Communication 1
S. I — C. 1

Etude des rapports entre, d'une part, la forme de la section transversale, la nature du sol, le système de revêtement et la répartition des vitesses de l'eau dans un cours d'eau, et d'autre part, la résistance à l'avancement, le rendement des hélices et les vitesses admissibles des bateaux, compte tenu des frais d'entretien du cours d'eau.

The relation between, on the one hand, the form of cross-section, the nature of the ground, the method of revetment and the distribution of the water-velocities in a waterway, and on the other hand, the resistance to movement, the efficiency of the screw (propellers) and the permissible speeds of the vessels in relation to the cost of the maintenance of the waterway.

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PAPER

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The Dutch canals are being used in an ever increasing degree by modern fast craft. These ships can be efficient only in so far as the canals are suited to fast navigation. The speed of navigation in a canal is for a great deal determined by the dimensions and the shape of its cross-section, and by the condition of its bank protection. Technical improvements on behalf of the speeding-up of traffic must therefore be directed to these points. Apart from this it must be endeavoured to reduce the delay at locks and other structures to the strictly necessary.

As has been demonstrated in the Dutch report for the VIIth Congress (lit. 2) a ship, propelled by means of a reaction on the water (propeller, paddle-wheel) cannot exceed a certain limit velocity regardless of the power of its engines. This also applies to a convoy consisting of a tug with one or more ships in tow. For a ship, propelled from the outside (f.i. towed from the bank) a higher velocity than the limit is theoretically possible. In that case however the water of the canal in front of the ship will be piled up and owing to this the ship will encounter an excessive resistance. The value of the limit velocity is dependent on the ratio between the beam-area of the ship and the cross section area of the canal and on the mean depth of the canal.

Owing to several reasons, as will be discussed later on, the limit velocity will seldom be attained in practice, even if a ship has the required engine capacity. Moreover there are a number of reasons that may compel the authority in charge of a canal to impose restrictions by regulation. These reasons may be the danger of erosion of the banks and the bottom of the canal due to the ship waves, the return current and the propeller-stream, the safety of the traffic and the hindrance which ships passing with too much speed may cause to ships moored along the banks, etc. It follows from these considerations that the canals have to satisfy high requirements in order to enable the inland navigation to make the most of the possibilities offered by the modern fast vessels.

In the first place they should have a large cross-section. Owing to this not only a high limit velocity is obtained, but also the resistance as well as the return velocity at an equal speed will be less. Moreover it will be possible to encounter and to overtake other ships with less loss of speed and so avoid delay.

In the second place the bank protections have to offer an adequate resistance against wave-attack, so that from this point of view the need for compulsory restrictions to the speed of navigation does not exist.

It is obvious that against the decrease of costs of the navigation effected by these means stand higher expenses for the construction of the canals. Therefore it will depend on the intensity of traffic, whether these higher expenses will be justified. One of the difficulties in considerations of this kind is that the calculations have to be based on a prognosis of the amount of traffic and this is generally an uncertain affair. The extent of future transport by water is among other things dependent on the facilities offered by the waterway.

The inland waterways in the Netherlands have been built in different periods and owing to this they do not all satisfy the same high demands. Some of the older canals are rather narrow and therefore not only inac-
cessible for the bigger craft but moreover they do not offer to smaller vessels the opportunity to run at a satisfactory speed. Nowadays they have only secondary importance. The primary waterways however are large, the passage through modern locks, bridges, etc. demands only a short time and many of the canals are open to vessels with a loading capacity of about 2000 metrical tons. The condition of the bank protection however is not everywhere sufficient to allow the skippers to choose their speed at their own judgment. The canals have for the greater part been dug in a not very firm soil, which is liable to erosion by a strong return-current. Mainly because of this reason a restriction of speed is compulsory for all canals, usually varying according to the size of the ship.

The fleet of river- and canal craft in the Netherlands is very differentiated with regard to size, which partly is due to the longevity of these ships. As a consequence of this considerable variation in size, ships of the biggest type allowed on a certain canal sometimes are found there in relatively small numbers. Therefore they are not necessarily conclusive for the depth and width to be given to a canal. In the Dutch report, issued for the XVIth Congress in 1935 at Brussels (lit. 1) have been compared for a number of canals the areas of the cross-section, of the beam of the biggest ship admitted and of the beam of a ship of average size. These data, affirm the assertion, that most of the waterways may be called large with regard to the ship of average size. Owing to this ships can pass each other on nearly every reach, whether going in the same or in opposite direction. This is necessary on the Dutch waterways, because of the variation, not only in types of vessels, but also in manner of propulsion. Fast self propelled ships (automoteurs) are met with in various sizes, but also tugs with barges in convoys of widely varying composition.

For the Netherlands, rich in water and densely populated, traffic along rivers and canals remains very important.

Traffic for the year 1951 was distributed as follows:

Tabel 1. — Distribution of traffic.

<table>
<thead>
<tr>
<th>Compared to:</th>
<th>Ship</th>
<th>Railway</th>
<th>Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In % of total</td>
<td>In % of total</td>
<td>In % of total</td>
</tr>
<tr>
<td>Number of tons transported</td>
<td>39.866.10³ 38%</td>
<td>16.128.10³ 15%</td>
<td>49.900.10³ 47%</td>
</tr>
<tr>
<td>Number of ton kilometers</td>
<td>3.933.10³ 52%</td>
<td>2.460.10³ 32%</td>
<td>1.248.10³ 16%</td>
</tr>
<tr>
<td>Average distance of transport</td>
<td>98.5 km</td>
<td>152.5 km</td>
<td>5 km</td>
</tr>
</tbody>
</table>

The variation in kind and size of the vessels is to be seen from the next table.
Tabel 2.—Composition of the Dutch fleet for inland navigation on 1st January 1951.

