barge and can leave the port side of the canal again in order to overtake the towing motor vessel on the starboard side of the canal.

5.4 Recommended canal section

If the boundary conditions are not changed, the navigation lane widths (b) of the different vessels may be interpreted as mutually independent stochastic parameters (the scatter in the navigation lane width is obviously caused by the helmsman). The probability of occurrence of values equal to or greater than $\Sigma b_{0.5}$ and $\Sigma b_{0.2}$ is approximately equal to 0.5 and 0.2 respectively, since the scatter in the navigation lane
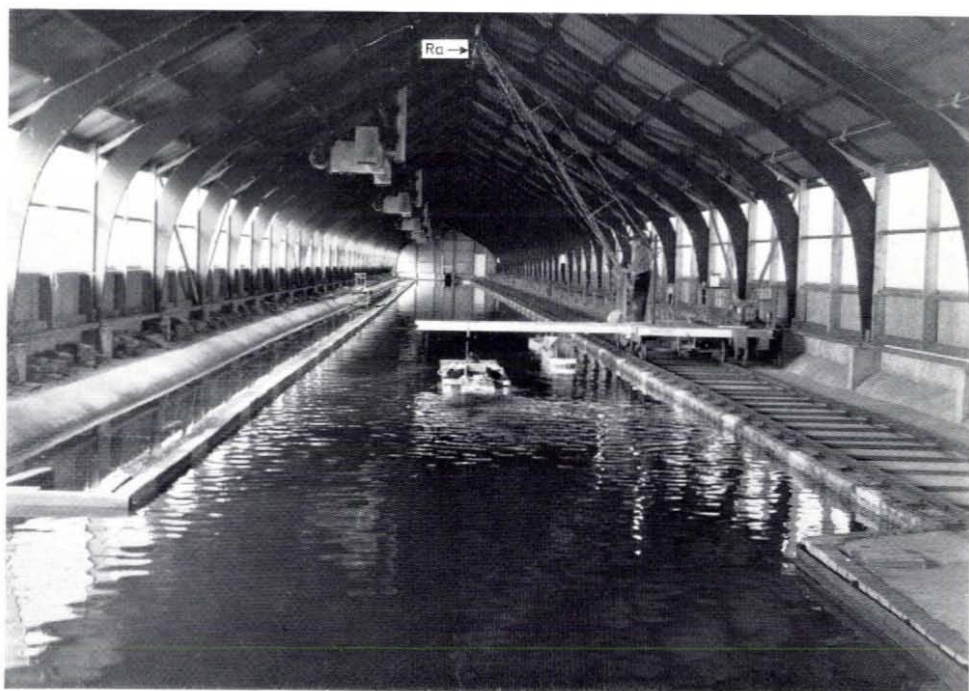
Photo 16. Instrument trolley with photographic apparatus on a boom used to determine the position of the ships.

widths of one of the vessels is generally high in relation to that of the two others.

These figures show that in addition to the navigation lane widths there must also be sufficient room left to reduce the probability of collisions to practically zero. Account must be taken in this connexion of:

a   the scatter in navigation lane widths due to the conduct of the helmsman;
b   the frequency at which a particular traffic situation occurs;
c   the consequences of a possible collision (generally consisting in one of the vessels scraping along another or along the bank);
d   differences between practical conditions and the model tests.

It may in future be possible to solve a decision problem of this kind with the aid of statistical and economic data. As this cannot be done at present, detailed discussions of the interpretation of the model results took place with the canal management which had commissioned the study and practical experts.

The scatter of the total navigation lane widths (Σ b) provided the basis for the criterion which was finally chosen. This scatter is characterized by the difference

between $\Sigma b_{0.2}$ and $\Sigma b_{0.5}$. The index here indicated the frequency with which Σb is reached or exceeded. The canal must be wide enough for the space ($R_{0.2}$) remaining in addition to $\Sigma b_{0.2}$ to be sufficiently large for the probability of collision to be kept to a minimum even when the navigation lane width is still greater. This may reasonably be expected to be the case when $R_{0.2} = 1.5 (\Sigma b_{0.2} - \Sigma b_{0.5})$. With the aid of this criterion we can calculate for each passing manoeuvre for which adequate data is known, how wide the canal must be to obtain the required degree of safety. The results of this calculation are shown in table I (rounded off to the nearest 5 m).

Passing manoeuvre	Canal width required in m	Water depth in m
1)	2)	
m-d-s	125	5
s-d-m	110	5
s-m-d	95	5
m-d-s	100	6
s-d-m	85	6
s-m-d	95	6
m-d-sm	90	6
sm-d-m	95	6
m-d-m	80	6
m-m-d	90	6

1) m-d-s   a barge train is overtaken by a push tow with an oncoming motor vessel; respective speeds 7, 10 and 15 kph.

     s-d-m   a motor vessel is overtaken by a push tow with an oncoming barge train; respective speeds 8, 11 and 7 kph.

     s-m-d   a push tow is overtaken bij a motor vessel with an oncoming barge train; respective speeds 10, 17 and 7 kph.

     m-d-sm   a tow barge, coupled alongside a motor vessel, is overtaken by a push tow with an oncoming motor vessel; respective speeds 8, 11 and 15 kph.

     sm-d-m   a motor vessel is overtaken by a push tow with an oncoming tow barge coupled alongside a motor vessel; respective speeds 8, 11 and 8 kph.

     m-d-m   a motor vessel is overtaken by a push tow with an oncoming motor vessel; respective speeds 8, 11 and 15 kph.

     m-m-d   a push tow is overtaken by a motor vessel with an oncoming motor vessel; respective speeds 10, 17 and 15 kph.

2)   The canal width should be measured at the keel plane of the ships.

Table I.   Canal width required to enable the above passing manoeuvres to be completed with maximum safety.

The minimum initial navigation speeds at which the motor vessel can still just overtake the push tow were determined for three initial push tow navigation speeds (9, 10 and

11 kph), and in two different canal sections with widths and depths of 100×6 m²
and 130×5 m² respectively.

At these minimum navigation speeds (see table II) the overtaking manoeuvre takes a
very long time. If the manoeuvre is to be completed smoothly the speed of the motor
vessel must be about 1 kph higher. The results show that there is practically no
difference in regard to the minimum speed of travel necessary for overtaking in the
two canal sections.

Push tow speed in kph	Minimum speed of motor vessel in kph	
	Canal profile	
	100×6 m²	130×5 m²
9.0	13.8	13.4
10.0	15.5	15.3
11.0	17.5	17.1

Table II. Minimum speeds of a motor vessel, necessary to overtake a push tow as a function
of the canal dimensions.

6 Special studies

6.1 Effects on the canal section

The banks of a canal in the vicinity of the water level are damaged by ship waves, caused primarily by fast (empty) motor vessels. Push tows do not create any extra difficulties in this respect.

Damage to the canal bed and slopes below the water level are due to the speed of the reverse flow and propeller race, and also to the water-level drop which may cause ground water over-pressure which forces off the slope lining or soil particles. These phenomena are likely to occur more extensively and for longer periods when push tows use the canal than in the case of conventional inland waterway vessels.

A brief study was made of these phenomena; the water-level drop and flow velocity around a push tow were measured, and information was gained with the aid of movable bank material on the mechanism of erosion. It was found that the eroding action on underwater slopes is greatest next to the push tow, level with the bilge. The propeller race of a moving push tow does not cause any special difficulties. Figure 30 gives an impression of the water-level drop.

6.2 Side-wind

An unladen push tow in 2×2 formation is difficult to steer in the presence of side-wind. On the Waal, unladen push tows therefore sail in swallow-tail formation (although with the introduction of more powerful pusher tugs, this formation has once again been largely abandoned). However, this is not a practical solution for canals, because the width of the tow is limited by the dimensions of the locks to two barge widths. Incidentally a solution may be found by providing a steering device at the front of the push tow (bow rudder, bow propeller etc.). These aids to manoeuvrability are being used on an increasing scale.

Another simple solution is provided by ballasting. A number of model tests were therefore carried out in which the load state and wind speed were varied. The drift angle needed by the push tow in all these instances to hold its course was used as a parameter to compare the difficulties likely to be encountered in any given situation. Good results were obtained when only one of the front barges was ballasted, as was

Photo 17. Overtaking manoeuvre of a push two and tow barge towed by a motor ship in the Eendracht bend of the Scheldt-Rhine Canal.
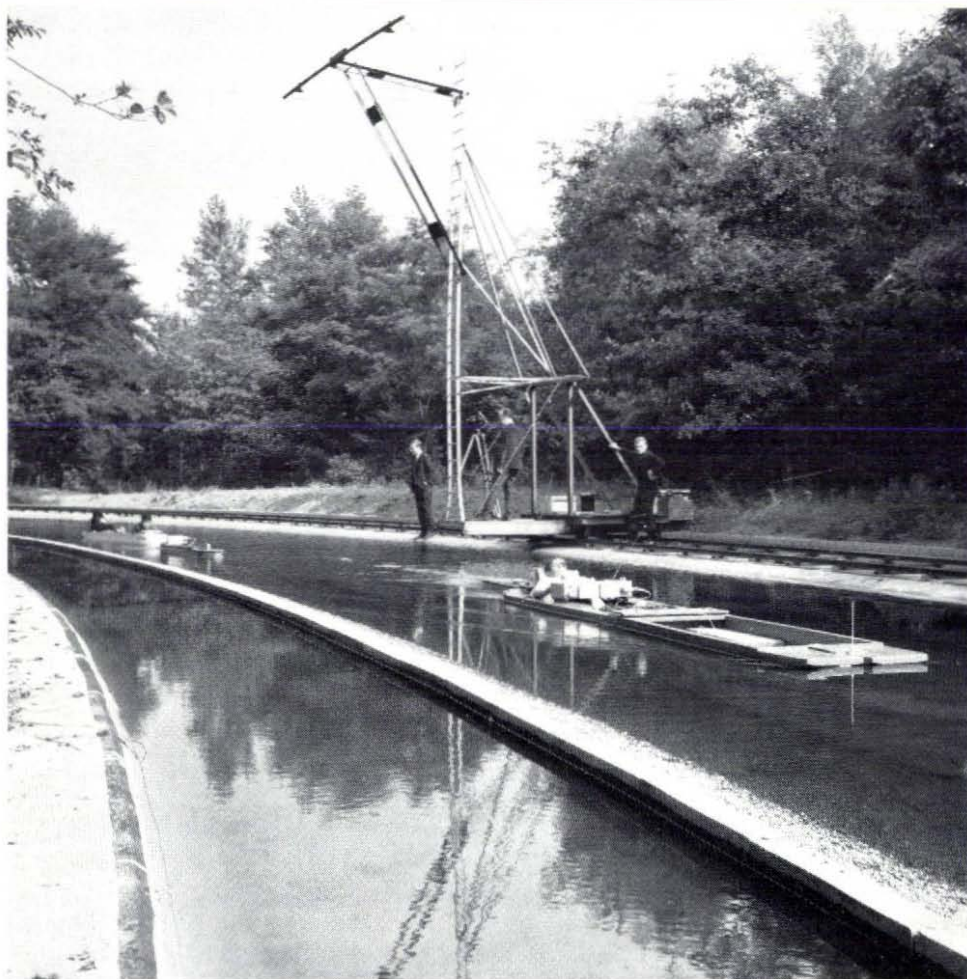
Photo 18.   Instrument trolley used to photograph the positions of the ships.

already known from practical experience. It was also found that good results are possible when the barges are fitted with a leeboard (see figure 31). The study did not enable the maximum wind speeds to be defined at which an empty push tow can still navigate on the canal: the greatest difficulties occur when the push tow has to stop or sail away from the lee shore, but the study was confined to push tows navigating at cruising speed only.

6.3   Scheldt-Rhine Canal/Eendracht bend

Following the manoeuvring study the question arises as to whether safety is as great

in a canal bend as in a straight canal of the same dimensions, and also whether the water-current velocity has any influence here. These problems are relevant to the design of the Scheldt-Rhine Canal with the bend at Eendracht in which tidal currents will probably still be encountered until the Eastern Scheldt works will be completed. The study showed that the current velocity has no noticeable influence on the behaviour of the ships in relation to the water. Safety was found to be just as high. In the bend too (with a radius of 3,000 m) the behaviour scarcely differed from that in a straight canal. The push tow simply deviated rather more from the required course than in a straight canal. In the light of this observation, it is recommended that in canal bends with a radius of about 3,000 m, the width of the cross-section should be 5 m larger than in the adjacent straight canal sections (see photos 17 and 18).

