NAVIGABILITY IN CHANNELS SUBJECT TO SILTATION

PHYSICAL SCALE MODEL EXPERIMENTS

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ABSTRACT

The paper gives a brief description of the studies carried out in France during the last years, especially on scale models, in order to improve the knowledge of the behaviour of ships progressing in approach channels subject to siltation.

1 - INTRODUCTION

The French Ministry of the Sea and three French port authorities - Port Authority of Nantes - Saint-Nazaire, Port Authority of Bordeaux and the Maritime Service in French Guiana - have been working together over the past few years on studies with two main aims :

- to allow ships to use port approach channels subject to siltation, taking full advantage of potential while at the same time ensuring excellent navigability conditions,
- to ensure that technical conditions and maintenance dredging programmes are correctly adapted to the real requirements of port operations.

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These works cover three aspects :

- development of devices and methods for measuring the physical and chemical characteristics of fluid muds, such as the JTD 3 gamma densimetric probe (CEA - ORIS) working at fixed point, the JTT 4 gamma densimetric probe (CEA - ORIS) and the SD 105 ultrasonic densimetric probe (Port Authority of Bordeaux) working continuously and the SR 10 rheological probe (LCHF - SOGREAH), which are now fully operational,(ref. 1, C. BROSSARD and al, 1990, and ref. 2, C. MIGNIOT, 1984),
- physical scale model studies of the behaviour of ships in channels subject to siltation,
- observations and measurements taken from ships navigating in such areas.

This paper gives a brief summary of the exploratory work carried out by the Laboratoire Central d'Hydraulique de France (LCHF) in 1986 and then deals essentially with the systematic scale model tests carried out by SOGREAH in 1989.

2 - EXPLORATORY STAGE (ref. 3, LCHF, 1986)

This included :

- a preliminary bibliographical search that illustrated the interest of the study, but which also revealed that very few results were available from laboratory or in situ observations,
- theoretical considerations on the dimensional approach to ship displacement in clear water, the rheological problems connected with mud characteristics, the similitude applicable to scale model tests and the manoeuvrability of a ship moving over muddy beds,
- qualitative tests at a scale of the order of 1/100, enabling the measurement technology to be finalised and initial information to be obtained, giving and idea of the behaviour of a ship sailing over muddy beds.

3 - SIMULATION METHODS USED IN THE SYSTEMATIC TESTS (ref. 4, SOGREAH 1990)

This section deals successively with the problems of similitudes and scales, the experimental apparatus and the modelling of the mud.

3.1 - Similitudes and scales

Dimensional analysis of the factors constituting resistance to progress and ship behaviour led to the definition of dimensionless numbers enabling an accurate representation of the various phenomena involved.

Perfect modelling is impossible, as this would involve keeping many dimensionless parameters. Given the nature of the problem, the following choices were made :

- compliance with the Froude number and Froude densimetric number, which involves a velocity scale equal to the square root of the length scale and a mud density gradient increased in reverse proportion to the geometric scale,

- compliance with the ratio of inertia forces to rigidity forces and the ratio of densimetric forces to rigidity forces, which involves reducing the rigidity in the ratio of the geometric scales.

In contrast, neither the Reynolds numbers for water and for the mud medium nor the Grashov number (damping of internal waves) are retained. The medium in the model is therefore too viscous and forces are overevaluated.

The scales adopted after choosing the similitude rules and taking into consideration three geometric scales (1/100, 1/70 and 1/55) to represent different analysis situations are defined in the tables of figure 1.

Nature	Scale	Values		
Length	1/n	1/100	1/70	1/55
Area	$1/n^2$	$1/10^4$	1/4 900	1/3025
Volume	$1/n^3$	$1/10^6$	1/343 000	1/166 375
Speed	$1/\sqrt{n}$	1/10	1/8.37	1/7.41
Rigidity	1/n	1/100	1/70	1/55
Density	1	1	1	1
Theoritical tractive force	$1/n^3$	$1/10^6$	1/343 000	1/166 375
Practical tractive force	-	$1/3.3 10^5$	1/130 000	1/65 000
Power	$1/n^{3.5}$	$1/10^7$	$1/2.87\ 10^6$	$1/1.23\ 10^6$