A. Classification according to loading-capacity.

<table>
<thead>
<tr>
<th>Tonnage Class</th>
<th>Number</th>
<th>Loading-capacity in $10^3$ tons</th>
<th>Transported load in 1950 in $10^3$ tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 - 100 tons</td>
<td>7.833</td>
<td>444</td>
<td>7.196</td>
</tr>
<tr>
<td>100 - 200 »</td>
<td>4.184</td>
<td>555</td>
<td>7.297</td>
</tr>
<tr>
<td>200 - 400 »</td>
<td>2.020</td>
<td>565</td>
<td>6.145</td>
</tr>
<tr>
<td>400 - 600 »</td>
<td>1.358</td>
<td>684</td>
<td>6.267</td>
</tr>
<tr>
<td>1000 - 1500 »</td>
<td>968</td>
<td>749</td>
<td>4.500</td>
</tr>
<tr>
<td>600 - 1000 »</td>
<td>587</td>
<td>751</td>
<td>2.032</td>
</tr>
<tr>
<td>1500 »</td>
<td>272</td>
<td>543</td>
<td>1.182</td>
</tr>
</tbody>
</table>

B. Classification according to manner of propulsion.

<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>Loading-capacity in $10^3$ tons</th>
<th>Transported load in 1950 in $10^3$ tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Towed barges</td>
<td>6.457</td>
<td>2.916</td>
<td>16.718</td>
</tr>
<tr>
<td>Steamships</td>
<td>150</td>
<td>42</td>
<td>70</td>
</tr>
<tr>
<td>Motorships</td>
<td>6.631</td>
<td>899</td>
<td>12.834</td>
</tr>
<tr>
<td>Ships pushed by motorboat</td>
<td>1.858</td>
<td>183</td>
<td>2.022</td>
</tr>
<tr>
<td>Ships with side-propeller</td>
<td>966</td>
<td>166</td>
<td>2.418</td>
</tr>
<tr>
<td>Sailing craft</td>
<td>1.091</td>
<td>78</td>
<td>440</td>
</tr>
<tr>
<td>Sailing craft with auxiliary motor</td>
<td>69</td>
<td>7</td>
<td>116</td>
</tr>
</tbody>
</table>

The existing waterways are still being improved, the possibilities being however often restricted by the intensive use of the banks for road-traffic, storage and establishing of industries.

In such cases the problem is to decrease with all available means the ship-resistance on passing through a canal with a given width of the watersurface.

2. FURTHER DISCUSSION OF THE THEORY.

In the Dutch report for the XVIIth Congress (lit 2) the water motion caused by a ship in a canal has been investigated along a theoretical way, making use of a few simplifying assumptions. The most important simplifications were:

- the return flow was supposed to be distributed uniformly over the cross-section of the canal;
- the repression of the waterlevel was taken to be the same over the entire width of the canal;
it was assumed that the ship at the place of her greatest beam-area follows
the depression of the waterlevel; the friction of the return flow along the bottom and the sides of the canal
was neglected.

By means of this approximative theory the existence of the before
mentioned limit velocity can be demonstrated.

It also appeared to be possible to calculate the amount of the depression
of the waterlevel and of the return flow. This has been elaborated in the
report of 1949 (lit 2) in the form of a number of graphs. (fig. 1 and 3).

The results of the calculations have been compared with model-tests
and with observations in practice. They corresponded well with regard to
the occurrence and value of the limit velocity. The settling of the ship due
to the depression of the waterlevel appeared from the observations in prac­
tice to be greater than could follow from the calculation.

The results of the approximative theory have now been further elabor­
atated, which makes it possible to formulate the conclusions more clearly.
Moreover a number of data from experiments on models and in practice
have become available, which have been used for a more detailed verifica­
tion of the theoretical findings.
21. CONTINUED ELABORATION OF THE THEORETICAL RESULTS.

Symbols used:

F. cross section of the canal,

h. average depth of the canal (cross-section: width at waterlevel),

f. beam area of the ship,

v. velocity of the ship with regard to the water,

s. velocity height associated with v,

z. depression of waterlevel,

u. velocity of return flow,

su. velocity height associated with u,

v. limit velocity of the ship.

In figures 1 and 3 of the report 1949 (lit 2) the results of the approximative theory are summarised in the form of diagrams with the coordinates f:F and s:h, in which curves of constant values of z:s resp. su:h are drawn. It has appeared preferable in practice to make use instead of the quantities s:h, z:s and su:h of v:vgh, z:h and u:vgh. Diagrams for reading z:h and u:vgh are constructed in figures 1 and 2. They provide more direct cal-

Calculations and therefore a clearer insight than the older diagrams. In both of the diagrams for each value of f:F the limit velocity can be found directly. Moreover in both of the diagrams the curve, corresponding with a velocity of 0.9 times the limit velocity, has also been drawn.
211. Influence of enlarging the cross-section.

The limit velocity is again given in fig. 3, as well as the associated values of $z:h$ and of $u:\sqrt{gh}$. In this diagram can be read in the first place in what degree the limit velocity increases by diminishing the ratio $f:F$, in other words what effect enlarging the cross-section of the canal has for speeding up the traffic. As long as the enlarging is effected by increasing the width only, the average depth $h$ does not change or at least very little. In that case the increase of $v_{1:}\sqrt{gh}$ with decreasing $f:F$ is a direct measure for the increase in possible speed. The diagram shows that in this case the depression of the water-level, to which the attack on the revetment as well as the resistance felt by the ship are in direct proportion (this is discussed in par. 223), remains practically the same: the proportion $z:h$ reaches a maximum of 0.192 when $f:F = 0.23$ and shows a substantial diminution only when $f:F$ becomes very small. The return-velocity however decreases owing to the enlarging of the cross-section, not withstanding the corresponding greater speed of ships and therefore the danger of erosion of the banks and the bed diminishes.