6.4 Amsterdam-Rhine Canal/Demka bend and Goyer bridge

The width of the Amsterdam-Rhine Canal between Utrecht and Maarssen is limited to about 95 m. In addition there is a bend at this point with a radius of only 1,000 m. Because it would be very expensive to widen the canal here, the canal width was an

Photo 19.   Demka bend — existing situation.
An empty motor vessel and a push tow with one barge meet a laden motor ship.
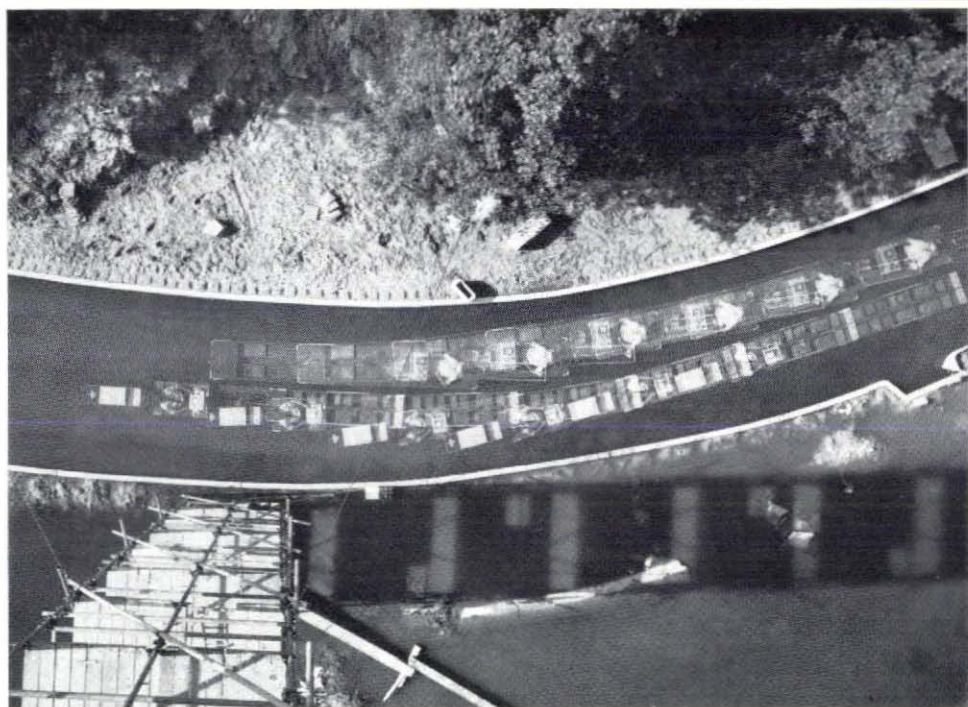
Photo 20.   Demka bend — widened situation.
Two push tows with four barges each meet.

invariable boundary condition for a study in which model tests are used to determine the passing manoeuvres which can be completed safely. Because of the short line of visibility (locally as low as 600 m) it is important for two push tows to be able to meet each other. This appeared possible. A motor vessel can still overtake a barge train with an oncoming push tow. Restrictions for navigation need therefore simply prohibit overtaking of or by a push tow immediately before or in the bend (see photos 19 and 20). A similar restriction must also be imposed temporarily at other local narrow stretches of the canal, e.g. near bridges with a relatively small span. For an existing bridge (Goyer bridge) and its sub-structure, it was determined which traffic situations were not permissible at this point with a number of alternative canal shapes. It was found necessary to widen the canal up to the bridge piers (passage width 68 m). There is then no problem if a push tow meets a conventional vessel. Two push tows cannot, however, pass in opposite direction at this point (see photos 21 and 22).

6.5   Beuningen outlet structure

In conjunction with the widening of the Betuwe reach of the Amsterdam-Rhine Canal, the old pumping-station that used to discharge water from the river Linge into the

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Photo 21. Goyer bridge — existing situation.
A laden tow meets an empty tow.
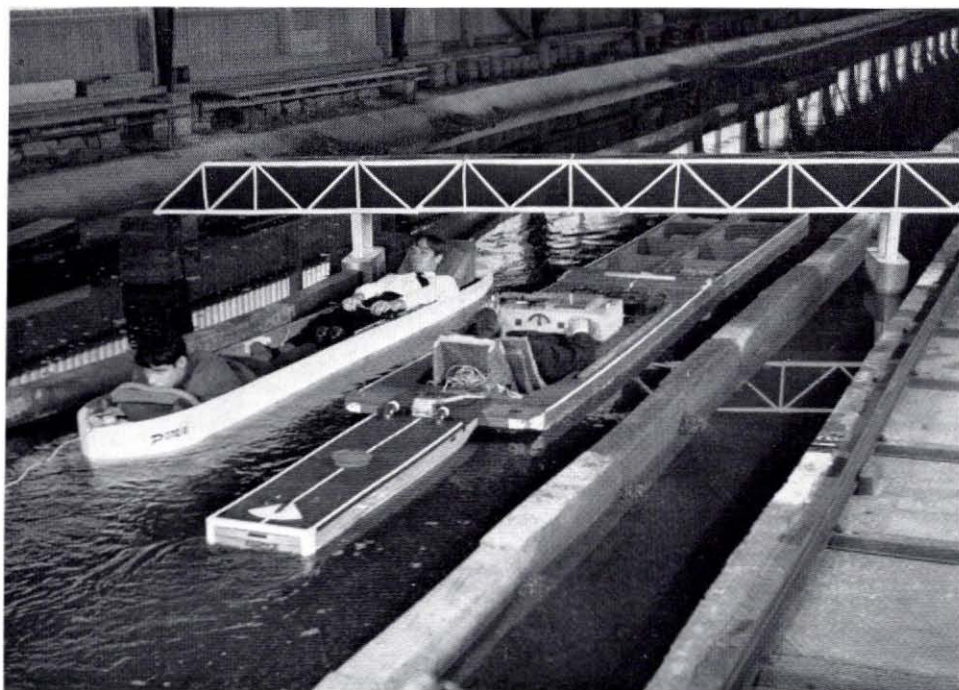
Photo 22. Goyer bridge — existing situation.
A push tow meets a barge tow.

canal must be demolished and replaced by a new pumping-station/discharge structure. The shape of the flow distribution structure on the outlet side must be such that ships sailing at a short distance from it are not adversely affected by the cross-current. Figure 32 shows the flow pattern encountered with a delivery from the structure of 30 m³/s, and the practically negligible influence on a push tow sailing alongside which in the model was ultimately achieved in the recommended layout.

6.6 Maarssen intake structure

To meet water supply requirements for the central and west Netherlands, it is assumed that in the vicinity of Maarssen water will be drawn off the Amsterdam-Rhine Canal at a maximum rate of approx. 60 m³/s. Ships sailing close to the intake structure must not be adversely affected; this places high requirements on the design of the structure. The study showed that especially relatively small motor cargo vessels (length up to 60 m) are influenced by the cross-current created here. By splitting the intake structure into three rather smaller units at distances of 60 m from each other, these vessels can sail past practically without hindrance. Figure 33 shows the ship movements as observed in the model.

Figures
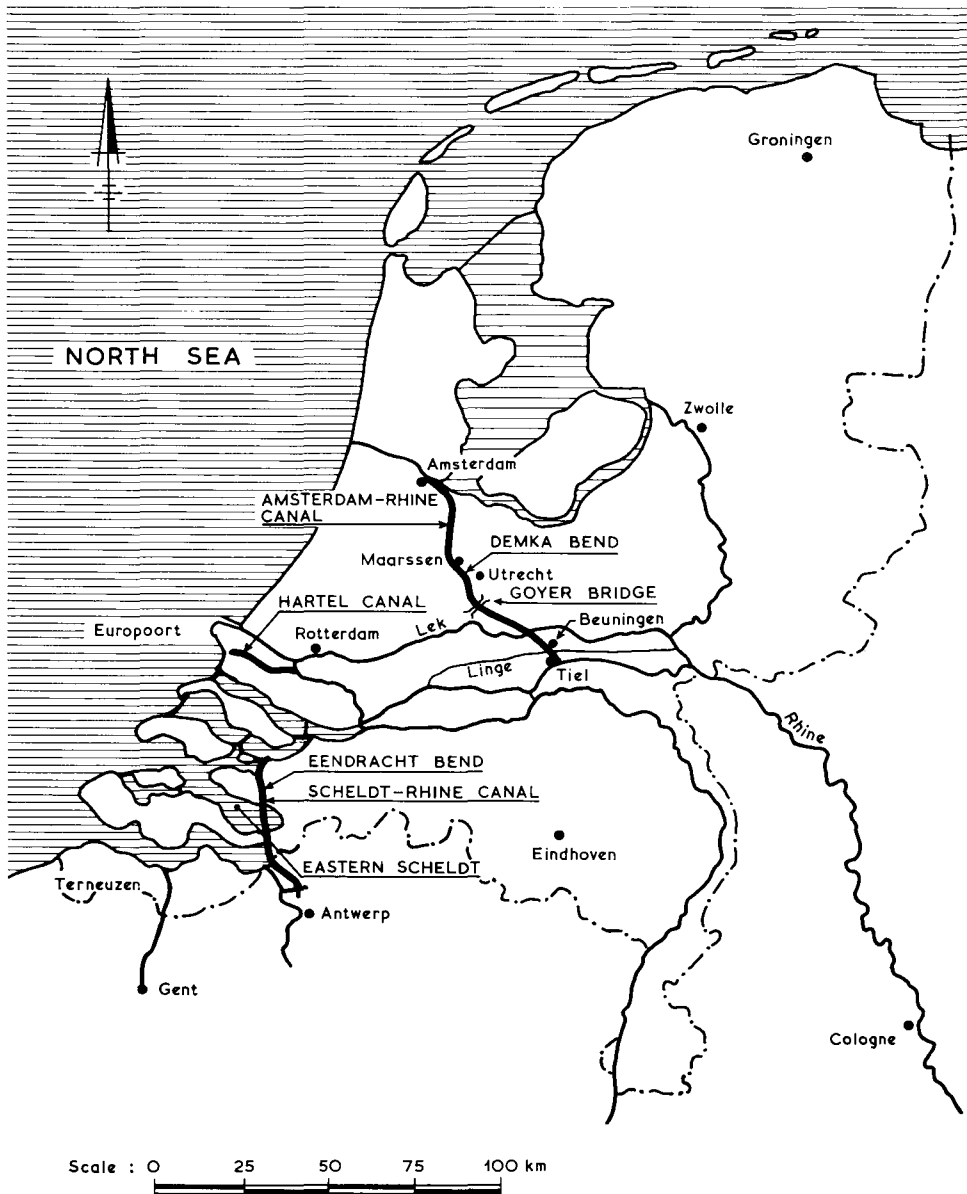
Figure 1.   Inland navigation canals in the Netherlands suitable for push tow navigation.
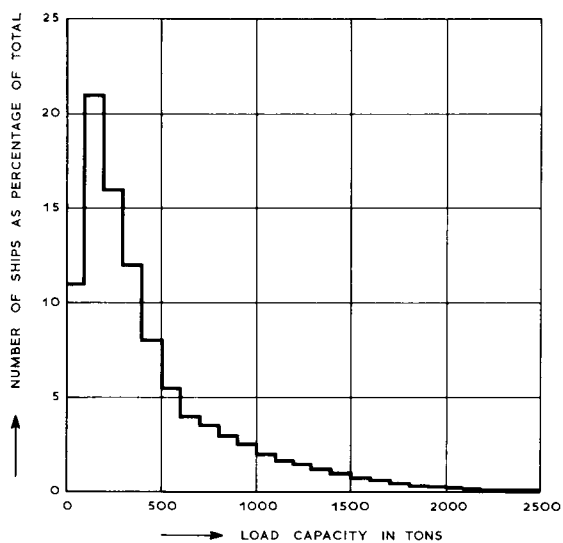
Figure 2.   Relative frequency distribution of load capacity of laden ships.
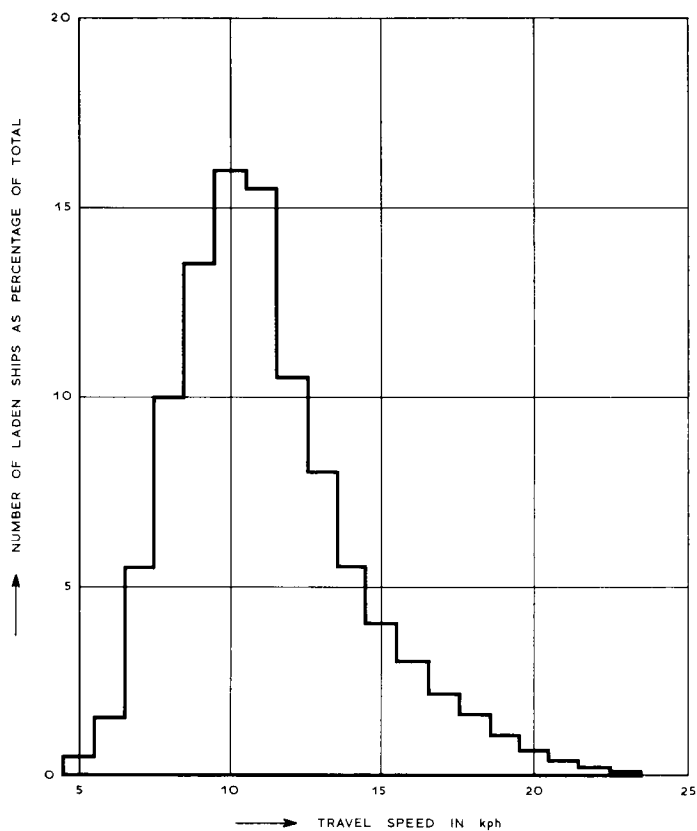
Figure 3.   Relative frequency distribution of travel speed of laden ships.
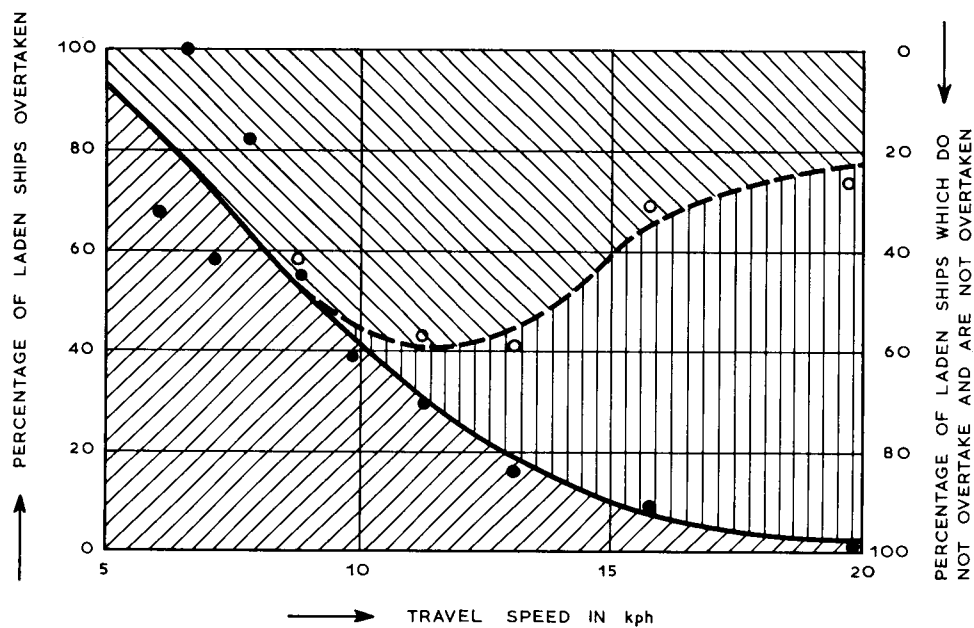
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Figure 4. Influence of travel speed on overtaking.
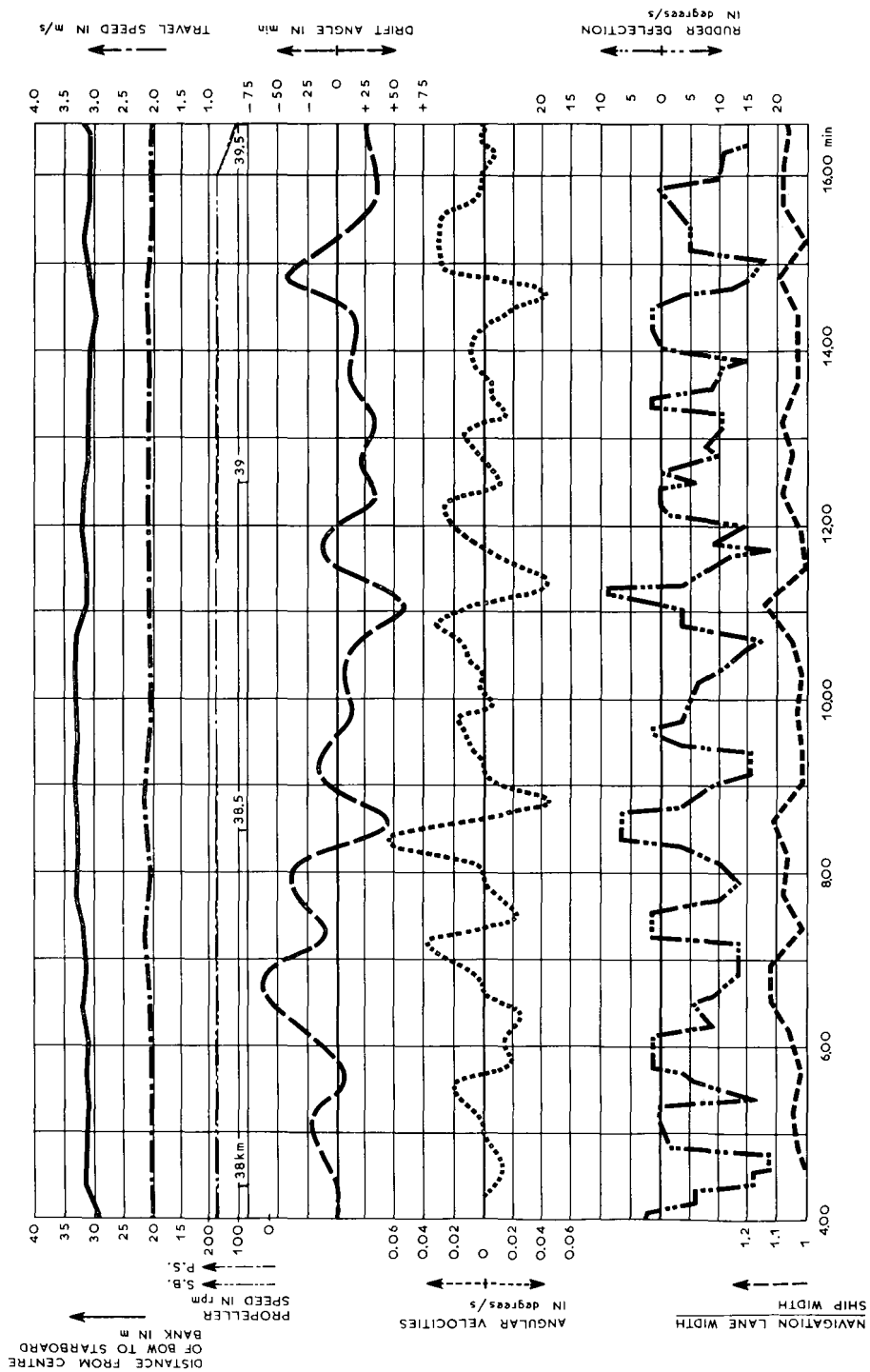
Figure 5.   Prototype measurement 'Jacob van Heemskerck'

