PAPER #706

Shallow River Pushboat Preliminary Design [1]

by

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[1] Paper n° 4Q6 to be read at :

VIII Pan American Congress of Naval Engineering
Maritime Transportation and Port Engineering
Washington D.C., September 1983.

Summary

This paper outlines the preliminary selection of pushboat power, hull and tunnel stern dimensions. The method is illustrated for 2 x 2 barge tow. An empirical formula for the ducted propeller pushboat thrust is introduced. The deep water tow resistance is estimated using a modified Howe's formula. The method of Apukhtin is extended to estimate the shallow water resistance. Matching the tow resistance and pushboat thrust gives the tow speed. The pushboat power is selected based on the desired tow speed. Then guidelines are used to dimension the pushboat hull and tunnel stern.

1. Introduction

Barge trains propelled by a pusher tug or towboat offer flexibility in cargo scheduling and cargo growth. The barge design can be standardized as is done in European waterways /7/, /17/. This facilitates planning and the rational development of the waterway for larger cargo volumes. The pushboat design can also be standardized based on installed horsepower P_D (Fig. 1).

While this paper is concerned with estimating the still water speed V of a barge train moving in deep and shallow water conditions, there are several other operational considerations which need to be mentioned. The barge train operates in three modes :

1. Ahead Operation
2. Astern Operation
3. Maneuvering Operation : Ahead/Astern.

Item 1 is discussed in a large number of articles /4/, /7/, /10/, /14/, /15/, /17/, /19/, /21/, /31/. Items 2 and 3 have been more difficult to study and are discussed in /8/, /9/, /16/, /28/. As this paper will illustrate, the preliminary selection of pushboat horsepower P_D is governed by the required speed $V_{req.}$ in the ahead operation. In this paper $V_{req.}$ is taken as the equilibrium speed V at which the pushboat thrust or "push", EP, is equal to the resistance of the barge tow resistance R_T

$$EP = R_T \tag{1.1}$$

Converting the pushboat thrust EP to horsepower at the tow speed

$$P_E = \frac{EP \cdot v}{K} = \frac{R_T \cdot v}{K}, \ HP \tag{1.2}$$

it is possible to determine the propulsive efficiency η_D:

$$\eta_D = P_E/P_B \tag{1.3}$$

The ahead operation of river pushboats is characterized by low propulsive efficiency, typically :

$$0.20 < \eta_D < 0.40$$

This remains a problem which requires model and full scale tests as well as theoretical studies. The reason for the low η_D values is the result of a number of factors :

I. Propeller loading related to the barge tow resistance :

1. Number and arrangement of barges
2. Loading draft of barges
3. Waterway depth and width
4. Current speed and direction.

II. Inflow into the propellers related to items 1-4 and the pushboat hull :

5. Hull lines especially the tunnel stern arrangement
6. Orientation of the ahead and flanking rudders
7. Propeller/Duct design.

In many cases the relationship of each item with the towboat propulsive efficiency is unclear. Experience has show the waterway depth is important. The waterway depth limits the propeller diameter and reduces the propeller efficiency. Nevertheless, the pushboat designer has been able to realize a steady increase in power. This has been accomplished by the use of systematic ducted propeller studies /18/, /25/, adopting a tunnel stern such as shown in Fig. 1 /7/, /10/, and using twin, triple, and sometimes quadruple propellers /1/, /14/, /15/.

It can be understood from this introduction that a large number of factors are involved in the pushboat design. Taking them into

account often makes the preliminary design of the pushboat lencthy. To facilitate the preliminary pushboat design, the design calculations are divided into the following four tasks :

1. Estimation of pushboat "push" EP
2. Estimation of barge tow resistance R_T
3. Selection of pushboat horsepower based on speed $V > V_{req.}$ where V is obtained from $EP = R_T$
4. For the pushboat horsepower determined in 3 determine the pushboat length, propeller diameter and tunnel stern arrangement.

These four tasks are illustrated in the following sections for a 2 x 2 barge tow project described below :

2. Project Design Specifications.

To illustrate the practical application of the following method, the river tow project specifications summarized in Table 1 are adopted. As indicated in Table 1, the final 2 x 2 barge tow has a 7 % cargo capacity margin over the level 1 specification. In the level 1 specification the desired speed V is defined as the still water speed. This implies that currents are neglected. The reasons for specifying the speed at conditions corresponding to a loaded barge tow travelling in shallow water is explained in /4/. The main reason is to avoid overloading the diesel engines in off-design operation. The channel conditions in Table 1 are taken as representative of a moderately shallow river.