Enlarging the cross-section by increasing the depth is more effective with regard to speeding up navigation than enlarging by increasing the width. An increase of the depth also means increase of $\sqrt{gh}$, as a result of which the same value of $v_{1:}\sqrt{gh}$ means a greater value for $v_{1}$. This is shown in fig. 4. The drawn curves represent the values of the limit-velocity $v_{1}$, with the corresponding depression of water-level $z$ and return velocity $u$ for a ship with a beam-area $f = 20$ m$^2$ in a canal of trapezoid
cross-section with a depth of 3.5 m and slopes at 1 in 3, when the width at waterlevel is varied from 30 m to 85 m. As abscissa has been taken the area of the cross-section F. The increase in width has as a result an increase of the limit velocity, whereas the depression of the waterlevel remains nearly constant. The return velocity gradually diminishes.

For comparison is also shown for five values of surface width, i.e. 30-40-50-60 and 70 m, what results deepening the canal would have. For the greatest depth is taken 5 m. It appears that with an equal increase of F — thus at equal quantities of earth removal — deepening has a greater effect in increasing the limit velocity than widening. The greater effect as regards limit velocity is accompanied however by an increase of the depression of the waterlevel, whereas the return-velocity does not change appreciably.

212. Influence of restricting the speed of ships.

Up till now only the limit velocity has been considered. However, as will be discussed in par. 321, ships rarely run at limit velocity. Therefore it is important to consider the influence of a lower speed. Although this may be seen from figures 1 and 2, a clearer insight is obtained with the aid of fig. 5. This diagram presents for a number of values of f:F, in its lower half the relation between \( v: \sqrt{gh} \) (abscissa) and \( z:h \) (ordinate) and in the upper half the relation between \( v: \sqrt{gh} \) and \( u: \sqrt{gh} \). For each value of f:F the speed can not exceed the limit velocity \( v_l \) for that value f:F. Both halves of the figure are therefore limited by the line \( v=v_l \). The curves for \( v=0.95 v_l \), resp. 0.9 \( v_l \), resp. 0.8 \( v_l \) are also drawn.

It is evident that, when following a curve of constant f:F the velocity approaches the limit, \( z:h \) as well as \( u: \sqrt{gh} \) grow rapidly, even to such a
degree, that as long as the speed of the ship does not exceed \(0.9 \, v_l\), the depression of the waterlevel is less than half of that at the limit velocity. The return velocity in that case remains below two thirds of the value at limit velocity and with small values of \(f:F\) also below half that value.

Figure 5: \(z:h\) and \(u:\sqrt{gh}\) as functions of \(f:F\) and \(v:\sqrt{gh}\)

22. MORE DETAILED TESTING OF THEORETICAL RESULTS.

When the report for the XVIIth Congress was prepared only a limited number of data was available for testing the results of the approximative theory. These data confirmed the existence of the limit velocity and also roughly its calculated value. Concerning the depression of waterlevel, the calculated values tallied reasonable well with the results of model tests with a towed ship. However observations in the field with a self-propelled ship, of which the variations of the trim were measured at different speeds, showed the rear of the ship to settle considerably more than the calculated depression. We have therefore proposed, in applying the theory to multiply the calculated depression of waterlevel with a factor 1.4 for the sake of safety. The reason for the difference was sought in the local influence of the propeller on the flow pattern.

After the report 1949 had been finished, more data have become available. They are partly derived from model tests in the Dutch Naval Research Station (lit 3) and in the David Taylor Model Basin (lit 4), and
partly from observations in the field. The latter have been taken in canals in the North east of the Netherlands and in the Amsterdam-Rhine canal. also the result of a single observation on the Suez-canal was received. In all cases self-propelled ships (screw) were concerned.

221. Limit-velocity.

As a result of the observations in the first place the existence of a natural limit-velocity for a self-propelled ship has again been confirmed. In a few of the model tests the calculated limit has been closely approached, but never exceeded. In this connection a number of tests on the reach Jutphaas-Wijk bij Duurstede of the Amsterdam-Rhine canal are of particular importance. Five ships have been run at full engine capacity in order to verify the limit velocity as well as to investigate the behaviour of the ships under these conditions.

The results of these tests are shown in fig. 6. Three of the ships could not attain the limit velocity. In each case the ship kept responding to increase of power by an increase in speed, so that it is reasonable to assume that with an engine of greater power the ship would have run at a somewhat greater speed yet. With the Annie and the Rooswijk the calculated limit speed was reached, with the latter even slightly exceeded. This has also been the case during the tests with the Brunings in the Wilhelmina-canal, described in the Report 1949. As explained in that report it is possible to surpass the limit slightly owing to the action of the bed-friction of the return-flow. Also slight measuring inaccuracies may be involved. The Annie as well as the Rooswijk had already attained their greatest speed before the full engine capacity had been applied, so that with these ships there is no doubt that the greatest speed actually is the limit-velocity.
222. Depression of the waterlevel.

The results of all observations where the depression of the waterlevel was measured have been collected in fig. 7. Here the quotient \( \varphi \) of the measured depression to the calculated depression is taken as ordinate with as abscissa the ratio of actual-speed to limit velocity. Except at the observation in the Suez-canal where the settling of the rear of the ship has been measured, the depressions of the waterlevel have always been measured near the bank, at the observation in the Panama-canal (model) also near the ship. The observations of lit. 3 and in the Dutch canals apply to canal ships of current types, those in the Suez- and Panamanacanal to oceangoing vessels.