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DIMENSIONS IN m

NARROW PUSH TOW

SIDE VIEW

3,20

10.00

2 x 9.50

19.00

38.00

2 x 70.00

178.00

PLAN VIEW
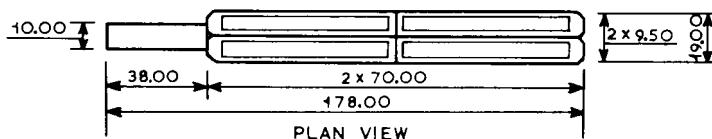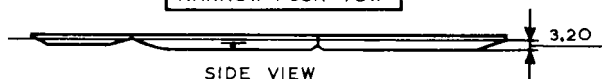
PUSHER TUG "VULCAAN I" WITH 2×2 E I BARGES

WIDE PUSH TOW

SIDE VIEW

3.30

10.00

2 x 11.40

22.80

38.00

2 x 76.50

191.00

PLAN VIEW

PUSHER TUG "VULCAAN I" WITH 2×2 E II BARGES

BARGE TRAIN

2.80

SIDE VIEW

2.50

11.90

99.90

60.00

80.00

9.50

PLAN VIEW
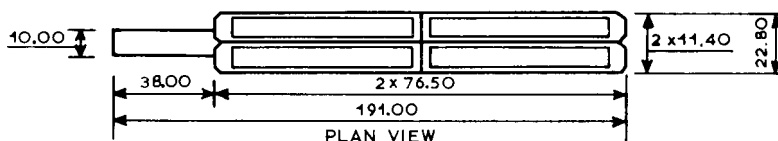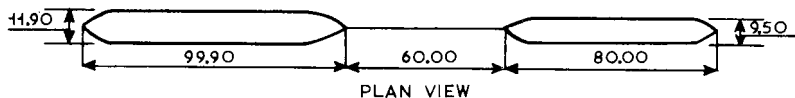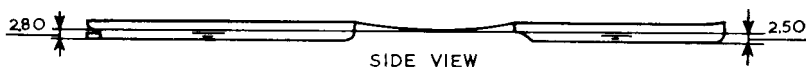
RHINE - HERNE CANAL SHIP "OLIVIER" WITH TOWING BARGE "DONALD"

SELF-PROPELLED SHIPS

SIDE VIEW

2.50

SIDE VIEW

2.50

8.20

9.50

62.00

80.00

PLAN VIEW

PLAN VIEW
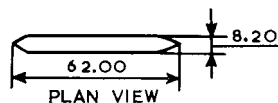
COASTER "MARCONI"
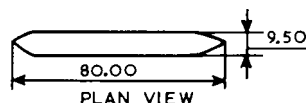
RHINE-HERNE CANAL SHIP "ADRIAAN"

Figure 6.   Principal dimensions of different types of ship.

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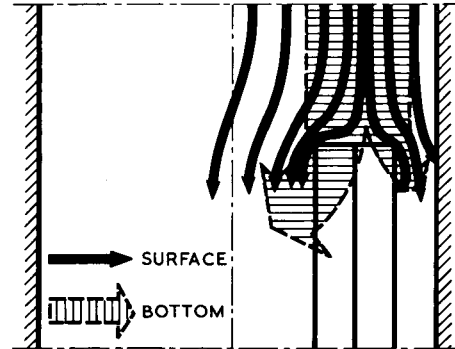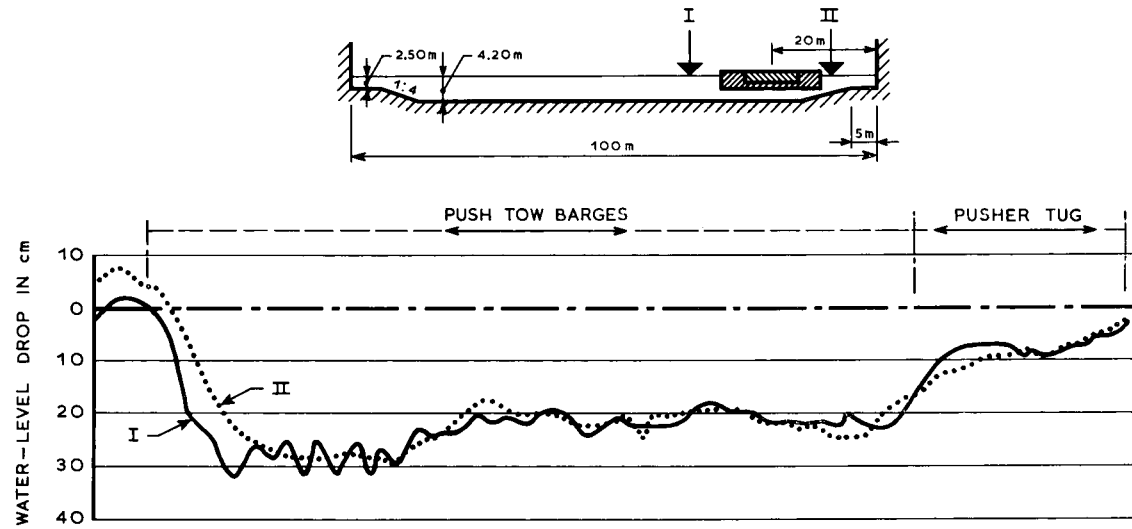
Figure 7.   Flow pattern and water-level drop around a push tow in a canal.
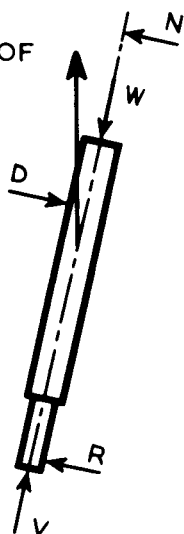
Figure 8.   Influence on drift angle of point at which canal bank force acts.
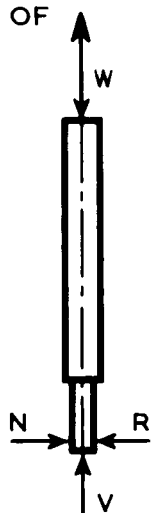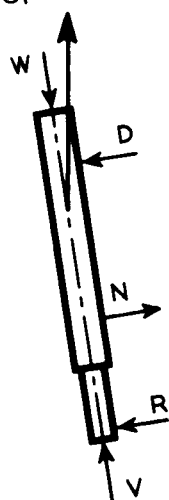
W = Resistance force   D = Drift force