3. Estimation of Pushboat Thrust or "Push" EP

The pushboat thrust or "push" EP is a function of the towboat horsepower HP, the type of propeller, water depth h, barge draft T, as well as the speed V. The author has developed the following empirical expression for preliminary design work :

$$EP = A \cdot HP[1.0 + C(h/T - 1.78)][1.0 - E \cdot V^2], \text{lbs} \tag{3.1}$$

$$1800 \leq HP \leq 5600, \ 1.78 \leq h/T \leq 5.0 \quad 0 < V < 12 \text{ mph}$$

where :

A : Power Coeff. for twin propeller pushboat
A = 19 for ducted propellers
A = 15 for open propellers

C : Depth Coeff.
C = 0.142

E : Speed factor

$$E = \left[0.00744 - 0.0052 \left(\frac{HP}{10\ 000} \right) \right]$$

Figure 3 illustrates the good agreement of equation (3.1), and the 5600 HP Pushboat EP values given in /4/. Two points for an 1800 HP Pushboat operating in deep water illustrate the utility of equation (3.1) for lower horsepower pushboats.

4. Estimation of River Tow Resistance R_T

Howe developed the following empirical relationship for estimating the barge tow resistance R_T /6/ :

$$R_T = F\, e^{\alpha}\, V^{\beta}\, T^{\gamma}\, L^{\delta}\, B^{\varepsilon} \qquad (4.1)$$

where :

α : Depth Coeff. $\alpha = 1.46/(h - T)$

β : Velocity Coeff. $\beta = 2.0$

γ : Draft Coeff. $\gamma = 0.60 + 50/(W - B)$

δ : Tow Length Coeff. $\delta = 0.38$

ε : Tow Width Coeff. $\varepsilon = 1.19$.

Howe originally proposed the tow factor F = 0.07289. Toutant has proposed modifying this value based on the tow type /29/ given in Table 2. For the 2 x 2 barge tow project in deep water a value of F = 0.027 was found to give good agreement with the data. This is shown in Fig. 4 for speeds of V = 8 and 10 mph. (12.9 and 16.1 kph)

Equation (4.1) with F = 0.027 for shallow water conditions is shown by the dashed line in Fig. 4. At V = 8 and 10 mph eq. (4.1) gives resistance values which are 64 % and 67 % of the shallow water project values shown in Fig. 4. Since this difference will lead to a large error in predicting the shallow water tow speed V, it is necessary to develop a more accurate shallow water resistance estimate.

Velednitsky /30/ has reviewed a number of methods for estimating shallow water resistance from deep water resistance data. Here we adopt the method of P.A. Apukhtin shown in Fig. 5. For a constant value of R_T, Apukhtin obtained the change in speed Δv between the deep water and shallow water curves. He found that $\Delta v/v_o$ was a function of two variables :

$$\Delta v/v_o = f(h/T,\ F_n) \qquad 0 \leq F_n \leq 1.6, \quad 3 \leq h_T \leq 14.0 \qquad (4.2)$$

where

Δv : change in velocity at a constant R_T, ft/s, m/s
v_o : vessel speed in deep water, ft/s, m/s
h : water depth
T : vessel draft
F_h : depth Froude number

$$F_h = \frac{V_o}{\sqrt{gh}}$$

Apukhtin developed Fig. 6 to obtain the value of $\Delta v/v_o$ for a given value of h/T and F_h. For the shallow water tow operation h/T = 1.78 which is outside Apukhtin's diagram. Therefore Fig. 7 was prepared for the cases of h/T = 1.78 and h/T = 1.33 using data from /4/.

Using the solid line in Fig. 7 for h/T = 1.78, the values of $\Delta v/v_o$ and V in Table 3 were estimated. The resulting resistance curve for shallow water is shown in Fig. 4. It is in excellent agreement for the project data point at V = 8 mph (12.87 Kph) and is higher at V = 10 mph (16.1 Kph). It is anticipated that a more detailed analysis with a smaller tow size would give lower $\Delta v/v_o$ values for F_h > .60. Typically the equilibrium speed V will be less than F_h = .60 so accuracy in the higher F_h range is not critical. For the project design this is the case.

5. Estimating Tow Speed V and Pushboat Horsepower.

The tow speed requires solving equation (1.1). This can be done using equations (3.1) and (4.1) and solving for the two speed V in deep water :

$$V = \sqrt{\frac{G}{J + G \cdot E}} \qquad (5.1)$$

where

$G = A \cdot HP \left[1.0 + C(h/T - 1.78) \right]$ (ref. eq. 3.1)

$J = F\, e^{\alpha}\, T^{\gamma}\, L^{\delta}\, B^{\varepsilon}$ (ref. eq. 4.1)

$E = \left[0.00744 - 0.0052 \left(\frac{HP}{10\ 000} \right) \right]$

Equation (5.1) is used to predict the deep water tow speed in V Table 4. The calculated speeds check with the tow speeds obtained graphically in Fig. 8-B. For shallow water a graphical solution is made in Fig. 8-A for the still water tow speed V. This graphical solution is shown for both deep and shallow water in Fig. 8. The tow speeds and corresponding values of propulsive efficiency η_D

are summarized in Table 4. It can be seen the shallow water conditions reduce the propulsive efficiency by 16-23 %. A slightly higher η_D value could be obtained from a search of barge tow arrangements meeting Level 1 specifications given in Table 1. This is left as a future study. For the present discussion the 2 400 HP towboat pushing the 2 x 2 tow at V = 7.7 mph (12.39 Kph) meets the design requirements. At this juncture checks would be made regarding the backing power and stopping ability. Assuming these are satisfactory, the design of the ducted propeller would proceed following the method outlined in /4/. In some projects shallow water model tests will be performed to confirm the initial estimates /9/, /14/, /21/, /31/.