From the latter data as well as from a number of visual observations it is concluded, that the depression of the waterlevel is not uniform over the entire width of the canal as has been assumed in the calculation. The depression is deepest near the ship and less near the bank. The difference will be the greater as the canal is relatively wider.

On account of a number of observations, where the depression of the waterlevel as well as the settling of the rear of the ship was measured, the impression has been received that the latter value roughly corresponds with the depression of the level near the ship, but may also be still more. This is probably influenced by the shape of the rear part of the vessel and by the pattern of the flow to and from the propeller.

Of the results gathered in fig. 7, those of the field observations show the greatest dispersion. They vary from 0.93 to 1.56. The points derived from model tests are considerably closer together. In general \( \varphi \) seems to show a tendency to increase when the limit velocity is approached, which however was not the case with the data from the Brunings observations.
The new results, with the generally considerably lower values of $\varepsilon$ than with the Brunings indicate that this ship is not representative for the current types of vessels.

On the strength of fig. 7 we think it may be put that for calculating the depression of the waterlevel near the bank a value of the factor $\phi$ of 1.0 to 1.4 should be taken and for the settling of the ship 1.2 to 1.6. For a stream, lined hull the deviation from the theoretical value will be small and therefore $\varepsilon$ will be near to 1. It should be observed that in lit. 4 it is stated that in the case of a towed ship the depression of the waterlevel is from 8 to 15% less than in the case of self-propelled ships.

223. Connection between depression of waterlevel and resistance.

In the model tests, described in lit. 3, the resistances have also been measured. Because the resistance of the test models in free water was measured as well it is possible to determine directly the additional resistance when running in the canal. In order to obtain a clear picture for each speed the resistance in free water $W_0$ has been deducted from the resistance in the canal $W$. The difference has been divided by $W_0$. The quotient thus obtained $(W-W_0) : W_0$, the relative additional resistance, has been presented in fig. 8 with the ratio actual speed to limit velocity as abscissa. The (measured) values of $z : s$ are also drawn.

![Figure 8](image)

It is obvious from the diagram that the additional resistance may be considerable; it even may amount to thrice the resistance in free water at the same speed.

Both groups of curves rise roughly parallel as the limit velocity is approached. Evidently the disturbance of the surface, characterised by the depression of the level, may be considered as a measure for the additional resistance encountered by the ship. It can be observed that model 91 having the highest values for the resistance, also as may be seen from fig. 7,
shows the highest values of \( z \), an illustration of the thesis that ships of better design will cause less erosion at the same speed.

3. ADDITIONAL FACTORS AND CONSIDERATIONS.

31. CURRENT IN THE CANAL.

In the foregoing it is tacitly understood, that in the canal the water is originally at rest. When this is not the case, the considerations and diagrams keep their validity, provided that for \( v \) is taken the speed with regard to the water (in reality ships running against the current will be obstructed somewhat more as a result of secondary effects, i.e. the slope of waterlevel owing to the current and the influence of non-uniform distribution of flow over the cross-section). When proceeding against the current the speed of a ship with regard to the bank is found by taking the difference between its own speed and the current-velocity. In practice the greatest travelling speed of a ship will therefore be about 0.9 \( v \) — \( w \) (\( w \) = current-velocity in the canal). Especially for relatively large vessels in narrow canals a moderate current-velocity may suffice to reduce the speed considerably. In order to avoid serious delay waterways used for transporting water should therefore be given a large cross-section, so as to increase \( v \), and to diminish \( w \). Care should also be taken to prevent bridges and other constructions from becoming serious bottlenecks. When in passing such a construction a big ship takes an important part of the cross-section, the local limit-velocity is locally increased, so that the danger is not imaginary, that a ship is unable to pass without assistance.

Example: clearance 12 m wide, 4 m deep, ship \( f = 20 \) m\(^2\). Therefore \( f : F = 0.417 \), whereby \( v_1 : \sqrt{gh} = 0.265 \), so \( v_1 = 0.265\sqrt{9.8 \times 4} = 1.67 \) m/sec.

The ship is able to pass through only if the discharge does not exceed 48 \( \times 1.67 = 80 \) m\(^3\)/sec.

With a clearance of 10 \( \times 3.5 \) m is found: \( f : F = 20 : 35 = 0.57 \), whereby \( v_1 : \sqrt{gh} = 0.16 \), therefore \( v_1 = 0.16\sqrt{9.8 \times 35} = 0.94 \) m/sec.

The maximum discharge then is 35 \( \times 0.94 = 33 \) m\(^3\)/sec. It is evident that under such conditions, the ship will encounter a considerable resistance.

In the case of a waterway, used for transporting water one should also take into account that for the determination of the velocity of flow along the walls of the canal during the passing of a ship, the return-velocity must be added to the initial current-velocity (\( W + u \)). Also from this point of view a large canal will as a rule be necessary.

32. BEHAVIOUR OF THE SHIPS.

321. Single ship.

As long as only one ship is in the canal, she will preferably keep to the centre of the canal. In that case a symmetrical current- and wave pattern is created, the main properties of which constitute the subject of the approximative theory.

Consequently, the speed of the ship cannot exceed a certain limit, no matter what the available engine capacity may be.
A great number of vessels destined for canal navigation do not possess the engine capacity, necessary to attain the limit velocity. But even if they do, when approaching the limit velocity as has been discussed in par. 223—such a strong resistance is encountered, that economic reasons (not considered compulsory speed-restrictions) prohibit, running at limit velocity, bar exceptional cases. In most conditions considerations of safety also impose a more moderate speed, especially when the canal does not offer much surplus depth. In that case the rear of a ship, nearing the limit velocity, will get close to the bottom owing to the settling. This may have a bad influence on the steering properties. This is one of the causes of «sheering out of line», a term denoting lack of obedience to the helm. In the next paragraph will be discussed a few other possible causes of this phenomenon, on which is loaded the onus of the majority of accidents.