V = Propulsion force   R = Rudder force

N = Canal bank force
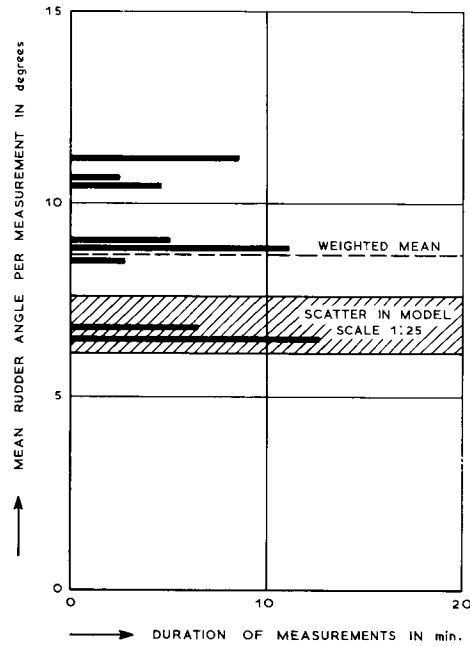
Figure 9.   Mean rudder angle and duration of some prototype measurements with width of 100 m.
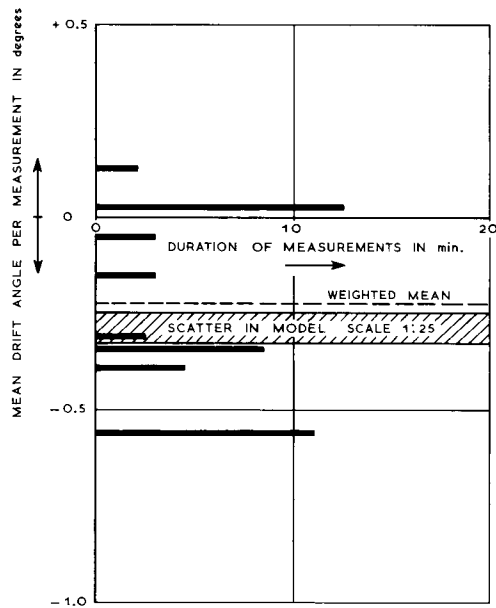
Figure 10.   Mean drift angle and duration of some prototype measurements with width of 100 m.
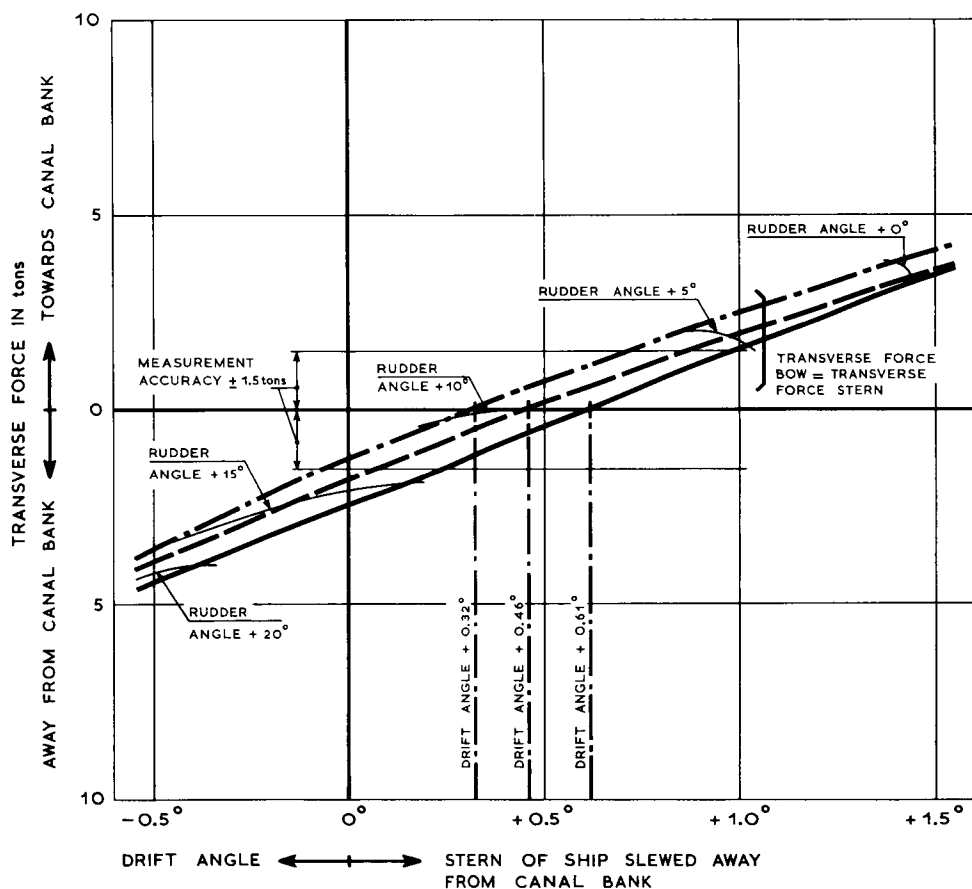
Figure 11. Transverse force bow equals transverse force stern.
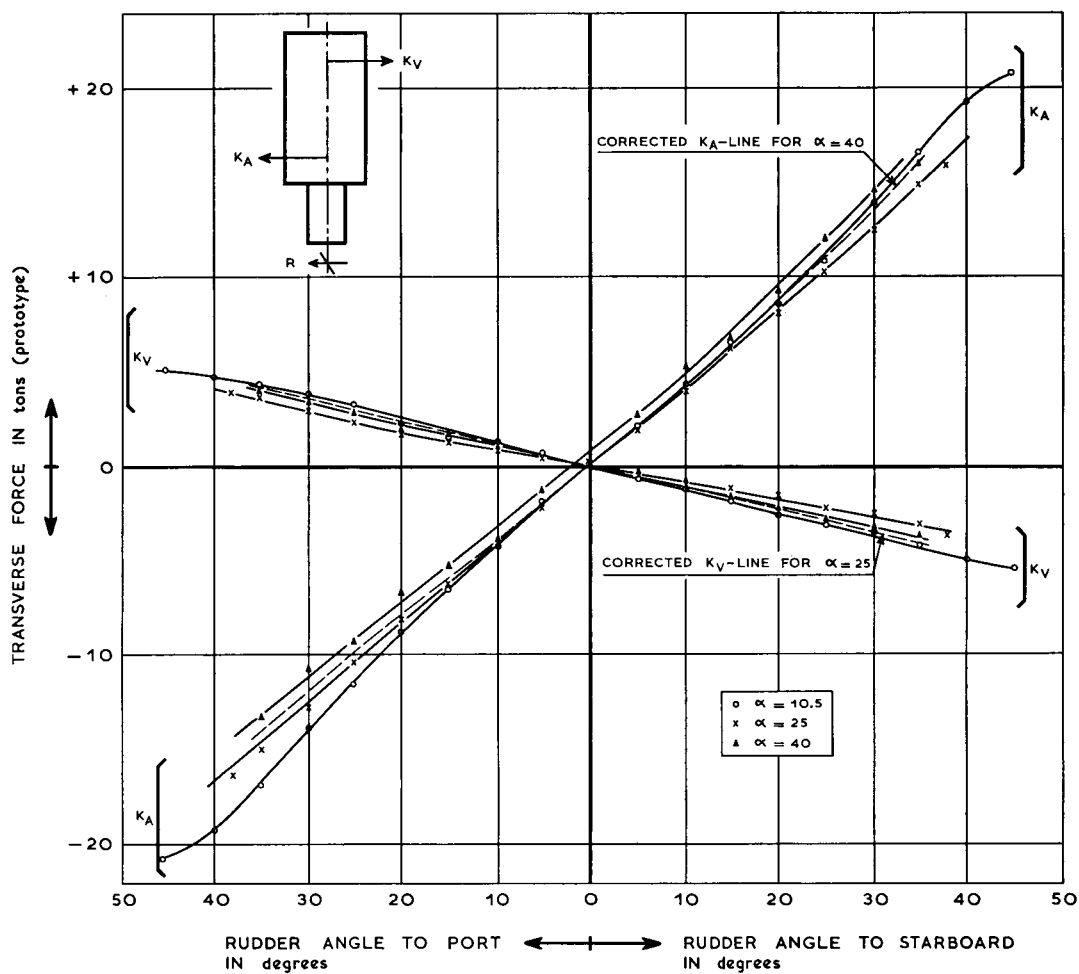
Figure 12. Initial transverse forces as a consequence of rudder deflection.

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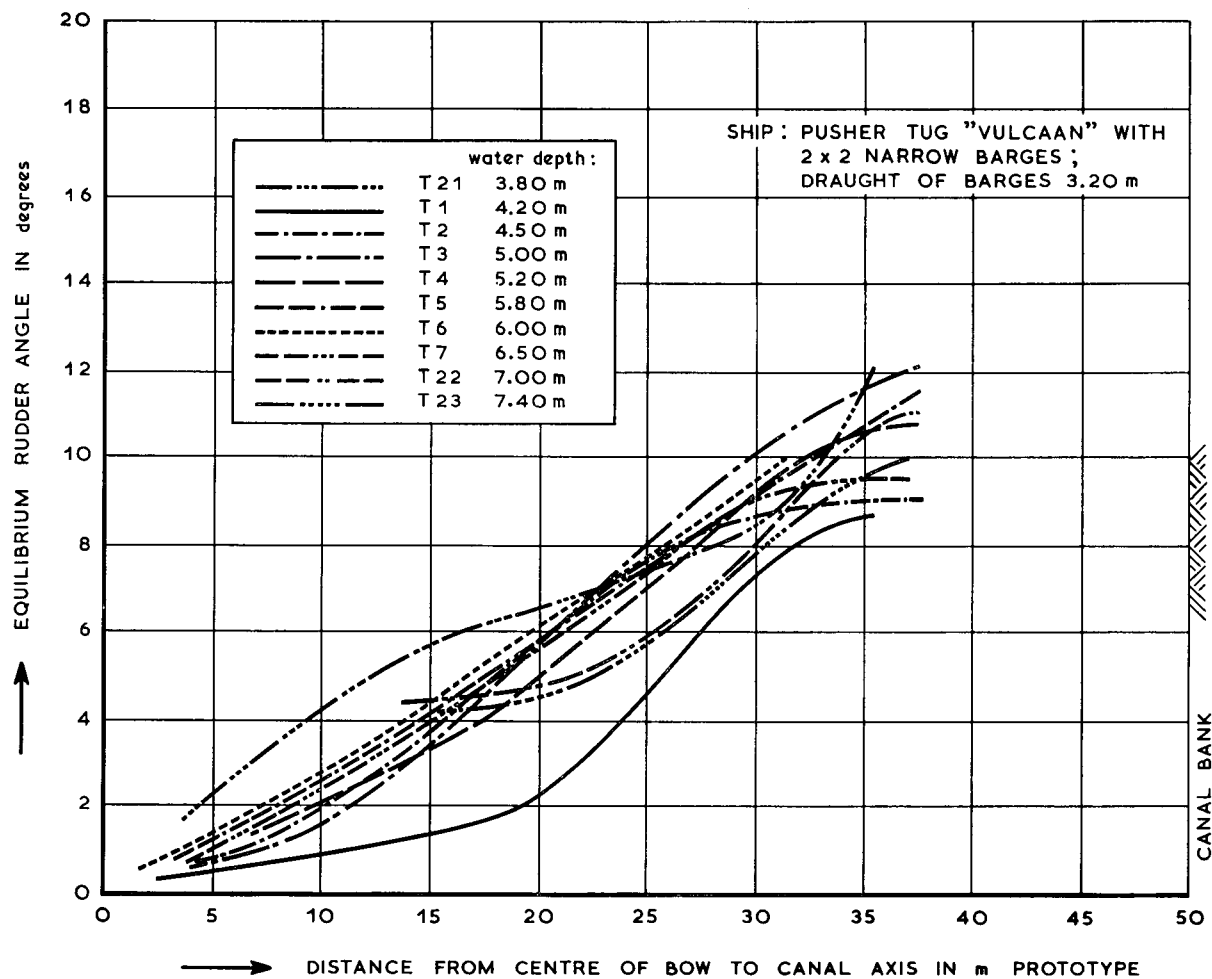
Figure 13. RUDDER ANGLE. Influence of depth (regtangular cross-section).

Figure 14.   DRIFT ANGLE. Influence of depth (rectangular cross-section).
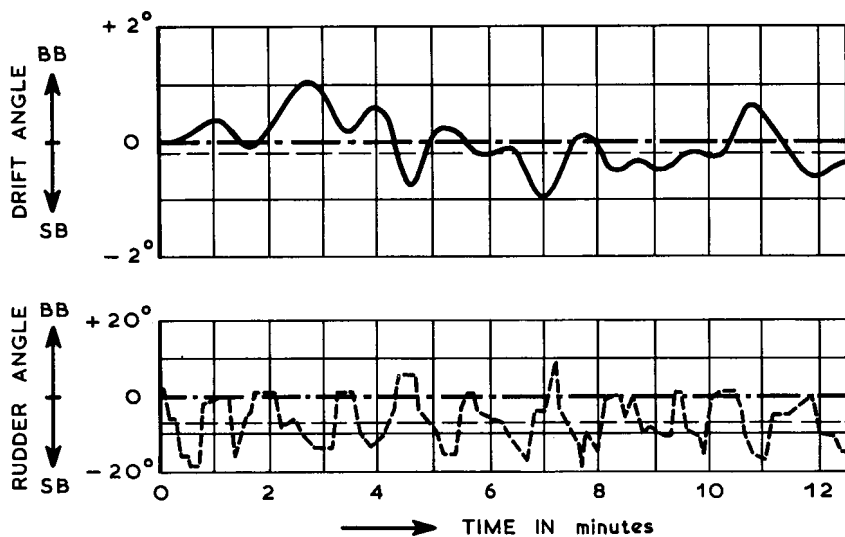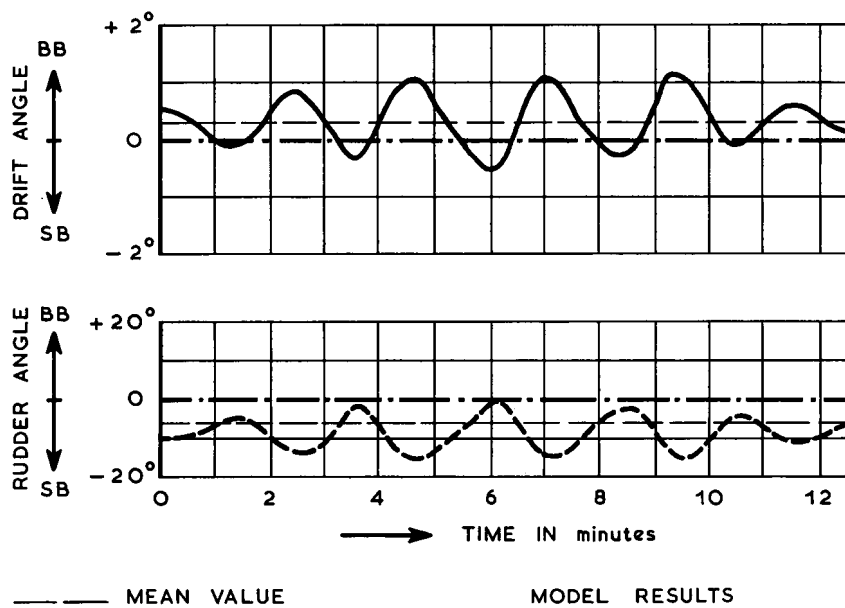
Figure 15. Behaviour of prototype push tow and model push tow with automatic steering.
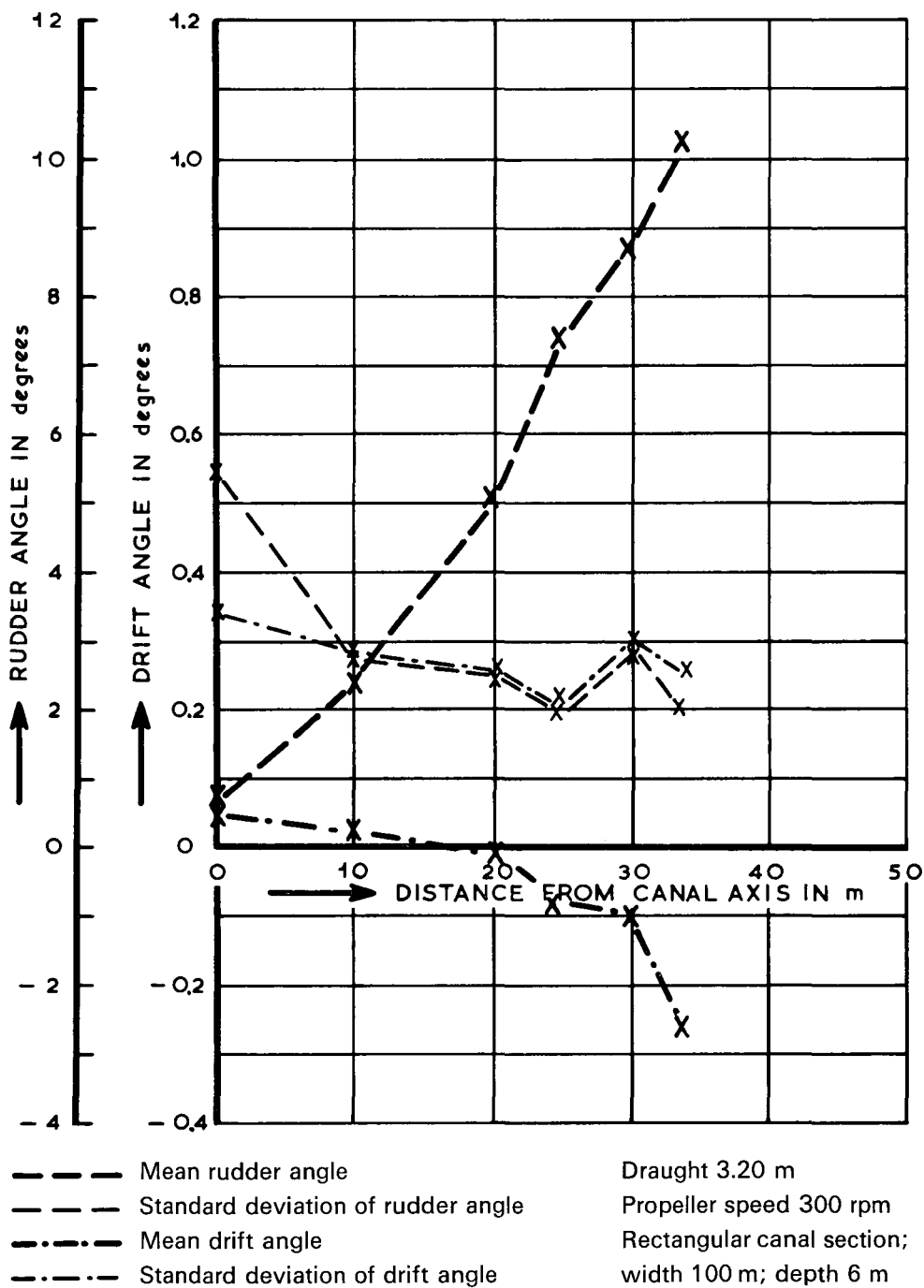
Figure 16. Dynamic equilibrium of rudder angle and drift angle as a function of distance between push tow and canal axis.