6. Pushboat Hull Dimensions and Tunnel Stern Arrangement /10/.

In reference /10/ empirical formulas for obtaining the towboat dimensions are presented. The length LP can be estimated from the following formula developed from the data shown in Fig. 9 /10/ :

$$LP = 62.0 + 7.5\,\chi - 0.235\,\chi^{1.8}\ \text{ft} \tag{6.1}$$

where $\chi = (BHP/shaft)/100.0$, $3.0 \leq \chi \leq 32.4$

For the twin screw 2400 HP towboat, the resulting preliminary length is LP = 131.4 ft (40.0 m).

An initial estimate of the pushboat propeller diameter D can be made using the mean line in Fig. 10 or by the following :

$$D = 3.5 + 0.35\,\chi - 0.005\,\chi^{2.0}\ \text{ft} \tag{6.3}$$

where $\chi = (BHP/shaft)/100.0$, $3.0 \leq \chi \leq 32.4$.

For the twin screw 2 400 HP pushboat, the preliminary diameter is D = 6.98 ft (2.128 m). However as figure 10 indicates larger propeller diameters have been used at this power rating. The propeller diameter is a detail to be worked out with the final propeller design. The designer can complete the accomodation and machinery arrangements following references /20/ /26/.

Using the guidelines in Fig. 11 it is relatively straight forward to develop the tunnel stern arrangement. Therefore in this section a brief discussion regarding the tunnel stern design is given.

A comprehensive review of the tunnel stern design was presented by Saunders /27/. This has since been updated in 1959 by Baier /2/ and in 1982 by Latorre /4/, /10/. A number of guidelines for

arranging the tunnel stern have been presented. They are given in Fig. 11. Baier summarized US towboat design following the design scheme shown in Fig. 11-A /2/. Bogdanov /3/ presented the guidelines in Fig. 11-B following the scheme of Baier (Fig. 11-A). Professor Lederer /13/ has used the propeller diameter D to characterize the ducted propeller tunnel stern as in Fig. 11-C. Heuser /8/ has given a very complete guideline summarized in Fig. 11-D for the ducted propeller tunnel stern. Based on a survey of pushboat designs, Latorre has introduced the tunnel flow angles θ_1 and θ_2 /4/, /10/ defined using the tunnel geometry in Fig. 11-A as :

$$\theta_1 = \tan^{-1}\left|\frac{h_T}{\ell_1 - \ell_2}\right| \quad \text{Inflow tunnel angle} \tag{6.3}$$

$$\theta_2 = \tan^{-1}\left|\frac{h_m - T}{\ell_2}\right| \quad \text{Outflow tunnel angle} \tag{6.4}$$

Examining Baier's data and successful designs it was possible to specify criteria to insure an adequate flow in the tunnel stern /4/, /10/ :

$$\text{I.}\quad \theta_1/\theta < 1.14 - 0.018\,\theta < 1.0 \tag{6.5}$$

$$\text{II.}\quad \theta_2/\theta < 0.886 - 0.0286\,\theta_1 \tag{6.6}$$

When the pushboat operates in extremely shallow water the flow from the sides become important. Bogdanov /3/ indicates that for pushboats fitted with nozzle propellers the amount of water sucked from the sides is larger than the amount of water sucked from under the keel.

For the designer concerned with extremely shallow water conditions, the problem of vibration from inadequate flow becomes a problem. In one case Professor Baier fitted special flow ducts. These ducts allowed the water to be sucked by the propeller action from the pushboat side into the tunnel top ahead of the propeller. A simplier method is to provide a liberal cutaway at the towboat sides. Allan /1/ discusses actual designs with this feature. In his paper he shows hull plans with a large cut away at the tunnel sides to allow proper inflow to the propellers and discusses the propulsive performance of these designs.

For the present case, this cut away appears to be unnecessary and the guidelines in Fig. 11-D would be applied to complete the preliminary design.

7. Conclusions.

This paper has outlined the preliminary selection of pushboat power, full, and tunnel stern. The method is illustrated for a 2 x 2 barge tow. From the various aspects discussed the following conclusions can be given :

1. The empirical formula (3.1) for the pushboat thrust or "push" was shown to be in good agreement with published data.
2. For deep water barge tow resistance estimates, the formula (4.1) of Howe with suitable tow factor F was found to be in good agreement with the 2 x 2 barge tow data.
3. For the shallow water barge tow resistance formula 4.1 was not satisfactory.
4. The shallow water barge tow resistance could be estimated using the extended Apukhtin diagram in Figure 7.
5. It was shown that the shallow water conditions reduce the propulsive efficiency η_D by 16-23 % depending on horsepower
6. Guidelines for the towboat length, propeller, diameter and tunnel stern arrangement were summarized.