When for whatever reason the ship is compelled to leave the centre of the canal, the flow pattern is symmetrical no longer. The deviations grow as the bank is approached closer. They cause the wave motion as well as the return velocity along the near bank to be stronger than in the symmetrical case. The hydrostatic pressures on the ship are out of equilibrium and as a result lateral forces are acting, that draw the ship bodily towards the near bank, and at the same time, try to bring about a deviation of course directed towards the centre of the canal. Running close to the bank, especially at great speed therefore requires great care. Designers and administrators of canals should try to avoid situations, in which ships have to follow a course too near a bank.

322. Towed ships.

What has been said with regard to the natural limit velocity, also holds for a ship towed or pushed by a tug or launch, but not for a ship towed from the bank.

In the latter case besides the depression of the waterlevel alongside the ship the water is heightened before the ship and lowered behind it. This might assume important proportions when the limit velocity is approached. In the Dutch canals towing of ships from the banks is practically non-existent, whereas towing by tugs as a rule is done with moderate speed.

323. Encountering and overtaking.

In encountering and overtaking ships are compelled to leave the centre of the canal. As long as they are completely or partly alongside each other, each of them undergoes, besides the influence of the vicinity of the bank, the influence of the current- and wave system of the other ship.

The motion of the water in these conditions is rapidly changing, rather complicated, and therefore difficult to analyse especially in a quantitative sense. As detailed considerations would not fall within the scope of this report, a few observations and conclusions of a more general nature will suffice.

During the encounter of two ships the two flow patterns partly annihilate each other. Also because of the short duration of the event, the difficulties experienced by the ships due to the action of transverse forces and longitudinal torques tending to change the course are relatively easy to overcome, provided that there is sufficient room. The studies on this subject on behalf
of the project of an open Panama-canal (lit. 4) have led to the formulation of the following directives: for the encounter of two ships:

- each vessel is allowed a lane of 1.7 times her greatest beam, the space between the two lanes should at least be equal to the beam of the biggest vessel;

- the space between the lane of each vessel and the near bank (to be measured at the level of the bottom of the vessel) should be somewhat more than the beam of the vessel.

In lit. 4 the encounter of a ship of 30 m beam and one of 18 m beam is treated according to these directives. A total width of the canal (at the bottom) of 180 m would be necessary. Though the experiments underlying these directives have been done with large sea-going vessels, we believe that the results of a similar investigation with fast inland craft would not greatly differ. For the encounter of two ships of 8 m beam they would lead to a width at the bottom of at least $(2 \times 1.7 + 3 \times 1) \times 8 \text{ m} = 51 \text{ m}$.

The greatest danger for encountering ships is caused by the fact, that the torque, which tends to deviate the ship from her course, changes direction several times. In a narrow canal only an experienced and vigilant steersman is able to keep his ship under control if the maneuver is executed at a fairly high speed. The varying play of forces during the encounter (as well as in overtakings) constitutes a second cause for «sheering out of line». This is especially dangerous when in busy traffic immediately after one encounter the ship is forced to go through the maneuver a second time, e.g. when encountering a tug with convoy.

Because the intensity of the forces and torques acting on the ships depends strongly on their speed — especially near the limit-velocity the forces increase considerably more than with the square of the velocity — the danger of accidents in case of encounters can be eliminated by slowing down in due time.

When a ship overtakes another one both wave and current systems reinforce each other. In particular when the difference in speed is small, the two ships keep running alongside during a long time, so that the hydrostatic forces have time to work their influence. This is the more so because the overtaking ship is slowed down automatically. Her limit-velocity is no longer determined by the full cross-section of the canal, because this also contains the slower ship. The two ships together have a limit-velocity which is derived from their total beam section and which therefore is less than the value for each ship separately. Moreover the retarding influence on the overtaking ship is accompanied by an accelerating action on the ship being overtaken. For the sake of safety it is therefore desirable that the slower ship, facilitates the maneuver by slowing down still more. In many cases this is even necessary to make overtaking possible at all.
Although skilled skippers can avoid accidents in narrow canals by careful manoeuvering, it is better to eliminate the dangers of encountering and overtaking by making larger canals. If there is a busy traffic the necessity of slowing down repeatedly means, quite apart from the danger, a serious delay for fast traffic.

4. CONCLUSIONS AND CONSIDERATIONS.

In our conclusions we will focus our attention principally on economically important and therefore much frequented waterways. For such waterways it may be stated that the economy of transport is served by creating favourable conditions for a fast navigation. The most economic transport will be obtained when the total costs of the waterways and of the traffic reach a minimum. We meet great difficulties if we try to establish calculations on this point, because the intensity of the (future) traffic plays an important part. Moreover navigation in the Netherlands does not contribute directly to the costs of maintenance on all waterways, so that the interests of the shipping may be served by creating a very ample waterway. Further it will be necessary, for such a calculation, to pay attention to the fact that the gain of time by a higher speed of navigation, sometimes is unimportant compared with the delay at bridges, locks and in ports. It is therefore not possible to set general rules for the dimensions of canals; every canal has to be considered separately and in relation with connected waterways.

Notwithstanding this, certain conclusions may be formulated which may point the way to the projecting engineer.