Minutes of the Netherlands Water Police dated March 22, 1966

At approximately 13.30 on 21 January 1966 the following accident occurred close to km 5 on the Amsterdam-Rhine Canal, involving:

A motor ship 'Rudolf Tiedtke'
   load capacity 1168 tons, carrying 662 tons of wheat
   dimensions: $73 \times 8.24 \times 1.92$ m
   engine: 600 hp
B motor ship 'Dirk Jan Boon'
   load capacity 745 tons, carrying 630 tons iron scrap
   dimensions: $60 \times 7.24 \times 2.10$ m
   engine: 630 hp
C tow barge 'Boezemsingel'
   load capacity: 1399 tons, carrying 1360 tons of ore
   dimensions: $80 \times 9.502 \times 2.53$ m

The initial speed of the ships was 8 to 10 kph.

After an unsuccessful attempt, the motor ship 'Rudolf Tiedtke' was again overtaking the 'Dirk Jan Boon/Boezemsingel' tow. The suction effect caused the tow barge 'Boezemsingel' to veer over instead of remaining straight. At a given moment the 'Boezemsingel' veered over so far to port that it collided with the 'Rudolf Tiedtke' although the latter was sailing well over to port. The 'Rudolf Tiedtke' was damaged in the collision.

The skipper of the tow barge 'Boezemsingel' was sailing right over to starboard before or at the beginning of the overtaking manoeuvre; this considerably increased the suction effect of the bank. In addition all the ships were sailing too fast during the overtaking manoeuvre. Subsequently the overtaking operation was completed without difficulty at very low speed. If the canal had been wider and/or deeper at this point the suction effect would have been lower.
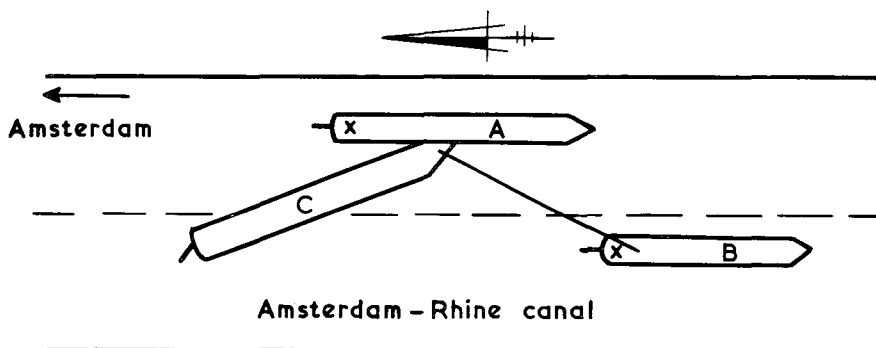
A. Motor ship 'Rudolf Tiedtke'   B. Motor ship 'Dirk Jan Boon'   C. Tow barge 'Boezemsingel'
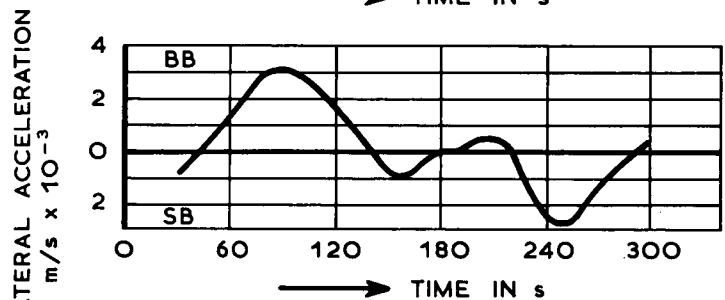
Figure 17.   Collision 4.

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Time labels: 0 15 30 45 60 75 90 105 120 135 150 165 180 195 210 225 240 255 270 285 300 315 330

TIME IN s

B−A = NAVIGATION LANE WIDTH, REAR TOW BARGE

A+C = SPACE NEXT TO NAVIGATION LANE OF TOW BARGE

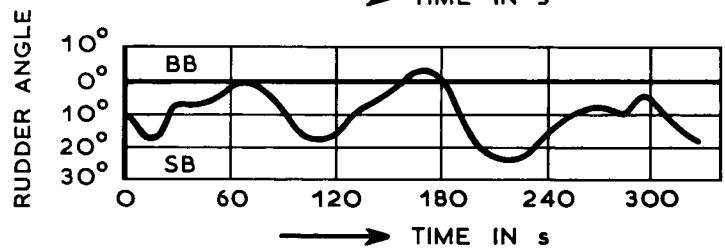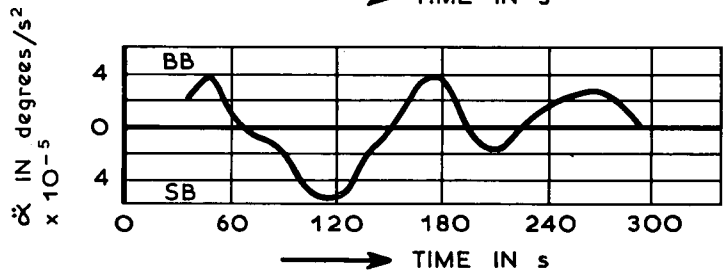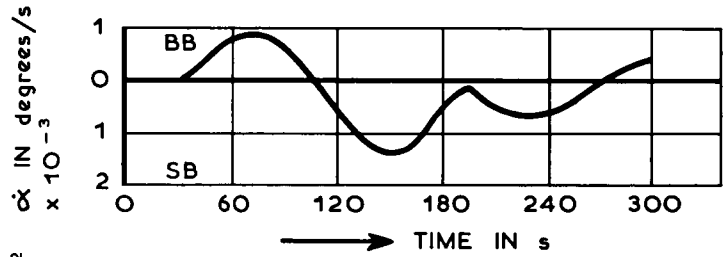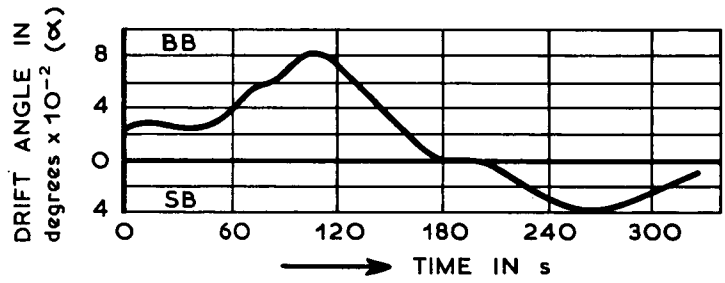RECTANGULAR CANAL SECTION
WIDTH : 100 m, DEPTH : 6 m
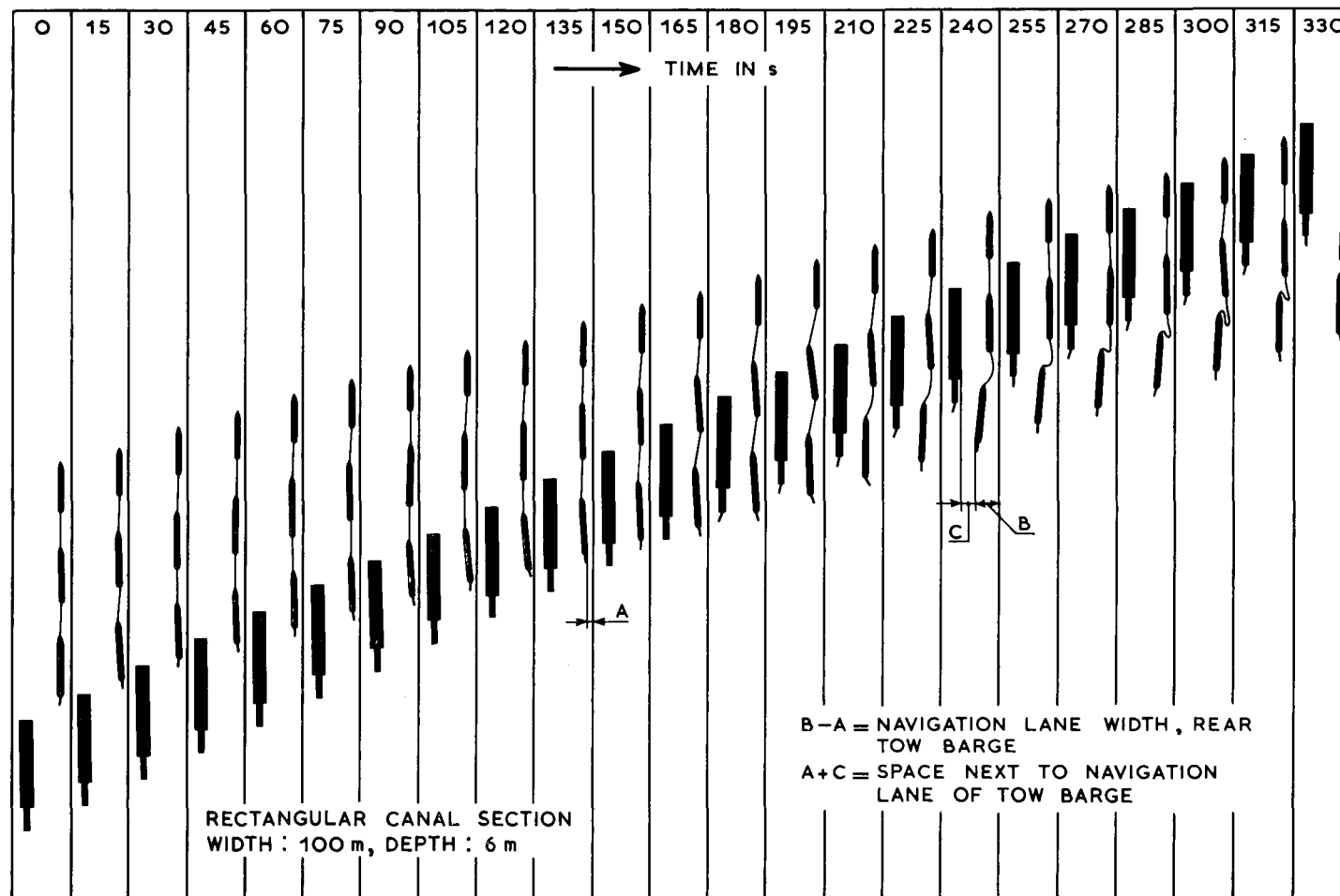
Figure 18.   Picture of ship positions (recorded photographically).