1.1 - Chosen scales

Model		1/100	1/70	1/55
Speed	0.2 m/s	3.88 kn	3.25 kn	2.87 kn
	0.3 m/s	5.82 kn	4.87 kn	4.31 kn
	0.4 m/s	7.76 kn	6.50 kn	5.77 kn
	0.5 m/s	9.70 kn	8.12 kn	7.21 kn
	0.6 m/s	11.6 kn	9.71 kn	8.65 kn
Draught	15.6 cm	15.6 cm	10.9 m	8.58 m
	12.2 cm	12.2 cm	7.8 m	6.16 m

1.2 - Correspondences with full - scale speeds and draughts

Fig. 1 - Scales chosen for the tests and correpondences with some full scale parameters

3.2 - Experimental apparatus

The tests were run in the looped wave flume at SOGREAH in Grenoble. This flume is 50 m long and 3.2 m wide. It has a trolley that runs on rails, used for pulling the model and taking measurements (fig. 2)

The model used was that of a tanker of classic type, 2.56 m long, representing :

- at scale 1/100, a ship of the same type with a displacement of 120 000 t,
- at scale 1/70, a 25 000 - 30 000 t bulk carrier with a high block coefficient,
- at scale 1/55, a ship of the type calling in at French Guiana.

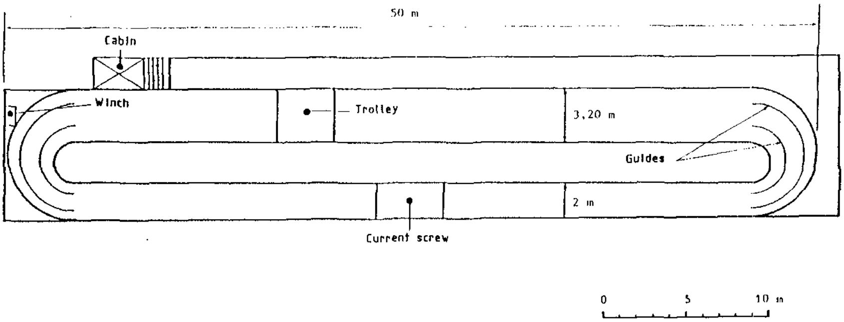

Fig. 2 - Plan of the looped flume

The model was equipped with sensors for measuring squat, trim and tractive force.

Four parameters were thus recorded simultaneously : foreward squat, trim, tractive force and speed (fig. 3).

The mud concentration was determined using an ultrasonic probe developed during the first stage of the study. Via two sensors, this measures the acoustic power transmitted through a layer of mud after direct immersion in the medium under study.

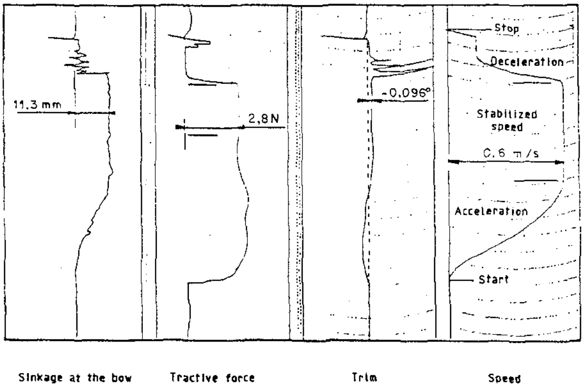

Fig. 3 - Examples of recordings

3.3 - Modelling of mud

In order to comply with the chosen rules of similitude, the mud had to be represented by a mixture which, at equal concentration, would have a rigidity value in proportion to the geometric scale, i.e. 1/100 for the basic configuration, and density gradients in similitude with those obtained in reality.

Following a review of the characteristics of mud deposits in the Loire, Gironde and Mahury (French Guiana), showing the variation of initial rigidity as a function of concentration and the density gradients in the deposits, it was decided to carry out tests with the following, in order to cover the entire range of possible situations :

- two types of mud : high rigidity and low rigidity,
- three concentration gradients as a function of depth : high, intermediate and low.

The techniques used to model the mud have allowed to respect, from the point of view of rheology and from the point of view of the density gradients, the conditions of similitude previoulsy considered.