41. CROSS-SECTION.

In order to make fast traffic possible, the cross-section should be large. This holds even for navigation by a single ship, because a ship propelled by a reaction in the water (propeller, paddlewheel) cannot go faster than a natural limit-velocity, which is higher than the cross-section of the canal is larger. A large cross-section is even more necessary when a busy traffic causes frequent encountering and overtaking.

A large cross-section does not lead to a decrease of the depression of the waterlevel and so to a lesser wave attack on the banks, at least not in so far as the traffic makes use of the opportunity to increase their speed. The velocity of the return flow however diminishes.

When only the single ship is taken into account enlarging the cross-section by deepening the canal has more effect towards increasing the speed than enlarging the width by an equal quantity of earth removed. From this point of view a deep and narrow canal would be preferable to a shallow canal with a great width at the water level.

For a canal with a busy traffic however a rather great width is desirable with a view to the frequency of encountering and overtaking. On the strength of the very interesting American studies for the project of a new Panama Canal (lit. 4) a width at the bottom of 6 ½ times the beam of the standard type of ship appears to meet rather high requirements for the encounter of two ships of this type. The manner of construction of the canal, the design of the banks and the composition of the soil may also present reasons for preferring a wide and relatively shallow canal.

The depth has to be sufficient however to guarantee — the depression of the waterlevel taken into account — a sufficient depth under the ship.
When no regulatory speed restriction has to be observed, the settling of the ship may exceed 0.2 times the mean depth of the canal. If moreover it is stipulated that the ship must remain at least 0.5 m from the canal bottom, in many cases a surplus depth with regard to the ship in still water of at least 1.25 m will be necessary (in canals for Ocean-going navigation considerably more; in the study for the open Panama-canal (lit. 4) a depth of 60 ft is estimated desirable).

In determining the depth it will be necessary in many cases to take into account a temporary lowering of the level by translatory waves, by wind or other causes. It should be considered that an insufficient depth not only increases the resistance of the ships, but also causes the danger of insufficient rudder action (sheering out of line).

An objection against a wide cross-section may be f.i. the vast and therefore expensive earth removal necessary when the canal has to be cut deep into the ground. It will be necessary to balance the greater costs of a canal with great width at water level against the advantage of a greater freedom of movement of the ships, an advantage which is difficult to assess in terms of money. The designer of the canal will have to weigh these factors according to his own views.

The manner in which the excavation is handled can be of influence on the choice of the cross-sections of the canal, in connection with the nature of the layers of soil to be cut through.

When the excavation is executed by dry methods the drainage of the pit may be very expensive, which may lead to the choice of a shallow canal. This may also be the case when at greater depth impermeable layers are encountered, the conservation of which is advisable with a view to keep the infiltration within bounds.

When the soil consists of loose fine-grained material the cost of stabilizing the banks may be an important part of the total cost of the waterway. If in such a soil for some reason vertical walls are to be made the cost will grow considerably with the depth.

Although we have by no means been complete in stating the factors influencing the choice of cross-section, the foregoing demonstrates clearly in our opinion, that it is of no use to try to establish general rules or formulas to determine the shape of the cross-section of a canal.

In every individual case the conditions are different and therefore an independent examination will have to be made.

The only «general» rule is perhaps that the possible future need to enlarge the waterway on account of a growing traffic should always be kept in mind.

It is obvious that from this point of view a wide, relatively shallow canal has the advantage, because then the cross-section can be enlarged by means of dredging to a greater depth without affecting the banks.

42. PROTECTION OF BANKS.

In the past the protection of the banks of canals did not have to satisfy high demands. There was but little navigation, the speed was low and if necessary by regulations bound to a maximum. A sufficient protection was obtained by cheap constructions hardly satisfying reasonable requirements
of stability, but suitable to be maintained in a sufficient state of repair at low cost.

As however the size of ships increased and a greater number of rapid self propelled ships appeared this was no longer possible and the expenses for a thorough improvement of many revetments could not be avoided.

The attack on the revetment is for one part the result of the wave motion. for the other part of the return current. Except for rather small ships (f.i. with \( F = 0.05 \) and less) the wave motion, caused by ships of different dimensions, each running at the same percentage of their respective limit velocities, differs only slightly (fig. 3 and 6). If therefore the condition of the protection necessitates a regulatory speed restriction, it should apply to all ships, except small craft. The exception should perhaps not be extended to small, very fast ships, whose bow waves, though superficial, may create enough turbulence to have an erosive action on the revetment near the waterline. If however a modern canal is built with a large cross-section suitable to accommodate a busy traffic of fast craft, the consequence should be to provide the banks with a protection able to resist the erosive action of wave motion. Such a protection may consist of:

a. a revetment of the sloping bank,
b. a stable vertical or nearly vertical retaining wall.
c. a combination of a and b.

### a. Bank revetment.

In principle this is only a protection of an intrinsically stable slope over such a height that erosion of loose particles by the action of waves and current is prevented. This is obtained by revetting the slope, for which purpose different means may be used. A distinction can be made between rigid and flexible constructions on one hand and between impermeable and open constructions on the other hand. Besides the costs of construction the expectations with regard to the probability of irregular settlement of the subsoil influence the choice between rigid slabs and flexible revetments. Rigid slabs are of course to be used only when irregular settling may be ruled out, so that the appearance of cavities underneath the revetment need not be feared.

The stability of the unprotected slope, adjoining the lower edge of the revetment should be completely safe, or else the toe of the revetment has to be protected against undermining in another way.

A flexible revetment will be able to follow a slight subsidence of a slope without danger. They may be constructed in many different manners and are often applied in the Netherlands.