RECTANGULAR CROSS SECTION;
WIDTH 100 m; DEPTH 6m

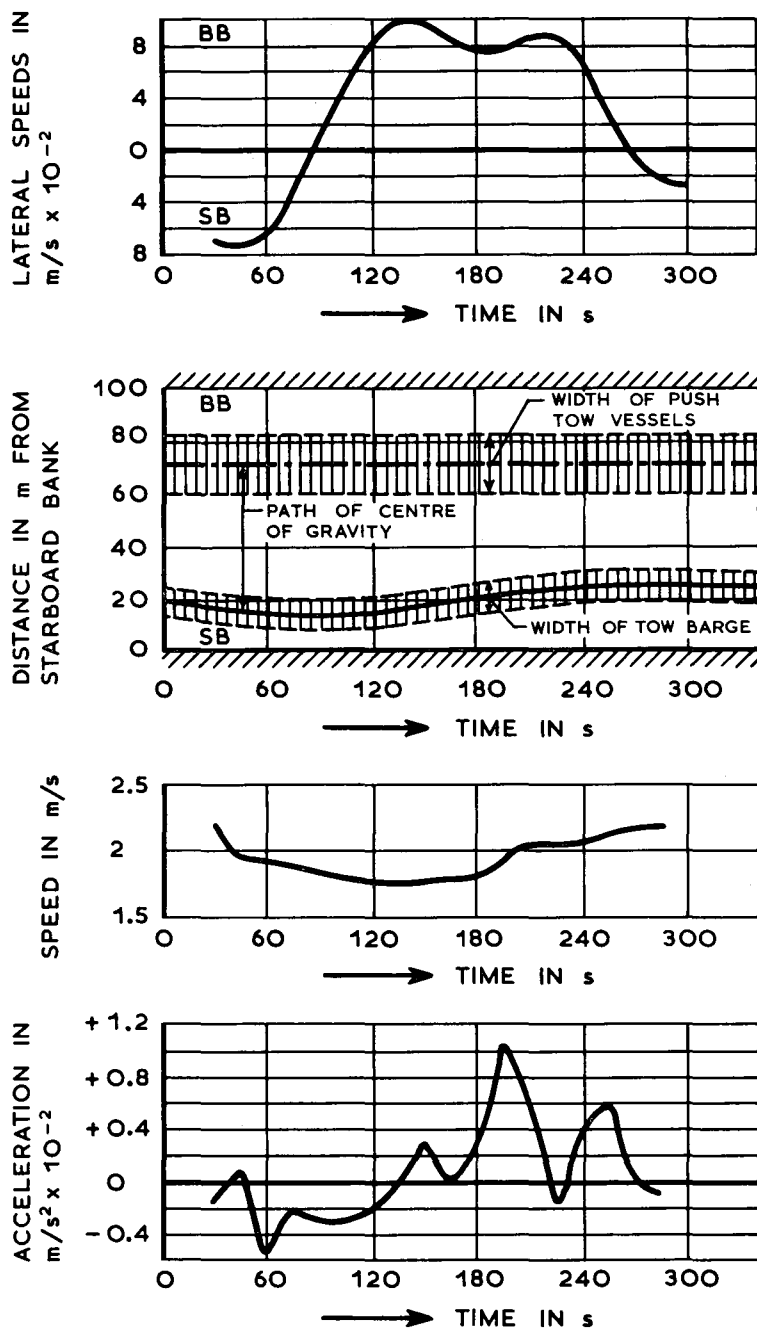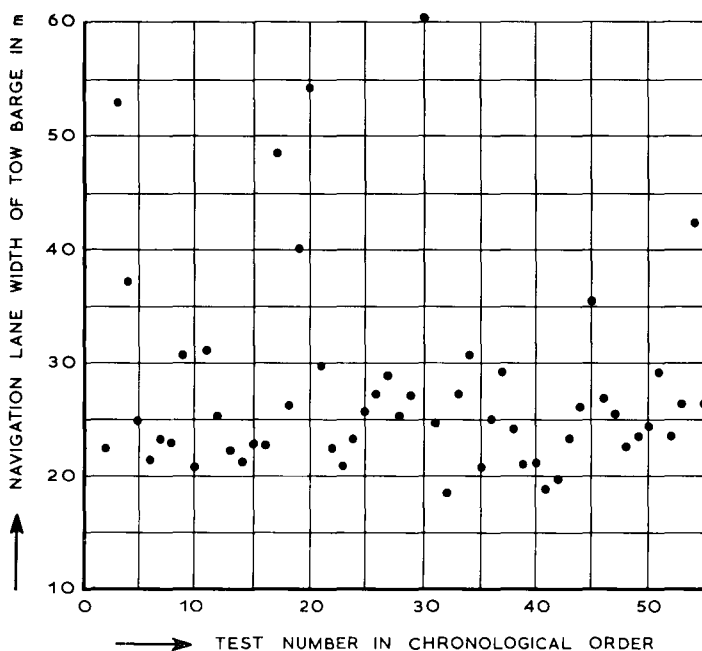Figure 19.   Results derived from positions of rearmost tow barge.

Figure 20.   Passing manoeuvre in which tow barge is overtaken by push tow.
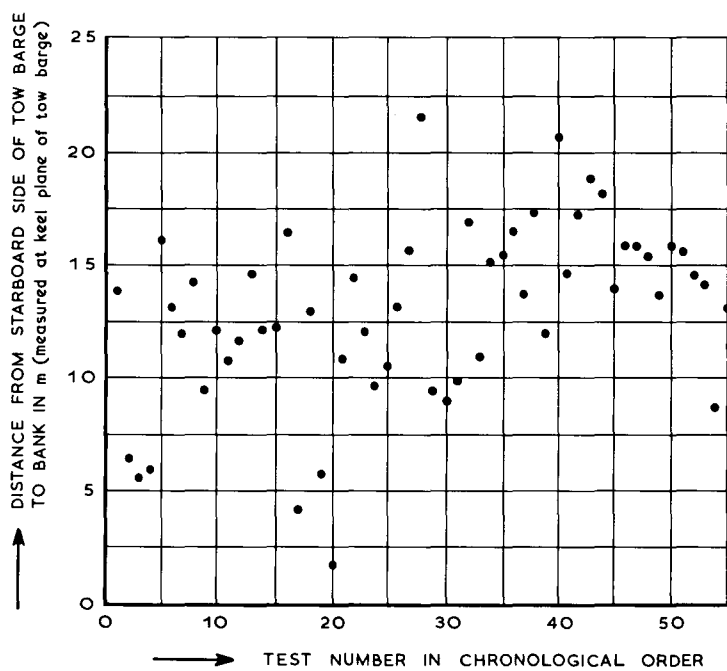
Figure 21.   Passing manoeuvre in which tow barge is overtaken by push tow.
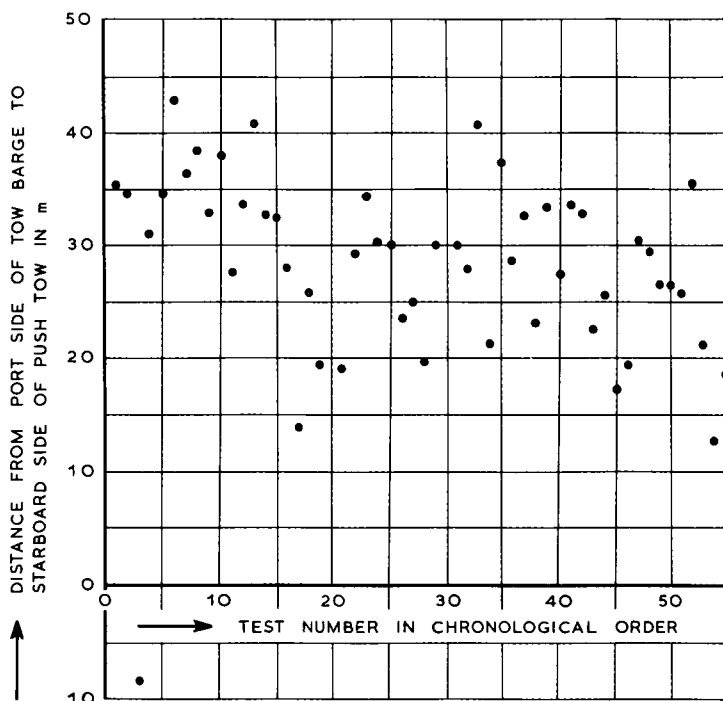
Figure 22.   Passing manoeuvre in which tow barge is overtaken by push tow.
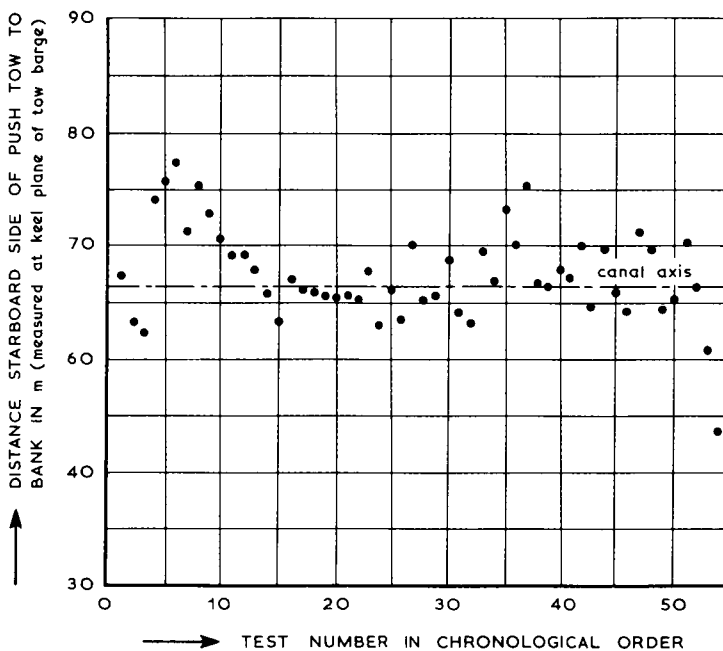
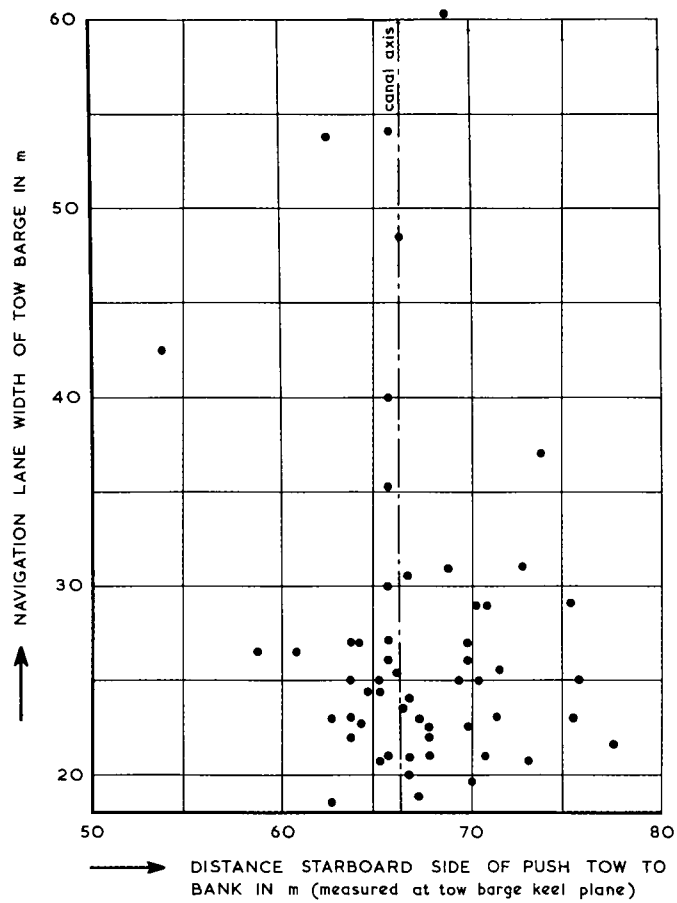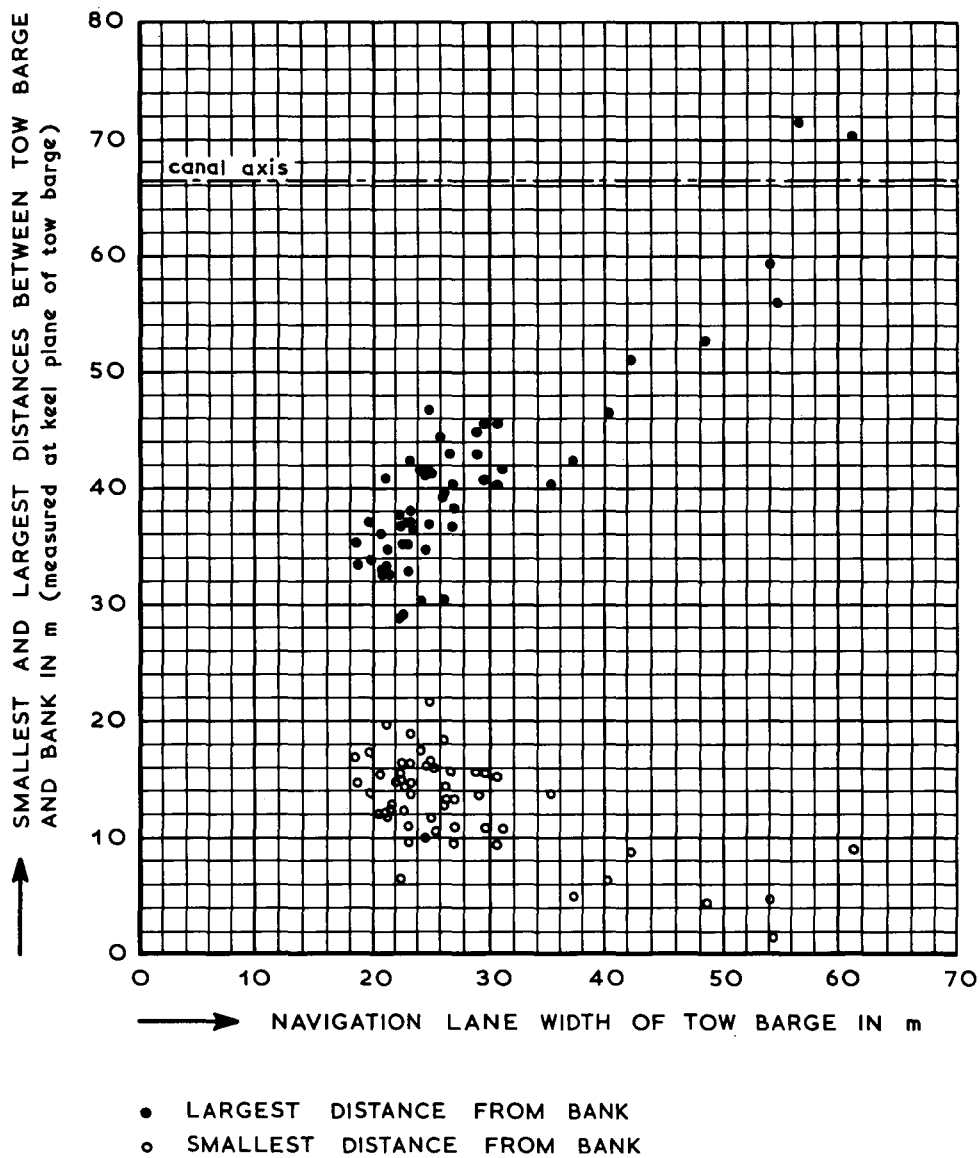Figure 23.   Passing manoeuvre in which tow barge is overtaken by push tow.