Figure 4 shows the gradients obtained on the model, for the mud of high rigidity, in conformity with those observed in situ and allowing profiles to be accurately repeated.

4 - TESTS IN CLEAR WATER

The aims of the tests carried out in clear water were :

- to check that the model behaved in conformity with the prototype,
- to gather information for comparing the results obtained with muddy beds.

4.1 - Programme of tests

The programme comprised 29 tests with :

- draughts of 15.6 cm and 11.2 cm with the ship at rest,
- speeds varying from 0.2 m/s to 0.6 m/s,
- under-keel clearances at rest varying from 8 cm to 0.5 cm.

The tests with large under-keel clearances at rest (6 and 8 cm) were carried out in order to appreciate the effect of reducing this parameter on the behaviour of the ship.

4.2 - Squat

The measurements were compared with the theoretical results obtained by applying the Barrass formula (1977) (ref. 5, L. Ribadeau-Dumas, 1982). The mean deviations observed were :

- 0.054 cm with a draught of 15.6 cm,
- 0.032 cm with a draught of 11.2 cm

i.e. about 0.3 % of the draught considered, which is less than the accuracy of the sensors.

4.3 - Trim

In the absence of known formulae, the measurements were compared only with the results of observations taken in the Netherlands Ship Model Basin (NSMB) and published by R. Sellmeijer and G. van Oortmerssen (ref. 6, 1983).

It appears that the results concur well for the narrow interval than can actually be plotted.

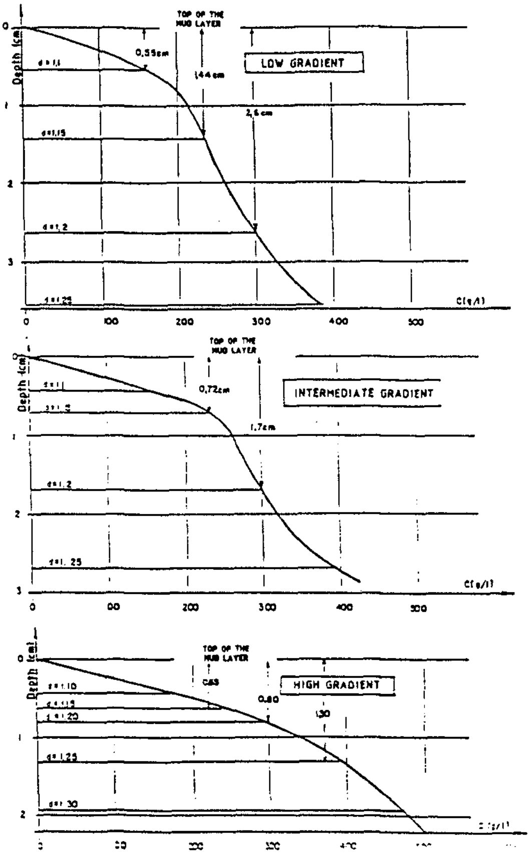

Fig. 4 - Density gradients on the model - Mud of high rigidity

4.4 - Tractive forces

4.4.1 - With the Froude similitude and a geometric scale of 1/100, the forces are theoretically in the scale of $1/10^6$ but on the model the viscous forces are actually increased owing to the fact that the Reynolds similitude is not respected, thus leading to a higher resistance than in reality.

Comparison of the in situ and model results indicates that the forces on the model are about three times too great with respect to the Froude similitude, which leads to the practical values shown on the table of figure 1.1, for example $1/3.3 \times 10^5$ for scale 1/100.

4.4.2 - The tests led to four types of conclusions :

- Forces increase when the under-keel clearance falls and forces are greater with a draught of 15.6 cm than with one of 11.2 cm.

- The difference between the tractive forces obtained for these two draughts is on average 5-10 % greater than could be expected from an increase in force based simply on the variation in hull area (+ 19 %).
- For both draughts, the force increases in an almost linear fashion as a function of the Froude number.
- A comparison of the forces measured on the model and those computed for the model shows that, overall, the forces measured are greater than those computed, though the differences are slight in the case of the lowest forces, increasing progressively with them. Given the lack of theoretical knowledge, uncertainties over the measurements, the methodology chosen and the aims pursued, it was considered that the model and sensors were adequate.