8. Acknowledgements.

This paper is part of an ongoing project /4/, /10/, /11/, /12/, to organize material on inland waterway pushboats, barge tows, and operations for teaching and student use in design projects. The author is grateful for the encouragement of many individuals in the inland waterway industry. He would like to acknowledge the encouragement from Professor Amelio D'Archangelo to prepare this paper for the VIII American Congress of Naval Engineering. Finally he would like to thank his Colleagues at the Bassin d'Essais des Carênes for their warm hospitality and in particular Madame C. Chamaud who typed this manuscript.

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Appendix - Notation

A : Power coeff. for pushboat
b : Barge beam
B : Barge tow beam
C : Depth coeff.
D : Propeller diameter
E : Speed factor
EP : Effective "push" of pushboat
F : Tow factor
F_h : Depth Froude number
g : Acceleration due to gravity
G : Pushboat push constant
h : Waterway depth
h_T : Stern tunnel height
HP : Pushboat horsepower
J : Barge tow resistance factor
K : Coeff. for EHP
$K = 550$ for EP in lbs, V ft/s
$K = 75$ for EP in kg, V m/s
ℓ : Barge length
ℓ_1 : Pushboat tunnel length
ℓ_2 : Pushboat propeller location
L : Barge tow length
LP : Pushboat length
P_B : Pushboat horsepower
P_E : Effective pushboat horsepower taken at tow speed
R_T : Barge tow resistance
t : Barge draft
T : Barge tow draft
T : Pushboat draft
v : Speed ft/s, m/s
v_o : Speed
V : Still water speed, mph, kph
W : Width of waterway
α : Depth coeff.
β : Velocity coeff.
γ : Draft coeff.

δ : Tow length coeff.
Δv : Change in speed in shallow water
ε : Tow width coeff.
η_D : Propulsive efficiency
θ : Tunnel centerline entrance angle
θ_1 : Inflow tunnel angle
θ_2 : Outflow tunnel angle
χ : Horsepower factor.

Table 1 River Tow Project Specifications.

Level 1	7000 LT (6890 MT) at V = 7.5 mph (12.07 km/hr) Still water speed. Channel Depth h = 16 ft (4.88 m), Width W = 700 ft (213.35 m)		
Level 2		Individual Barge	2 x 2 Barge train
	Length	ℓ = 200 ft (61 m)	L = 400 ft (122)
	Beam	b = 50 ft (15.24 m)	B = 100 ft (30.48)
	Draft	t = 9 ft (2.74 m)	T = 9 ft (2.74)
	Weights :		
	Steel	380 LT(374 MT)	1520 LT (1496 MT)
	Cargo Capacity	1870 LT (1841 MT)	7580 LT (7362 MT)

Table 2 Tow Factor K in Equation (4.1)

Tow Description Ref. :	Howe /6/	Non Integrated /29/	Semi Integrated /29/	Mixed Tow /29/	Fully integrated /29/
K value	0.07289	0.050	0.040	0.034	0.027

Table 3 Estimation of V from Fig. 7 for h/T = 1.78

V_o mph (kph)	2 ([illegible].22)	4 (6.44)	6 (9.66)	8 (12.87)	10 (16.1)	12 (19.3)	14 (22.5)
F_h	0.129	0.26	0.39	0.52	0.65	0.78	0.91
$\Delta v/v_o$	0.078	0.099	0.13	0.17	0.22	0.295	0.33
V mph (kph)	1.84 (2.96)	3.60 (5.79)	5.22 (8.40)	6.64 (10.69)	7.8 (12.55)	8.46 (13.61)	9.38 (15.09)

Table 4 Estimated Tow Velocity V and η_D (Fig. 8)

HP (MHP)	1800 HP		2400 HP	
Condition	Deep	Shallow	Deep	Shallow
V (Fig. 8)	9.0 mph (14.49 kph)	7.1 mph (11.43 kph)	9.7 mph (15.62 kph)	7.7 mph (12.40 kph)
V eq. (5.1)	8.97 mph (14.44 kph)	-----------	9.69 (15.60 kph)	-----------
η_D eq. (1.3)	31.4 %	24.25 %	29.27 %	24.9 %