The difference between the watertight and the permeable revetment is of course essential as the latter in contrast to the former will not be exposed to hydrostatic pressure in one or the other direction. The thickness of the open revetment is determined only by the condition that the underlying slope will be protected against erosion. It therefore will depend on the material used for the construction. Of course the composing parts should each be stable in itself. The impermeable revetment however will have to resist a certain hydrostatic pressure, created by the incident wave. Dependent on the surface area of each separate unit the hydrostatic pressure, acting during a short time and directed towards the canal may be a dominating factor in determining the thickness of the revetment.
b. The retaining construction may consist of sheet piling, which may be anchored or not, dependent on the unsupported length, or of a wall, finding its support on the subsoil either directly or by means of piles. The constructions, belonging to this group, are always rigid and nearly always made as impermeable as possible. They can easily bear the small differences in hydrostatic pressure created by passing ships and in other respects also they are immune to wave attack, provided the foundation is protected against undercutting.

c. The combination of the protected slope and the vertical or nearly vertical wall is often met in the Netherlands, the slope being in some cases above the vertical part and in other cases below it.

The first mentioned case occurs f.i. when timber sheetpiling is applied, the upper end of which has to remain below the waterlevel for the sake of durability. This timber curtain supports a revetted slope which reaches well above the waterline.

In the other case the vertical wall is supported by the slope below it. Revetment of this slope may then be necessary to prevent undercutting.

Along the heterogeneous system of the Dutch canals the types of bank revetment sketched above are met within nearly every thinkable variety, as well as a number of lighter constructions that do not or only as an exception come into consideration for modern waterways with busy traffic. A detailed discussion is to be found in the Dutch report nr. 15 presented in Brussels to the XVIth Congress (lit 1) and may therefore be omitted here. A few recent constructions, not yet mentioned there, are now given in figure 10.

For wide waterways where a slope revetment can be applied, the use of asphalt undoubtedly deserves the attention. The durability of this product increases when it is applied as an impermeable layer. A slope revetment of this kind is not only tight but also it can easily follow the movements of the subsoil. As asphalt behaves like a rigid plate during rapidly changing loads (passing of a wave) a localised pressure directed towards the canal will thereby be distributed over a much larger area. For that reason a relatively thin layer of asphalt will be sufficient.

For the new Amsterdam-Rhine-canal, recently come into service, the asphalt layer has been reinforced with a core of rubble, which prevents sagging of the revetment. Figure 10 shows more details.

About the depth, to which the soil is liable to be eroded in front of a vertical wall, it has been stated in the Dutch report for the XVIIth Congress (lit. 2) that it is safe to count with a depth of 2 1/2 times the deepest depression of the waterlevel. When instead of a correction factor of 1.4 is taken f.i. 1.2 (par. 222) this leads to $2.5 \times 1.2 = 3$ times the calculated maximum depression. The absolute maximum of the calculated depression is 0.192 h, so that for the depth in front of the sheet piling should be taken 0.55 to 0.6 times the mean depth of the canal.

With regard to the fact that ships only exceptionnally will run at their limit velocity, this recommendation might seem rather pessimistic. It should be kept in mind however, that the wave motion set up by a ship navigating at same distance from the centre is stronger than normal along the near bank, whereas the direct influence of the propeller stream may also have a scouring effect.
43. RESTRICTION OF SPEED.

Even without a compulsory speed restriction, the limit velocity normally will not be attained. In approaching this limit the resistance increases to such a degree that the engine capacity of many ships is insufficient to exceed 90 to 95 percent of the limit velocity. A few categories of ships, as tugs, navigating separately, river craft, coasters, which have an excess of engine capacity for normal canal navigation and so might succeed in attaining the limit speed, nevertheless in practice rarely will exceed a speed of about 90 percent of the limit, because in that case due to the growing resistance navigation would become very uneconomic and moreover risky. If the canal is provided with a modern bank protection of adequate strength there is no reason to impose a speed restriction to navigation for the sake of preventing erosion by wave action. In this regard a discrimination between ships of different size is not needed because, except for very small ships, the intensity of the wave motion is practically the same for ships of all sizes.

In the case of towed ships the return flow is distributed fairly uniformly over the cross-section. Most canals are dug in erodible soil, which means that at a certain velocity along the bed particles will be set in motion. A slight transgression by the return flow of this velocity need not to be estimated harmful, because the particles will undergo displacements over small distances only. Unprotected parts of steep banks will be eroded in the long run however and therefore for each separate case a limit will have to be set to the return velocity.

Automoteurs cause — apart from the general return flow — a concentrated stream unto and from the propeller. As a rule no serious damage to the canal bottom need to be feared on this account. Special measures may have to be taken however in places, where shipping repeatedly runs near the bank and especially in conditions, where during a fairly long time the propeller-stream may be directed towards the bank.

The size of ship which, as has been seen, has little influence on the intensity of the wave-motion, is however of real importance for the return flow (fig. 3 and 6). On this account a speed restriction for ships above a certain size might be considered, for instance if among the different types of ships circulating in a given canal one type stands out by its frequent appearance. If moreover the amount of transport by bigger ships than this type should be only a small part of the total transport, it may be economically justified to choose a cross-section in which ships of this «standard» type (and smaller ones) can navigate freely, but to impose a speed restriction on the relatively rare ships of greater dimensions. As may be derived from fig. 5 and 6, a moderate restriction, i.e. to 90 percent of the limit velocity (a value which practically never is exceeded), already results in a considerable reduction of the return velocity.

Meanwhile it should not be forgotten that it is easy to issue regulations restricting the speed, but difficult to maintain them in practice, if not impossible.