5 - TESTS WITH MUDDY BED AND NO CURRENTS

5.1 - Test programme

A programme of 99 tests was carried out.

The test or navigation conditions were characterised by five parameters, two linked to the mud :

- concentration-rigidity relation (type of mud used),
- concentration gradient of the mud deposit,

and three linked to the ship :

- draught at rest,
- under-keel clearance,
- speed.

5.2 - Squat

When the ship is above the top of the mud, the squat measured is of the same order of magnitude as with clear water when the keel is close to a hard bed, but when the keel is in the mud, the squat values differ according to navigation conditions.

- The type of mud has little effect on the squat values obtained.
- The draught has little effect on the squat values obtained, but, as in clear water, the squat values observed with a draught of 11.2 cm are very slightly higher than those obtained with a draught of 15.6 cm.
- Generally speaking, the greater the mud density gradient, the more the squat decreases algebraically.
- When the ship's keel is in the mud, the squat may be considered as the resultant of the hydrodynamic force connected with the speed and of the hydrostatic thrust.

. The observations made on the model at low speed, especially in the case of low and intermediate gradients, can be explained in this way.

. In the case of high gradients, in contrast, the ship is lifted more, as her trim is then positive, and this tends to cause the ship to climb on the top of the mud, all the more so as the speed increases.

. At high speeds (0.4 and 0.6 m/s), in the case of low gradients, there is an increase of the squat in comparison with the values obtained when the ship is above the mud.

- Considering the position of the keel when the vessel is at rest in comparison with density level 1.2, the squat values observed are greater than those obtained with clear water (with respect to the solid bed), even with under-keel clearances of the order of 10 % of the draught with low gradients and speeds of 0.4 to 0.6 m/s.

- The squat values vary in proportion to the square of the speed (fig. 5) :

. With low gradients, the squat values obtained in the presence of mud are higher than those observed in clear water, from about 0.5 m/s upwards.

. Independently of the density gradient, the positive squat values obtained with the under-keel clearances considered (vessel at rest) only appear with speeds above about 0.3 m/s.

All these various observations show that the density level is not, in fact, the only parameter to be taken into account, but that the density gradient is also an important factor.

5.3 - Trim

As far as manoeuvrability is concerned, a variation in trim is significant as soon as it corresponds to a difference of about 30 cm between fore and aft draught, i.e. an angle of the order of 0.068°. This phenomenon is significant especially in the case of a ship with a negative trim.

- The trim values obtained are very low with a mud of low rigidity, so that the effect of the other parameters may be examined only with rigid mud.

- Trim values increase with gradient, keeping the same speeds and under-keel clearances relative to the top of the mud, and, when the under-keel clearance decreases, the higher the gradient, the earlier the transition from a negative to a positive value.

- In the case of high gradients, the trim values remain lower for a draught of 11.2 cm than those observed, with the same under-keel clearance, for a ship with a draught of 15.6 cm.

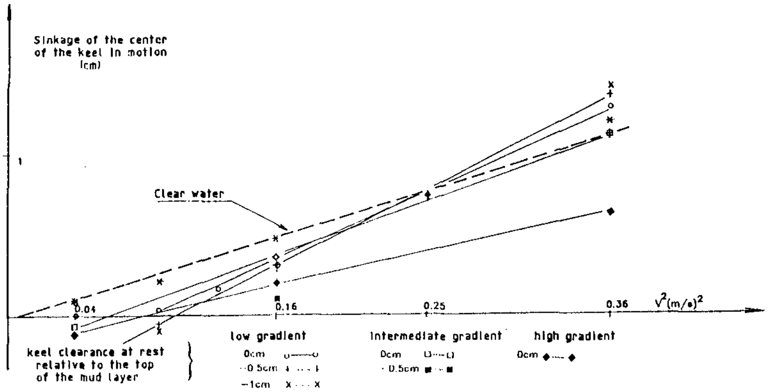

Fig. 5 - Tests with mud bottom and without current - Variation of the value of the squat with the speed - Mud of high rigidity - Draught 15.6 cm

- Generally, the trim changes from a negative value to a positive value as the hull penetrates the mud. The lower the speed, the earlier the transition to a positive value.