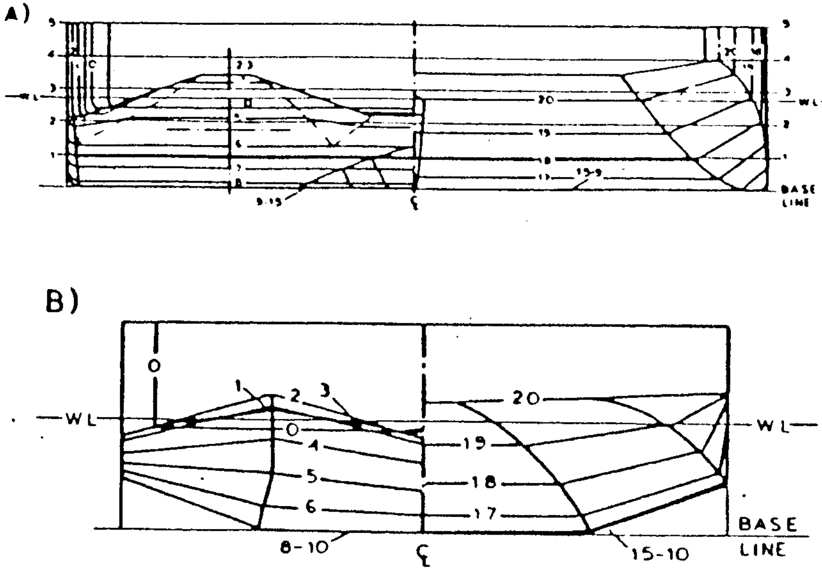

Fig. 1 - Pushboat hull lines plan /10/

A) Rhine river pushboat 3000 HP, L = 115 ft (35 m) B = 46 ft (14m) T = 5,75 ft (1,75m)
B) U.S. River pushboat 4000-6000 HP L=145 ft (44 m) B = 48 ft (14,6m) T = 9 ft (2,74m).

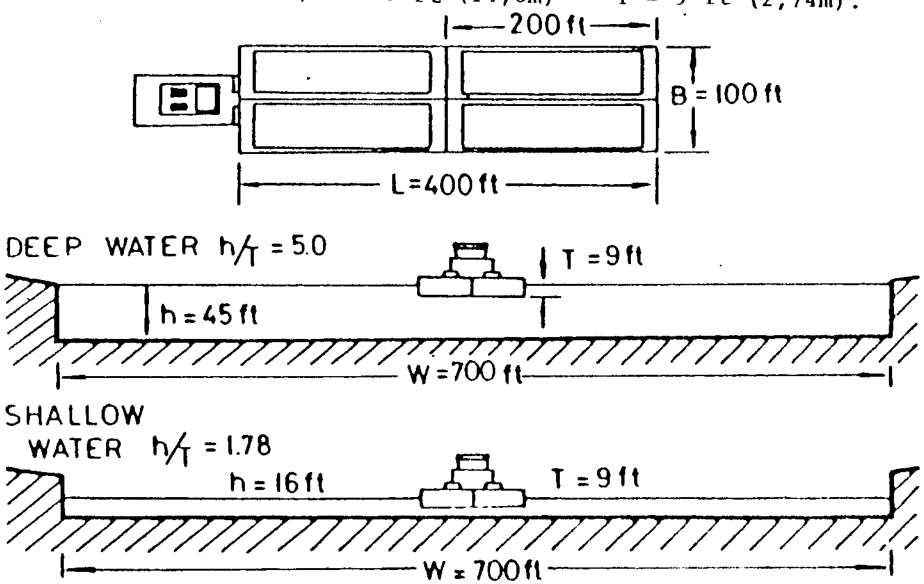

FIG. 2 TOW ARRANGEMENT AND CHANNEL GEOMETRY

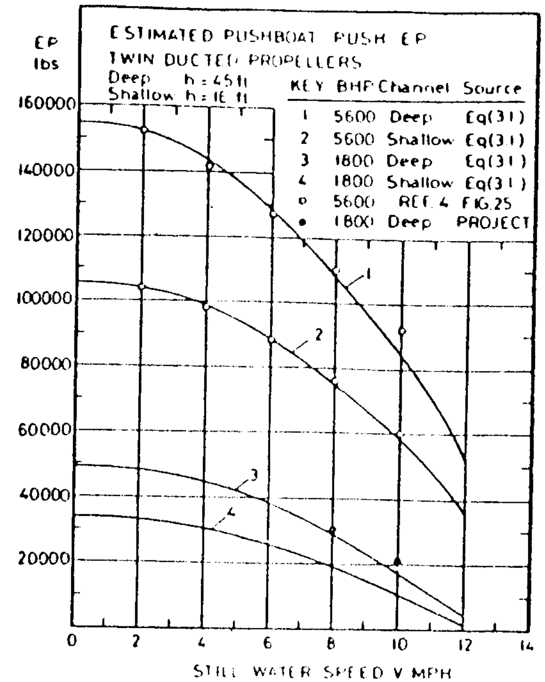

Fig. 3 - Estimated (pushboat thrust or "push" versus tow speed for 5600 HP and 1800HP twin screw pushboats.