Figure 24.   Passing manoeuvre in which tow barge is overtaken by push tow.

60

Figure 25. Relationship between navigation lane width of tow barge and its distance from bank.
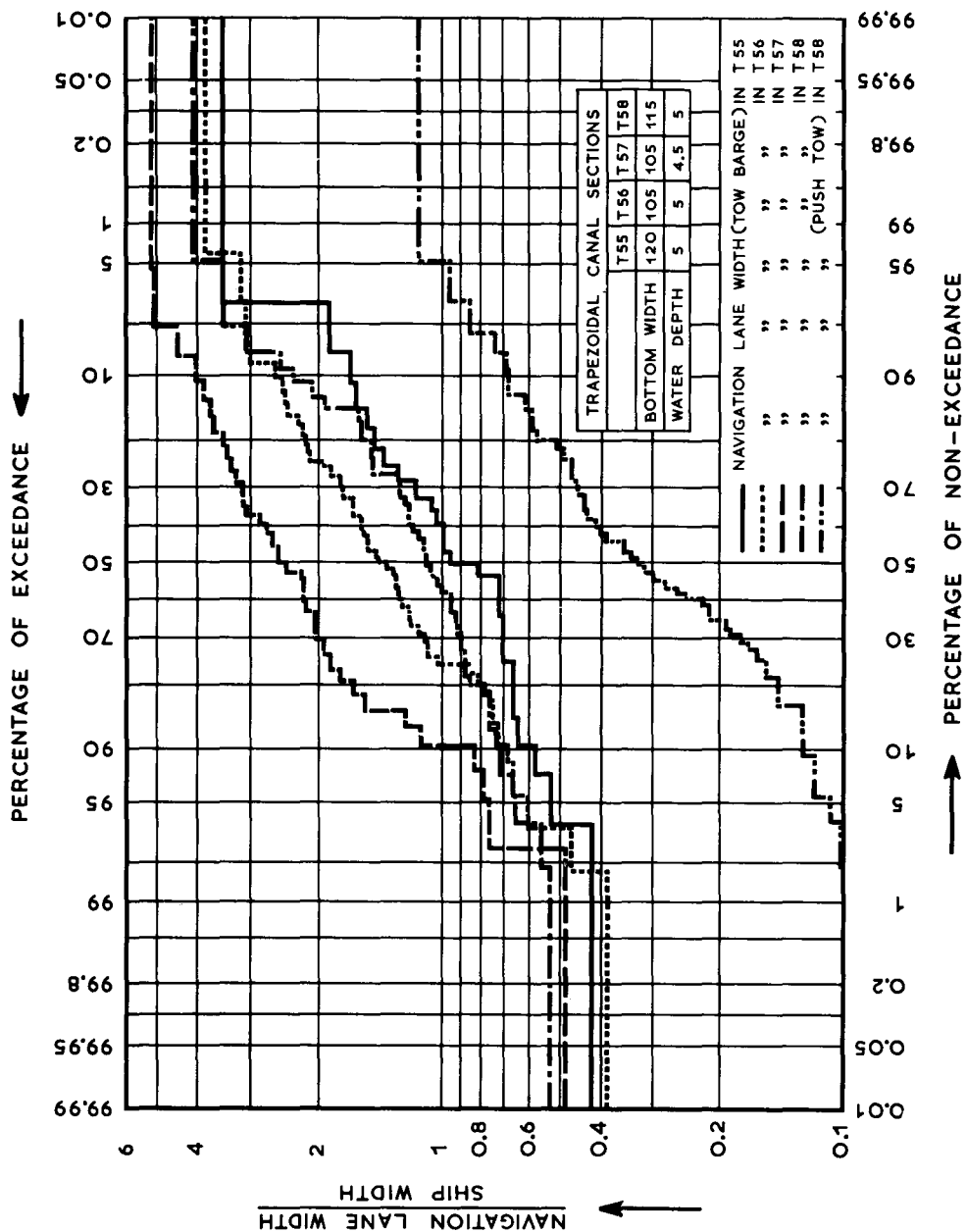
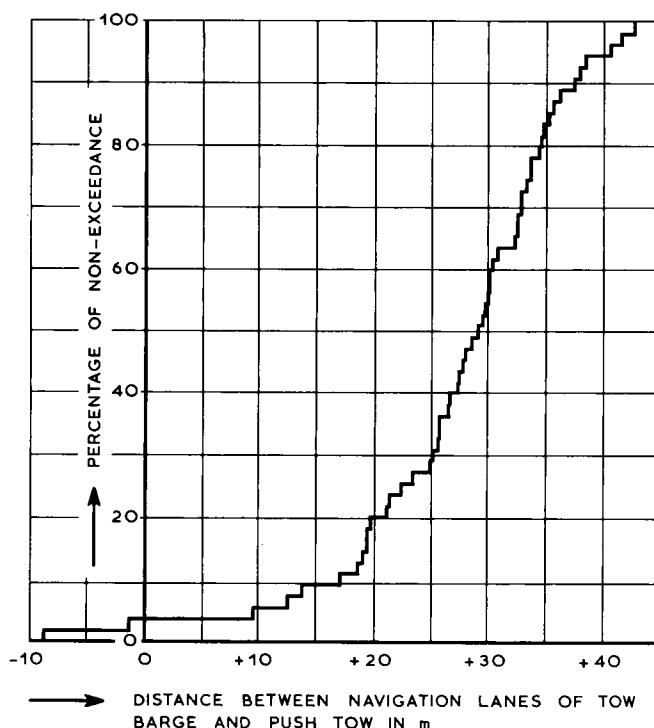Figure 26. Passing manoeuvre in which tow barge is overtaken by push tow.

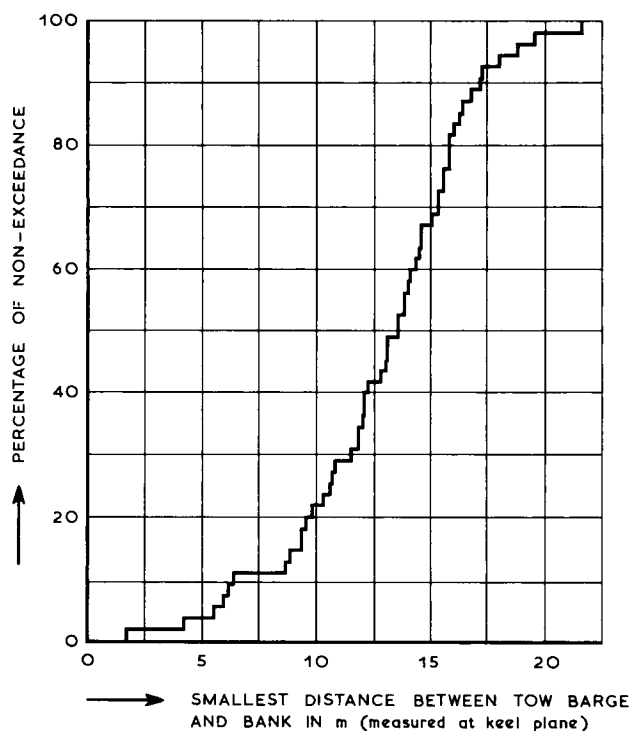Figure 27. Passing manoeuvre in which tow barge is overtaken by push tow.

Figure 28. Passing manoeuvre in which tow barge is overtaken by push tow.
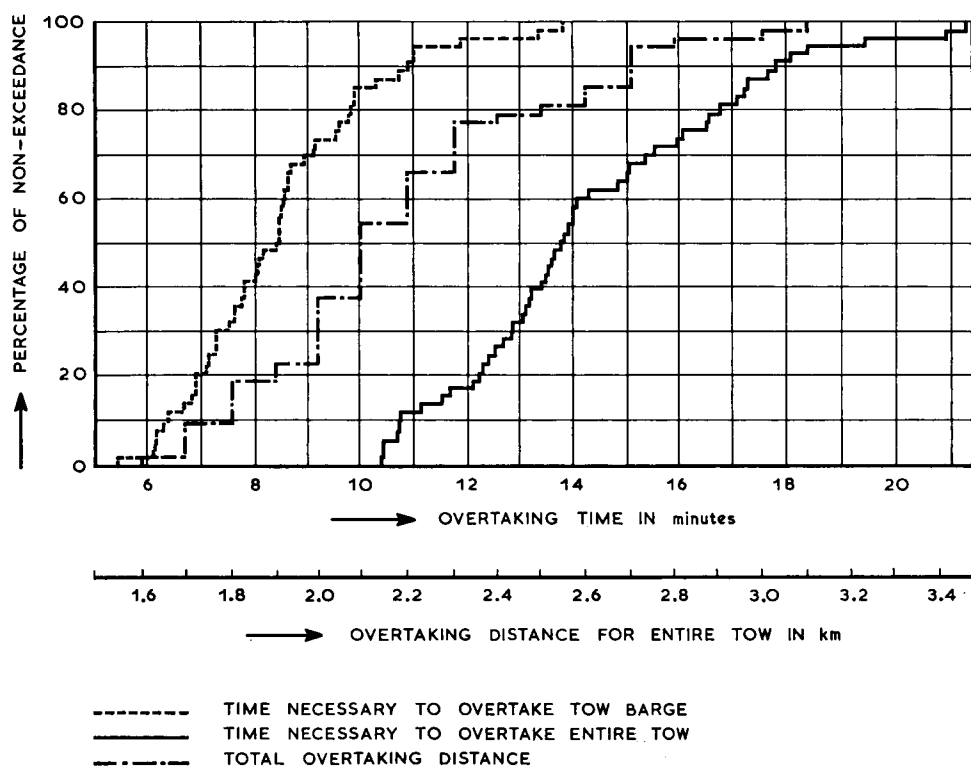
63

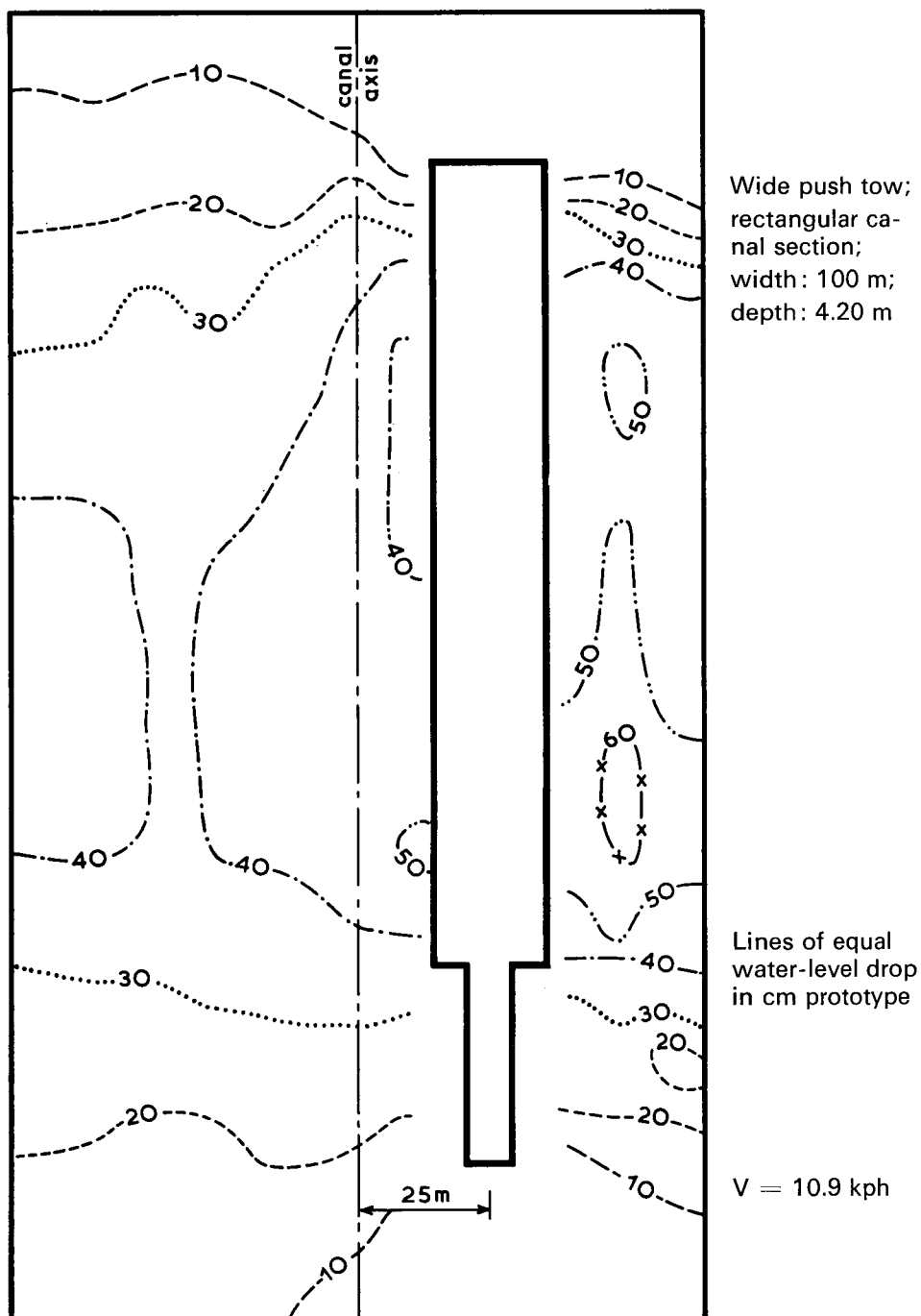Figure 29. Passing manoeuvre in which tow barge is overtaken by push tow.