- The trim varies in proportion to the square of the speed (fig. 6) :

. with the same under-keel clerance and the keel in the mud, the greater the speed, the more the trim decreases, to the extent where it may become negative ;

. the variation in trim resulting from an increase in speed is, however, less in the presence of mud than with clear water.

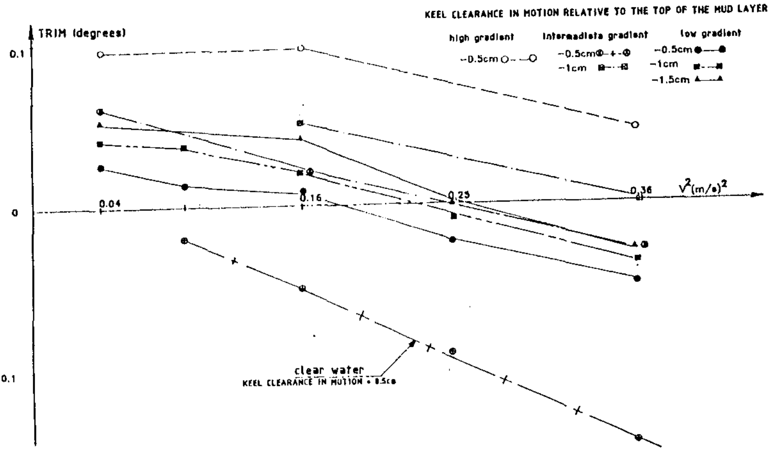

Fig. 6 - Tests with mud bottom and without current - Variation of the value of the trim with the speed - Mud of high rigidity - Draught 15.6 cm

5.4 - Tractive forces

Given scale effects, the forces involved should be mainly considered as relative.

Generally speaking, so long as the keel of the moving vessel is well above the top of the mud, forces are of the same order of magnitude as those observed in clear water. As the ship penetrates the mud, forces increase rapidly, but in a different way, however, depending on navigation conditions. In certain cases, a local maximum is observed when the ship's keel is just above the top of the mud.

- The effect of mud rigidity is felt particularly at low speed. The higher the speed and the less sinkage in the mud, the greater the relative proportion of the tractive force linked to the rigidity value. In areas where there may be differences in mud rigidity, this should be taken into especial account during periods of low-speed navigation and even more so during manoeuvring as, depending on the rigidity of the mud, the forces required may be very different.

- Low density gradients appear more favourable (less force with the same under-keel clearance during motion) than high gradients, considering the top of the mud as reference level. In contrast, low gradients appear less favourable if the 1.2 density level is taken as reference, because in this case and with the range of under-keel clearances used in the tests, the gentler the gradient, the greater the force appears to be with the same under-keel clearance.

- Tractive forces are generally higher with a draught of 15.6 cm than with one of 11.2 cm, and they vary in a relatively similar way depending on the under-keel clearance as the ship advances. The relative differences are of the order of 28 % for a speed of 0.4 m/s and 20 % for one of 0.6 m/s.

- Three types of variation in force may be distinguished, depending on the under-keel clearance during motion with respect to the top of the mud (fig. 7) :

. A variation as in clear water, when the ship's keel is distinctly above the top of the mud.

. A slight variation, when the ship's keel is close to the top of the mud. This type of change does not occur systematically.

. A very rapid increase with the sinkage of the ship in the mud. The speed at which this occurs increases with the gradient.

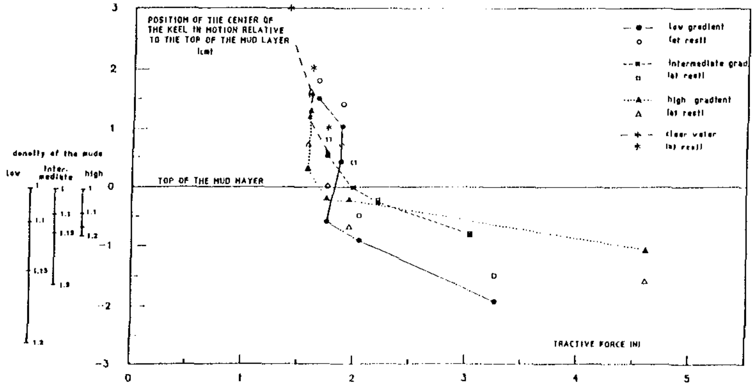

Fig. 7 - Tests with mud bottom and without current - Variation of the value of the tractive force - Mud of high rigidity - Draught 15.6 cm, v = 0.4 m/s