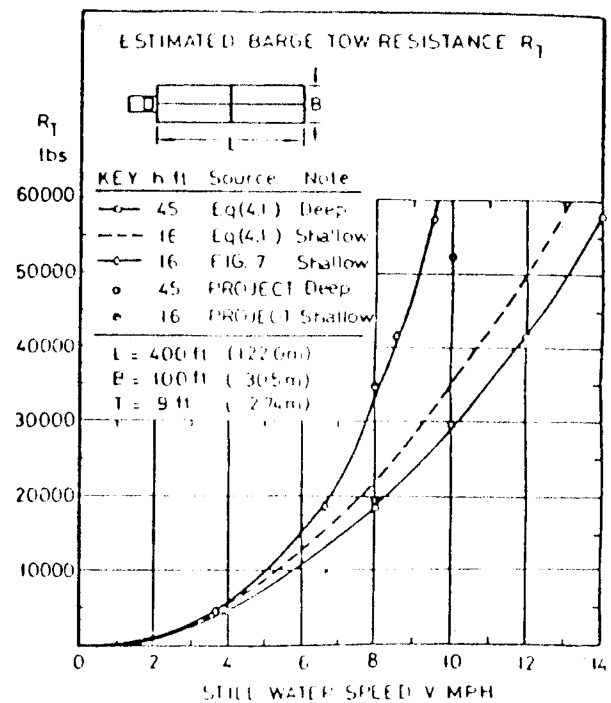

Fig. 4 - Estimated barge tow resistance versus tow speed for 2 x 2 barge tow.

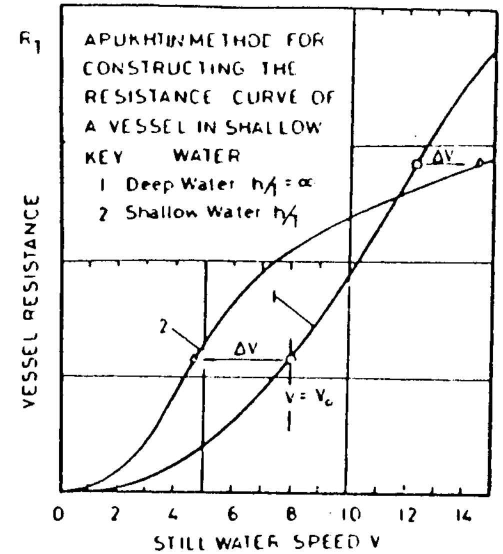

Fig. 5 - Apukhtin method for constructing the shallow water resistance curve from the deep water resistance curve /30/.

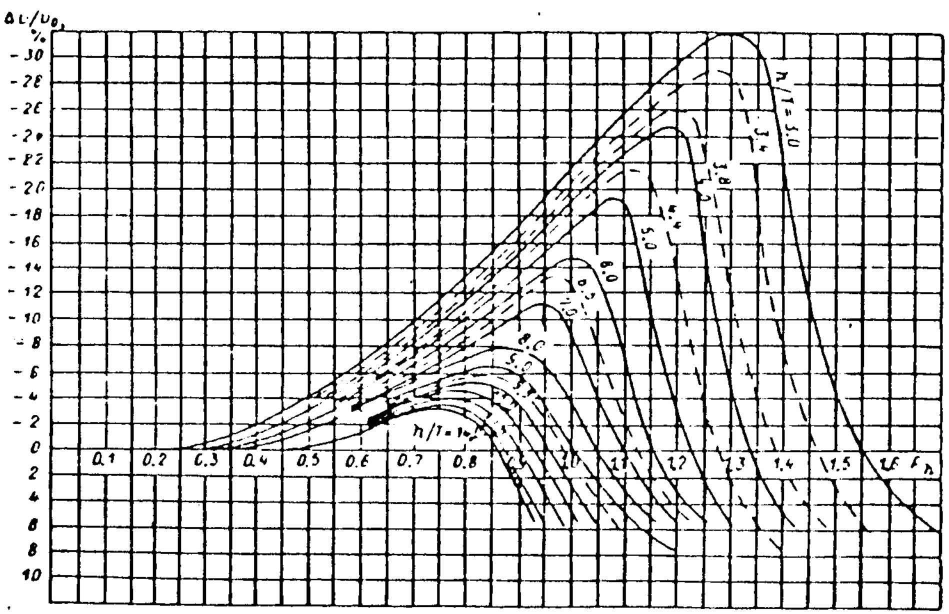

Fig. 6 - Apukhtin's Diagram for determing change of ship speed when moving in shallow water of depth h /30/.