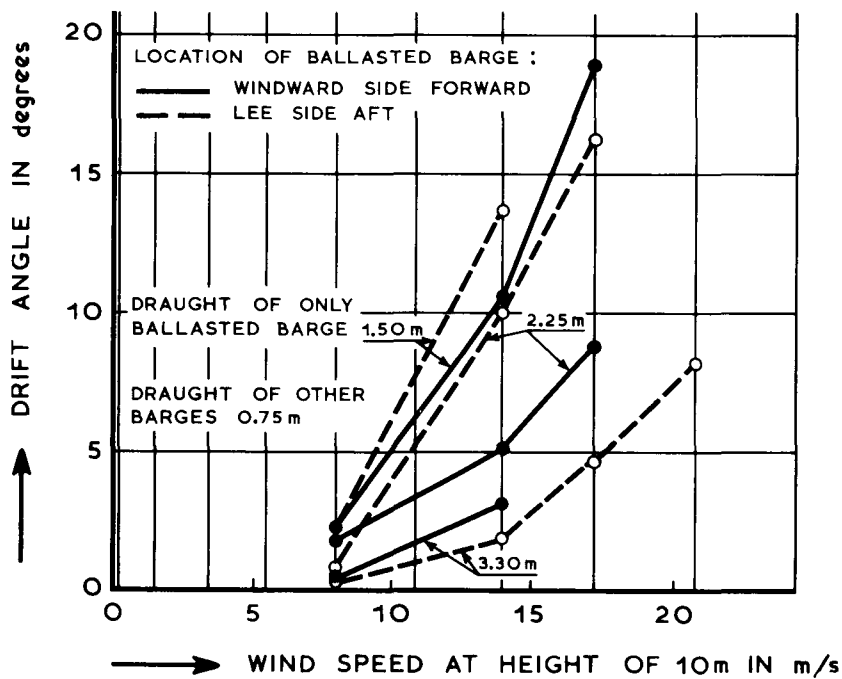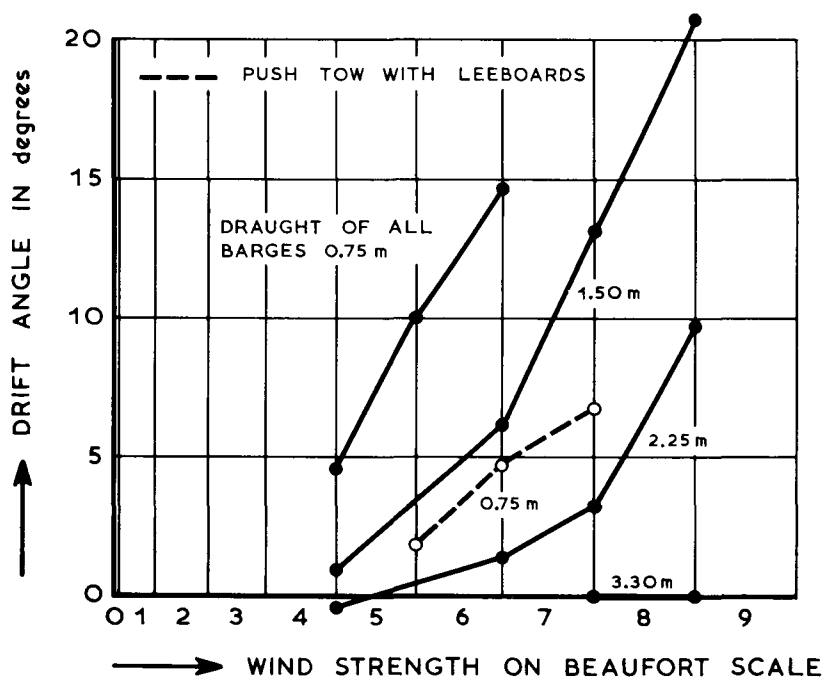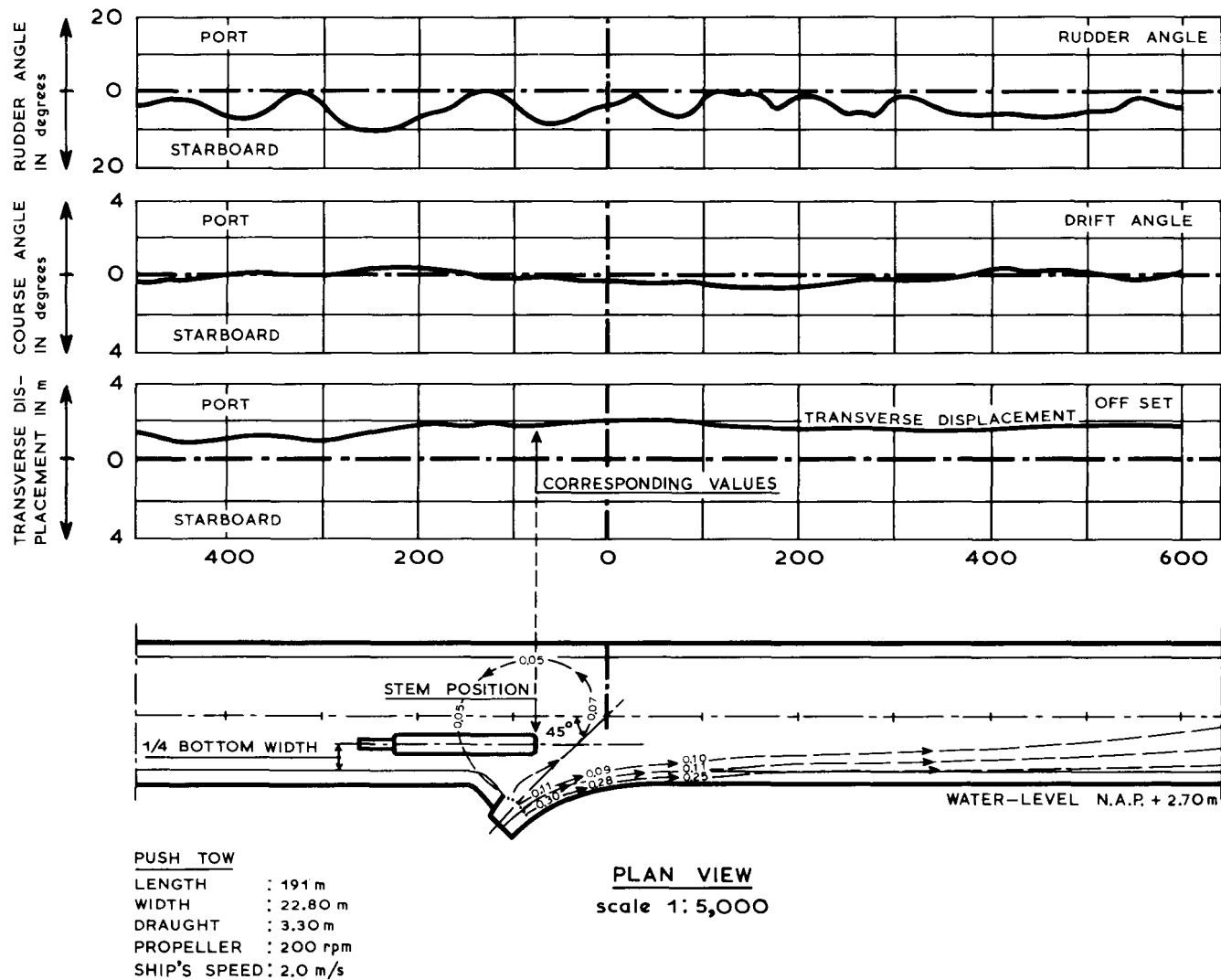Figure 30. Water-level drop around moving push tow.

Figure 31. Influence of wind and draught on drift angle.

Figure 32. Behaviour of push tow near Beuningen outlet structure ($Q = 30 \ \text{m}^3/\text{s}$).

RUDDER ANGLE IN degrees

PORT

STARBOARD

RUDDER ANGLE

COURSE ANGLE IN degrees

PORT

STARBOARD

DRIFT ANGLE

TRANSVERSE DIS-PLACEMENT IN m

PORT

STARBOARD

TRANSVERSE DISPLACEMENT | OFF SET

CORRESPONDING VALUES

400   200   0   200   400   600

STEM POSITION

1/4 BOTTOM WIDTH

45°

0.05

0.07

0.05

0.10

0.11

0.09

0.11

0.30

0.28

0.28

WATER—LEVEL N.A.P. + 2.70 m

PUSH TOW
LENGTH   : 191 m
WIDTH   : 22.80 m
DRAUGHT   : 3.30 m
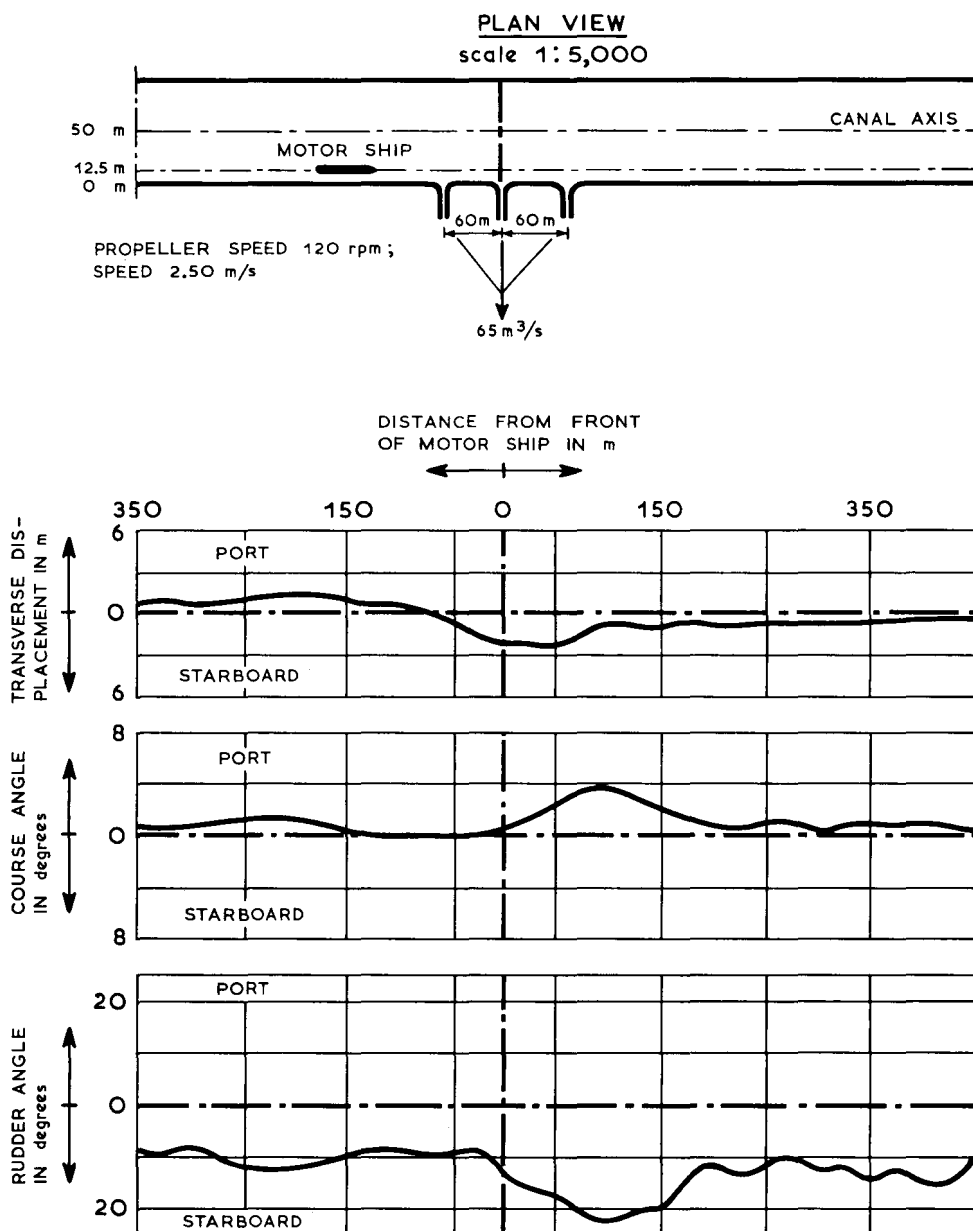PROPELLER   : 200 rpm
SHIP'S SPEED: 2.0 m/s

PLAN VIEW
scale 1 : 5,000

Figure 33. Behaviour of motor ship near Maarssen intake structure (Q = 65 m³/s).

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