Feasibility Study and Design of Shallow Draft Ore Carriers for Inland Waterways

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ABSTRACT

The surge in iron ore exports from the Indian state of Goa has increased the demand for larger size inland iron ore carriers. Operating economics of these inland vessels have resulted in a steady increase in their carrying capacity. However, attempt to increase the deadweight of these vessels has encountered challenges in form of loading and unloading point restrictions, increased squat, sway force and yaw moment at shallow waters. The present work, based on a request from Ministry of Shipping, Government of India, examines the present ore transportation system, the bathymetry of the Mandovi and Zuari rivers and the operating economics of the barges ranging from 750 to 3000 tonnes deadweight capacity. A new improved design for 3000 tonnes deadweight barge is presented. Alternate stern shapes are examined using CFD software SHIPFLOW®. The hull form is model tested. The propeller geometry is optimized for the given engine and a suitable gear box. The proposed design is then investigated for its manoeuvring ability in shallow waters. The hydrodynamic sway forces, yaw moments and nominal wake distribution for port and starboard propellers during manoeuvring motion are estimated by CFD software SHIPFLOW®. The barge's directional stability performance is investigated for twin-propeller twin-rudder configuration.

Keywords: inland waterways, ore carriers, shallow water, manoeuvring, squat, sway, hull design, CFD, SHIPFLOW®.

RESUMEN

Provide here a concise abstract in Spanish, which should not exceed about 1000 characters / 200 words and shall be written in a single paragraph. The corresponding abstract in English is reported above. The font for the content of the abstract is 10pt, Times New Roman, Italics, fully justified (use the style "AbstractContent"). The title "RESUMEN" should have Font: Arial, 14pt, bold, Italics, capital, centred, 24pt spacing before and 12pt spacing after (use style "AbstractTitle"). Note that the title, the list of authors with affiliation and e-mail addresses and both the abstract in English and Spanish shall be contained in the first page. The paper will start, with the introduction section, in the second page. Apart from minor differences due to translation, abstracts in English and in Spanish will have the same content. The Conference Secretariat will be happy to provide support to all those authors needing help in translating their paper's abstract from Spanish to English or from English to Spanish.

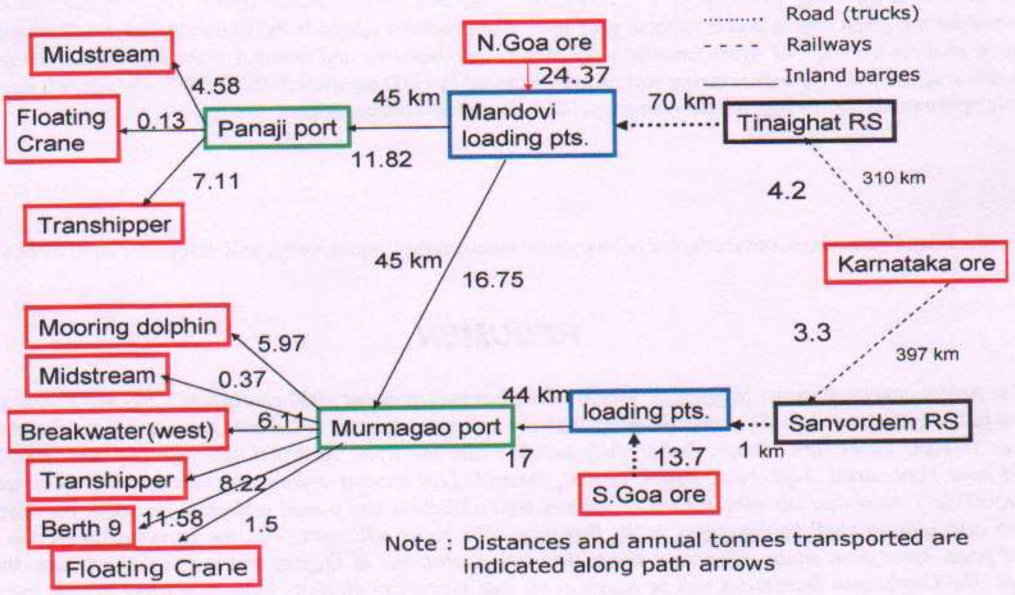
Keywords: after "Keywords: " put a list of up to 10 keywords or keywords phrases (in Spanish) separated by semicolon (e.g. river transportation; sustainable development; shallow water manoeuvring.). Font: Times New Roman, 10pt, fully justified (use style "KeywordsList")