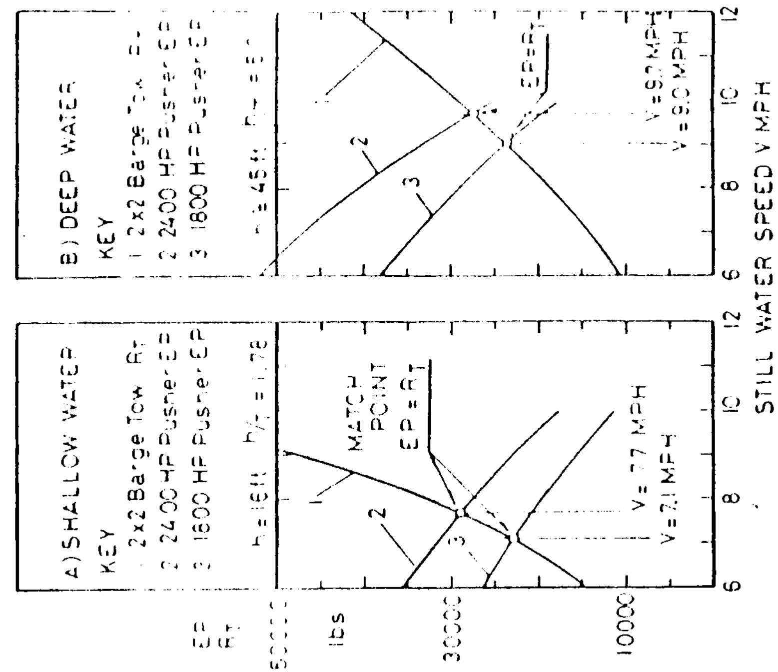

Fig. 8 - Estimate of Loaded barge tow speed V.

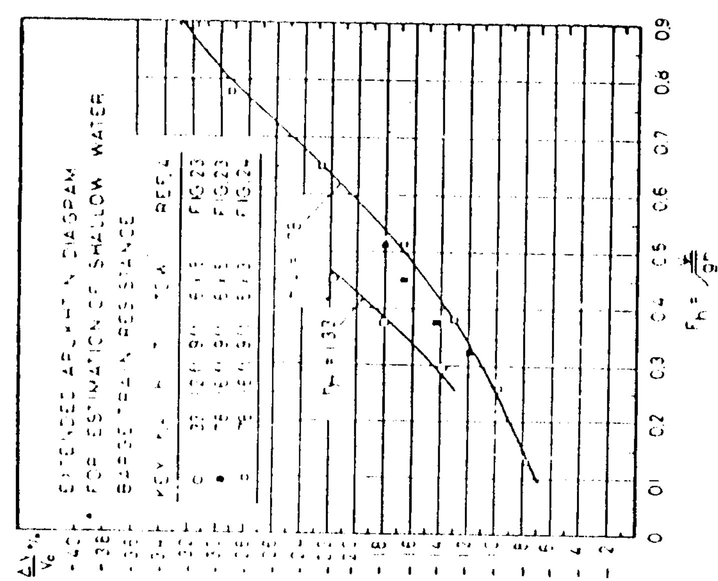

Fig. 7 - Extended Apukhtin Diagram for barge tow resistance.

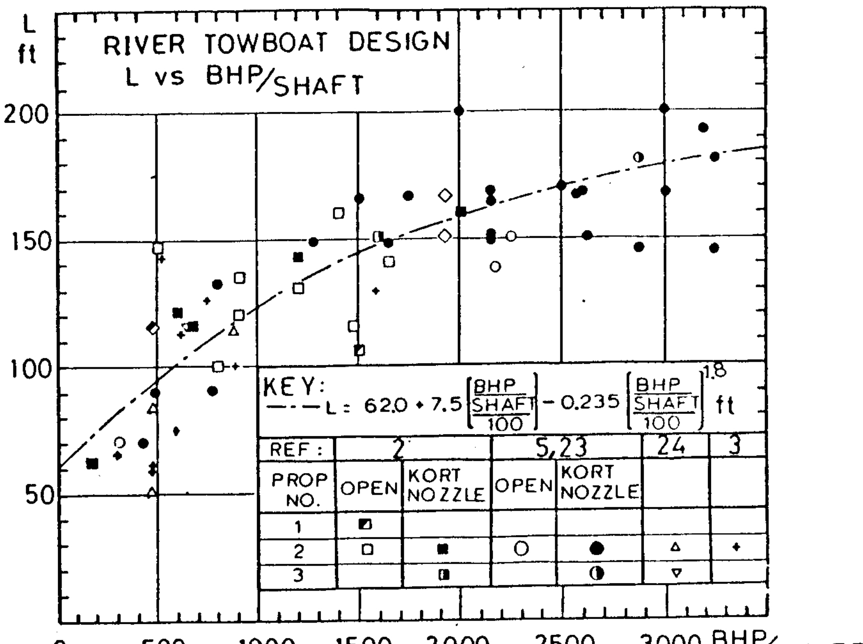

Fig. 9 - Pushboat length versus BHP/SHAFT /10/.