Notwithstanding these considerations on most of the Dutch waterways a speed restriction is in vigour, generally differentiated with relation to the size of ships, in which the velocities allowed as a rule are lower than 90 percent of the limit velocity.
The reasons are found in the following circumstances.
1. Many bank protections are not wholly adequate.
2. In the narrow canals the return current can exceed the admissible limit.
3. In the shallow canals the ship can sheer out of line at a higher speed and thus suffer damage or cause damage.
4. Ships moored to the bank are in danger of being broken adrift by the water motion caused by passing traffic.
5. Encountering and overtaking of ships is also dangerous in the narrow canals.

It is to be expected that the first mentioned circumstance will not be of a permanent character; the improvement of the banks along the most important canals in the Netherlands is steadily proceeding. The other reasons for speed-restriction are more permanent, especially those, mentioned under 3, 4 and 5.

Because of considerations of safe navigation, experienced skippers will slow down in certain situations, with or without speed regulations, for instance when passing through bridges, sluices, locks and other permanent or temporary obstructions or when encountering or overtaking other ships etc. It is up to the canal builder however to eliminate as much as possible the occurrence of permanent or occasional obstructions which impede free navigation.

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1) XVIth International Congress of Navigation, Brussels 1935
   1st Section, 1st Communication.
   Section I communication 2. Report by J.B. Schijf.
3) Ir. J.G. Koning:
4) C.A. Lee and C.E. Bowers.

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RESUME.

L'accroissement du nombre d'automoteurs rapides dans la navigation intérieure incite à examiner les mesures à prendre pour faciliter le trafic accéléré.

La théorie approximative du rapport néerlandais (litt. 2) présenté au XVIIIé Congrès International de Navigation (Lisbonne-1949) a été complétée et vérifié au moyen d'observations qui ont été faites depuis. L'existence d'une vitesse limite, qui ne peut pas être dépassée par des bateaux à propulsion propre ni par des bateaux remorqués ou poussés et uniquement au coût d'une énorme résistance présentée par les bateaux, s'ils sont halés sur rive, a été confirmée au moyen d'essais spéciaux.

Il apparaît qu'en s'approchant de la vitesse limite la résistance croît à un tel degré, que la navigation à une vitesse supérieure à 90 % de la vitesse limite est très anti-économique et pour ce motif sera évitée en pratique. Une autre raison pour ne pas s'approcher de cette vitesse limite est la sécurité de la navigation (danger de glisser hors de la route).

Dans un canal à large section transversale les bateaux ont une forte vitesse limite. L'approfondissement d'un canal est plus efficace que son élargissement. Ce dernier ne produit, pas en général, une diminution du mouvement ondulatoire, au moins quand la navigation profite de l'occasion d'accélérer sa marche, mais cela ne diminue pas la vitesse du courant de retour.

Compte tenu du caractère très différencié de la flotte néerlandaise intérieure (tableau p.3), on doit prendre en considération la présence de bateaux à vitesses variées; il en résulte qu'il faudra réserver assez de largeur pour la rencontre et le frémissement des bateaux.
Des résultats d'études américains (litt. 4) on peut déduire que, pour la rencontre sans obstacle de deux bateaux de mêmes dimensions, une largeur de platond égale à 6 1/2 fois la largeur de la coque est exigée. Pour ce qui concerne la profondeur, on doit envisager la possibilité d'un enfoncement de la poupe plus fort que les 0,20 de la profondeur moyenne du canal.

La construction d'une grande voie d'eau, dans laquelle de grands bateaux peuvent utiliser leur vitesse, a comme conséquence l'établissement de protections des berges, qui peuvent résister à l'érosion due au mouvement ondulatoire, accompagnée d'une dépression maximum du plan d'eau.

Dans le cas de murs verticaux protégeant les rives on doit compter sur un affouillement atteignant 0,55 à 0,60 de la profondeur moyenne.

Si des bateaux de dimensions différentes naviguent tous à leur vitesse limite propre ou à un pourcentage proportionnel de cette vitesse, la dépression du plan d'eau et le mouvement ondulatoire qui l'accompagne sont pratiquement indépendants des dimensions du bateau.

Cependant la vitesse du courant de retour est d'autant plus élevée que le bateau est grand. Ceci peut servir d'argument pour imposer la réduction de la vitesse des bateaux au-dessus de certaines dimensions pour un canal construit dans un terrain meuble.

La question de savoir si la construction d'un canal à grande section se justifie dépend de l'intensité de la navigation. On pourrait être tenté de réduire le coût total d'une voie d'eau et les frais d'exploitation du trafic à un minimum. Mais quand on essaye de faire un tel calcul on rencontre de grosses difficultés par suite du fait que l'importance du trafic futur doit être estimée et du fait qu'un certain nombre de facteurs, notamment le gain de temps, peuvent être difficilement exprimés en monnaie.

Il est aussi impossible d'établir des règles générales en ce qui concerne la forme la meilleure de la section transversale d'un canal. Ensuite pour les vitesses que peuvent atteindre les bateaux et pour la sécurité à leur rencontre ou à leur trématage un grand nombre de facteurs jouent leur rôle, comme la nature du sol, la méthode de construction, le niveau de la flottaison du canal par rapport au terrain etc.

Beaucoup de canaux existants ont une défense de rive qui n'est pas adéquate pour la navigation rapide moderne. Il en résulte que des restrictions coercitives de la vitesse sont encore nécessaires dans beaucoup de cas. D'autres motifs de restriction peuvent résulter du danger de vitesse de retour excessives et de la sécurité indispensable de la navigation. Comme l'action du mouvement ondulatoire le courant de retour aussi bien que la succion exercée sur les rives par les vitesse limite, on devra prescrire de ne pas dépasser 90% de la vitesse limite.

A titre de supplément au rapport présenté au XVIe Congrès (litt. 1) on donne quelques observations pour ce qui concerne la voie d'eau améliorée d'Amsterdam au Rhin.