INTRODUCTION

The ore carriers operating on the Mandovi and Zuari rivers of Goa contribute to 90% of inland transport in India [1]. The exports of Goan iron ore have steadily increased over the years [2]. Inland self propelled barges are used to transfer the iron ore from inland loading points to Mormugao and Panaji ports where the ore is loaded on to Panamax and Capesize ocean-going vessels. The economy of scale has forced the barge operators to progressively increase the deadweight of the barges. This was, however, done mainly through the experience of the barge operator. Little thought was given to the propulsion aspects when increasing the size of the barges and this has resulted in barges having very low propulsive efficiency. In the present regime of high input energy costs this impacted on the operating profits of the barge operators. The behaviour of such vessels in waters of restricted depth and their manoeuvring characteristics in Mandovi and Zuari rivers with many twists and turns is an area that also needs to be examined carefully. The present paper is an attempt to arrive at a new design of the barge carriers that is to operate on the two rivers that is efficient and will result in higher operating margins for the barge operators and at the same time meet the increasing demand of ore transportation.

ORE TRANSPORTING MODEL AND RIVER BATHYMETRY

The transportation model of the Goan and adjoining state Karnataka iron ore is shown in Figure 1. The data is based on statistical data of 2009 [2].



Note : Distances and annual tonnes transported are indicated along path arrows

Figure 1 : Present transportation model with loading and unloading points

Hydrographic charts for Mandovi (18 charts) and Zuari rivers (13 charts) were collected from Captain of Ports, Goa [3]. The details from these charts were entered in a AutoCad® file and a colour code was used to indicate the mean river depth. This allowed a better understanding of the navigable channel, river bends and critical areas of navigation in the channel for Mandovi and Zuari rivers. Figures 2 and 3 show the bends, available draft and critical navigation points Mandovi and Zuari rivers, respectively. Navigated route is approximately 20-24 nautical miles on river Mandovi and 25 nautical miles on river Zuari. The navigation is tidal with tidal draft variation of 2 metres.The sand bar at the mouth of river Mandovi at Aguada renders the trade on this route to be closed during monsoon. At certain locations the vessel has to wait for the tide to navigate.