- An initial approximation of the variation in tractive force as a function of velocity may be written as follows (fig. 8) :

$$F = F^o + k\ V^2$$

The values of F^o and k depend on the under-keel clearance during motion relative to the top of the mud, the density gradient and the type of mud.

. The value of F^o is nil when the keel is above the top of the mud and rises to 1.4 N for a high sinkage of the keel in the mud, with a rigid mud and a high density gradient.

. The values of k are higher by 20-50 % than that noted for clear water (10.5 N/m^2), depending on the type of mud deposit.

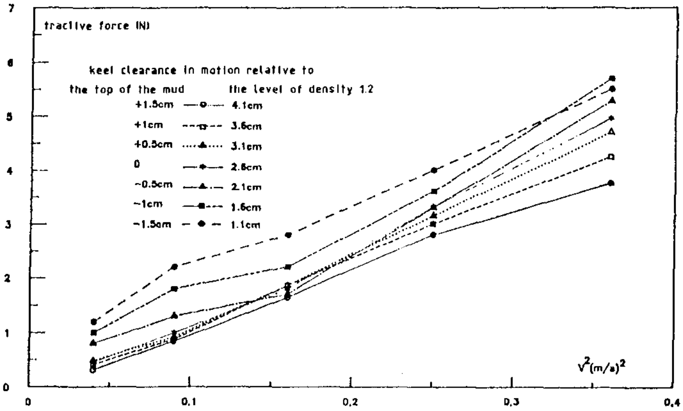

Fig. 8 - Tests with mud bottom and without current - Variation of the value of the tractive force with the speed - Mud of high rigidity - Low gradient - Draught 15.6 cm

5.5 - Internal waves

Internal waves were analysed on the basis of photographs taken through the flume observation window.

Internal waves are not visible with the most rigid mud, irrespective of speed, nor with the least rigid mud, with a speed of 0.2 m/s, but they appear with the least rigid mud and speeds of 0.4 and 0.6 m/s.

They generally occur in the form of a double-bump undulation above the top of the mud at rest, the first bump being less pronounced than the second one. The main characteristics are as follows :

- Distance between the two bumps, parallel to the keel centre line, of the order of 1 m, with the total wave length being of the order of 2 m.
- Wave crest making an angle of 30-50° with the centre line of the ship.
- Wave propagation speed perpendicular to the wave crest between 0.4 and 0.6 m/s.
- The amplitude of the internal wave depends little on the draught of the ship and on the density gradient. It increases with speed and reaches a maximum of 4-5 cm when the ship's keel during motion is close to the top of the mud and reaches a more or less constant value of 1.5-2 cm when the keel sinkage in the mud is of the order of 1 cm.

These observations concur, for the most part, with those published by R. Sellmeijer and G. van Oortmerssen (ref. 6).

6 - TESTS WITH CURRENTS

In order to assess the impact of a current on navigation in silted channels, some tests were also carried out with current in clear water and with muddy beds, using a ship with a draught of 15.6 cm.

The current speeds are denoted as positive when currents run in the same direction as the ship's motion, and negative in the opposite direction.

6.1 - Tests in clear water

Two series of three tests each have been performed, with an under-keel clearance of 1.6 cm (10 % of draught) at rest, with ship speeds in relation to the bed of 0.3 m/s and 0.4 m/s. Each series consisted of three tests : no current, a current of + 0.1 m/s and one of - 0.1 m/s.

The values obtained show that the results should be compared with those obtained under no-current conditions and with the same surface speed (i.e. in relation to the water).

With a current, squat is about 25 % greater and trim identical, irrespective of the current direction in relation to the ship's motion.

With the same surface speed, the tractive force is about 30 % greater than that observed in the absence of current when the current is in the same direction as the ship's motion and about 5 % less when it is in the opposite direction.