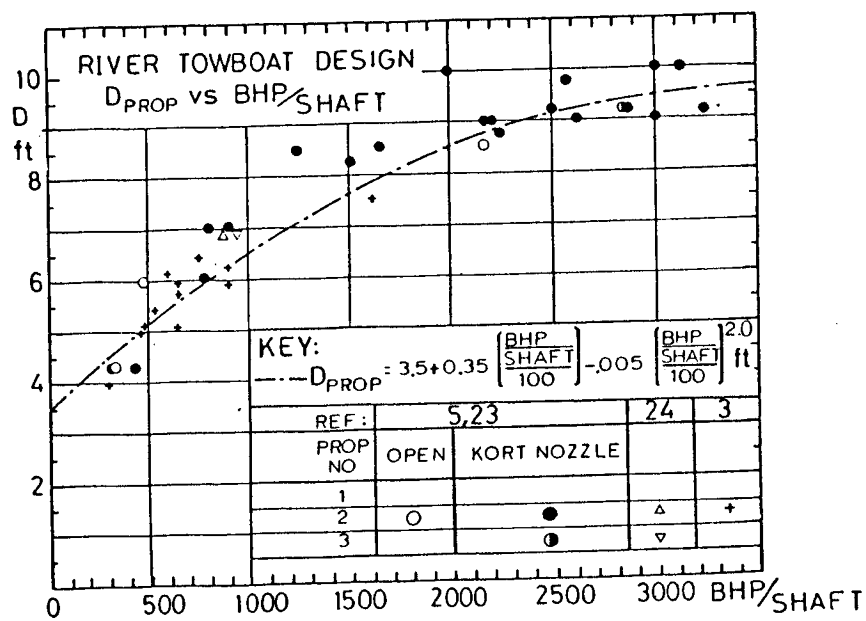

Fig. 10 - Pushboat Propeller diameter versus BHP/SHAFT /10/.

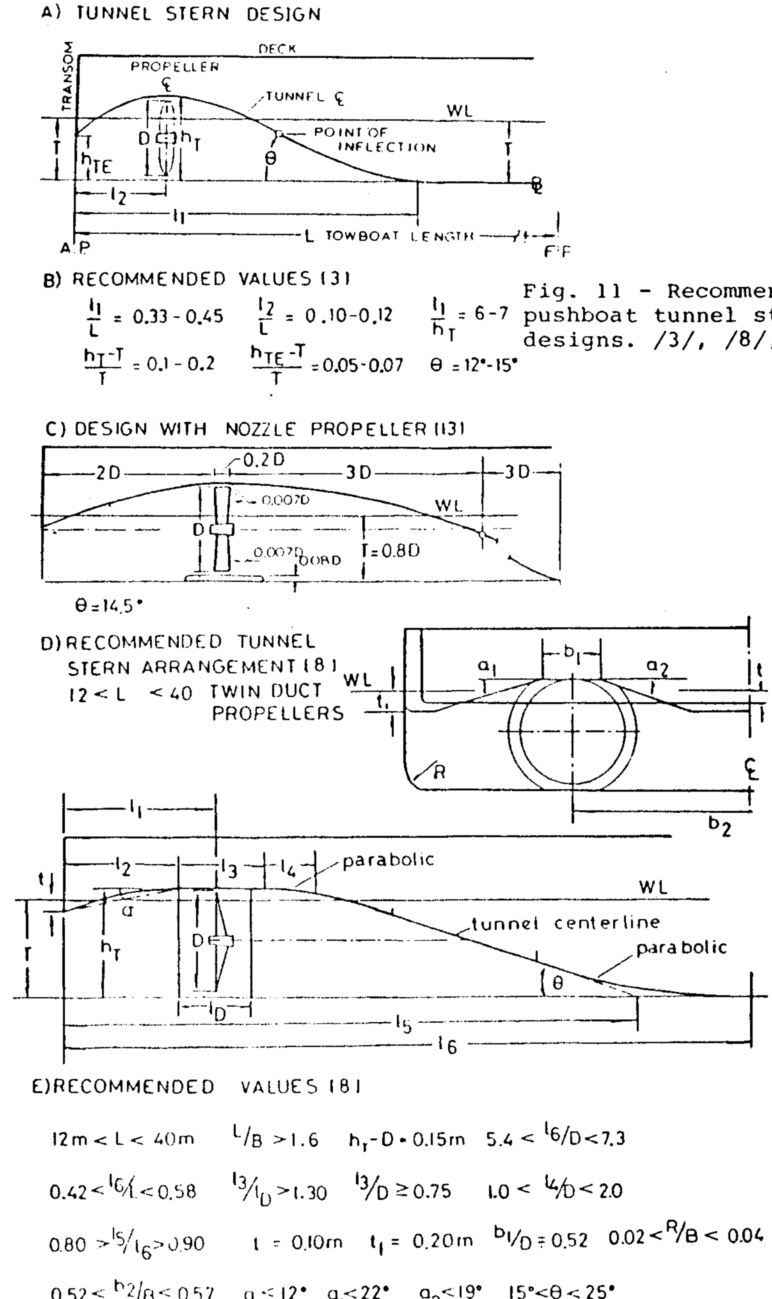

Fig. 11 - Recommended pushboat tunnel stern designs. /3/, /8/, /13/.