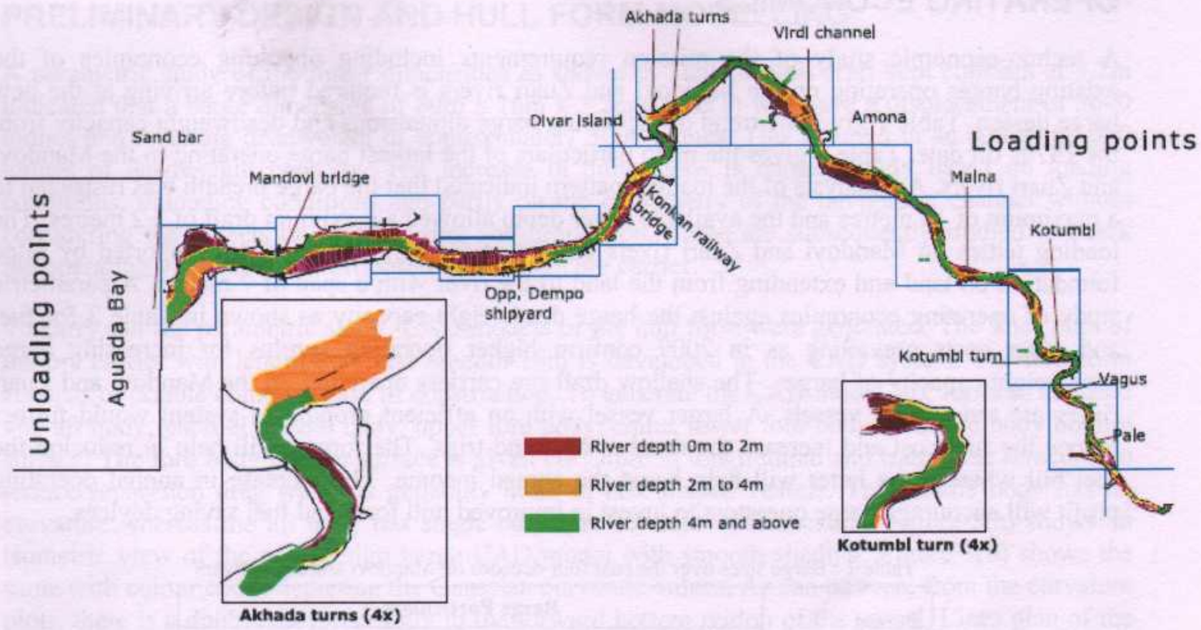


Figure 2 : Critical navigation points on Mandovi river

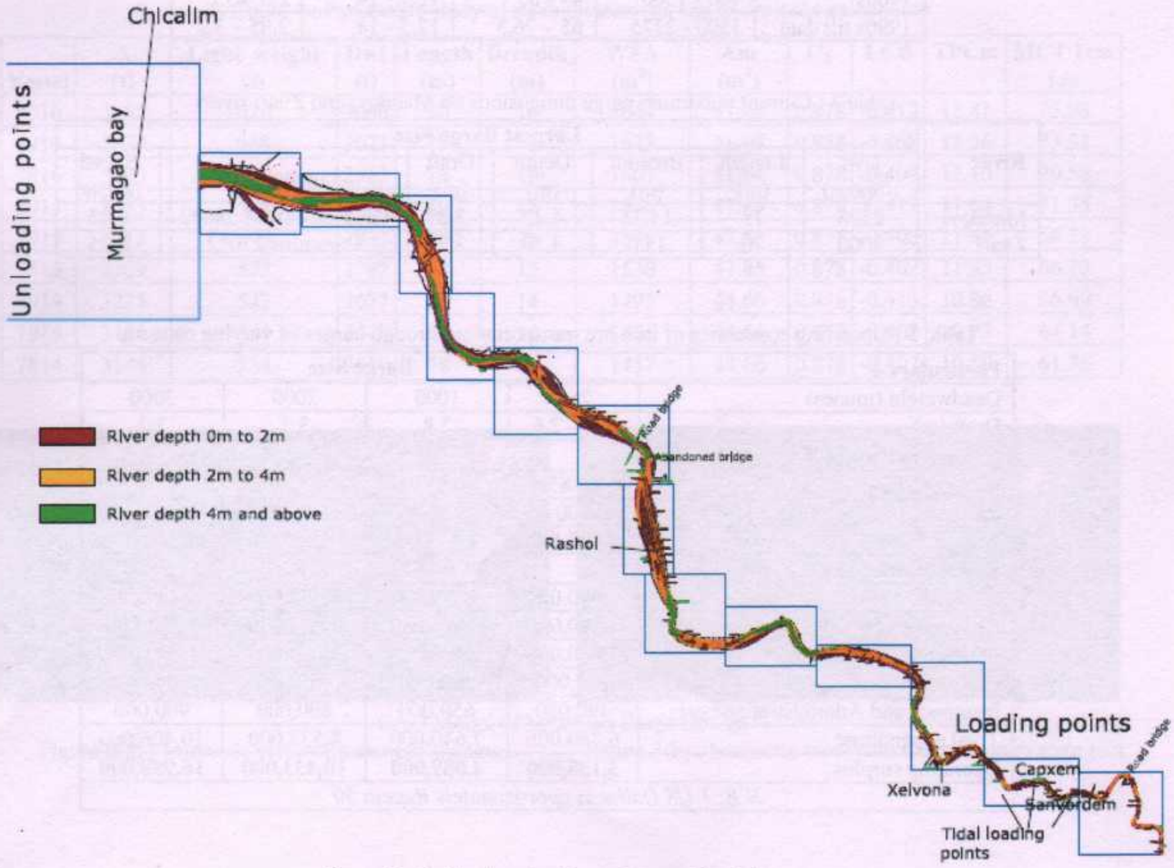


Figure 3 : Critical navigation points on Zuari river

OPERATING ECONOMICS

A techno-economic study of the mission requirements including operating economics of the existing barges operating on the Mandovi and Zuari rivers is required before arriving at the new barge design. Table 1 gives the trend of increasing barge dimensions and deadweight capacity from the 1970s till date. Table 2 gives the main particulars of the largest barge operating in the Mandovi and Zuari rivers. An analysis of the loading pattern indicated that the barge breadth was restricted to a maximum of 14 metres and the available water depth allowed a maximum draft of 3.2 metres. The loading jetties on Mandovi and Zuari rivers consist of a cantilever structure, supported by piled foundation on land and extending from the land to the river with a span of 7 metres. A parametric study of operating economics against the barge deadweight capacity as shown in Table 3 for fuel and other costs prevailing as in 2009 confirm higher operating surplus for increasing barge deadweight capacity of barges. The shallow draft ore carriers operating on the Mandovi and Zuari rivers are twin-screw vessels. A larger vessel with an efficient propulsion system would further reduce the fuel cost and increase the number of round trips. The former will help in reducing the fuel bill whereas the latter will help boost the annual income. The increase in annual operating profit will encourage barge operators to invest in improved hull form and fuel saving devices.