6.2 - Tests with muddy bed

Two series of three tests each were carried out, with the most rigid mud.

With the same surface speed and a muddy bed :

- squat decreases with a counter-current and is practically nil in the opposite situation,
- tractive forces are, as in clear water, slightly higher with a current.

With the same speed relative to the bottom and in the presence of a current, the tractive force is greater than in the absence of a current when it runs opposite to the direction of the ship's motion and is lower in the opposite situation. An initial approximation of the force may by obtained by considering that, with a given bottom speed and current, the force is close to that measured in the absence of a current considering the ship's speed to be equal to the bottom speed plus the current velocity.

7 - TENTATIVE APPLICATION OF TEST RESULTS TO REAL CASES

The study was completed by an attempt, suggested by ship's captains, to examine how the results obtained during the tests could be applied to real situations, in the form of nomographs.

The nomographs are formed by superimposing two families of curves (fig. 9).

- The first one, deduced from the tests, is taken from a set of ten figures corresponding to the ten categories of tests carried out (fixed rigidity, gradient and draught at rest). For known underkeel clearances at rest, this gives the force-speed curves (F-V), which can be transposed to real situations by applying the scales given in fig. 1.1.

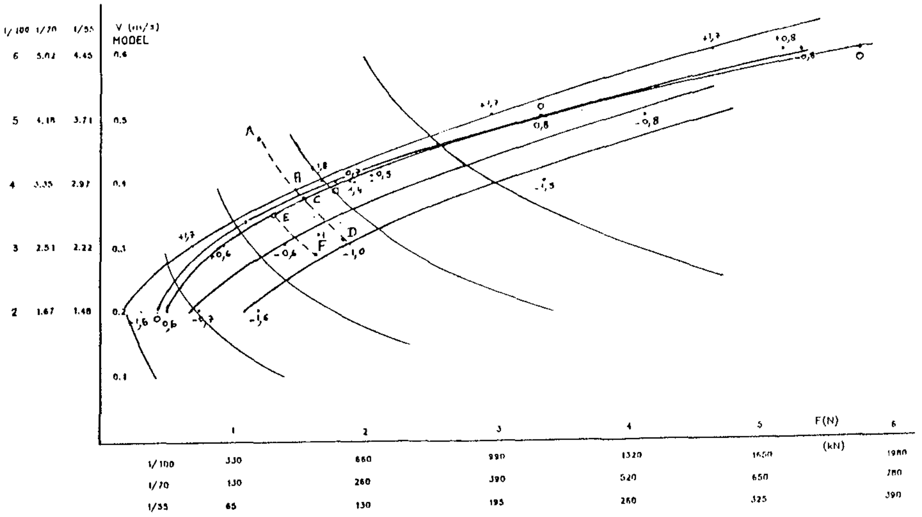

Fig. 9 - Diagram giving the conditions of navigation - Mud of high rigidity - Low gradient - Draught 15.6 cm

- The second family of curves represents the characteristics of the ships. Isopower curves are defined in the plane F, V by the relation :

$$P = F\ V$$

with the curves being calibrated by the approximately verified relation for unconfined waters :

$$P = k\ V^3$$

in which k is a coefficient depending on the characteristics of the ship. A set of three figures represents the isopower curves of the three ships considered.

The ship's operating curve is represented schematically on these nomographs by successions of displacements along the isopower curves when the engine power can be maintained and along the curves of constant under-keel clearance at rest relative to the top of the mud when the engine power is reduced.

Three practical cases have been examined, concerning the ports of Nantes - Saint-Nazaire, Bordeaux and French Guiana.

8 - CONCLUSIONS

The scale model experiments enabled substantial progress to be made in understanding the behaviour of ships sailing in channels subject to siltation. The nature of the phenomena observed and the orders of magnitude of the parameters for characterising these phenomena were acknowledged to be quite valid by the mariners and pilots involved in the study.

The first attempts made to establish nomographs defining navigation conditions in real situations are encouraging, but they must of course be treated with great caution. Precise measurements under real navigation conditions should constitute the next stage of study, enabling the theoretical nomographs derived from the scale model studies to be adjusted to real navigation conditions.

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