Table 1 : Barge sizes over the past four decades on Mandovi and Zuari rivers

Period	**Barge Particulars**			
	Dwt (tonnes)	Length (m)	Breadth (m)	Draft (m)
1970s	500 - 900	49 - 52	12.5 - 13	2.2 – 2.8
1980s	900 - 1500	49 - 65	12.5 - 14	2.6 – 3.2
1990s till date	1500 - 2525	65 – 76.5	12.5 - 14	2.95 – 3.2

Table 2 : Current maximum barge dimensions on Mandovi and Zuari rivers

River	**Largest Barge Size**						
	Dwt (tonnes)	Length (m)	Breadth (m)	Depth (m)	Draft (m)	Engine (hp)	Speed (knots)
Mandovi	2525	75	14.32	4.23	3.2	Greaves MWM 280*2	9.45
Zuari	2000	70	13.0	4.10	3.2	Cummins 270*2	8.25

Table 3 : Operating economics of iron ore transportation through barges of varying capacity

Particulars ↓	**Barge Size**			
Deadweight (tonnes)	750	1000	2000	3000
Draft (m)	2.5 – 2.6	2.8	3.2	3.2
Income in Rupees↓				
Rate per tonne	65.85	65.85	65.85	65.85
Round trips per annum	200	180	160	160
Annual Income	9,877,500	11,853,000	18,965,000	27,394,000
Expenditure per year in Rupees ↓				
Fuel cost	2,920,000	3,285,000	3,748,000	4,829,000
Crew wages	1,480,000	1,629,000	1,904,000	2,327,000
Maintenance and Repair	1,650,000	1,900,000	1,600,000	1,750,000
Port charges and Taxes	200,000	300,000	480,000	600,000
Insurance and Administration cost	490,000	650,000	800,000	900,000
Total expenditure	6,740,000	7,640,000	8,532,000	10,406,000
Operating surplus	**3,138,000**	**4,089,000**	**10,433,000**	**16,988,000**

N.B: 1 US Dollar is approximately Rupees 50

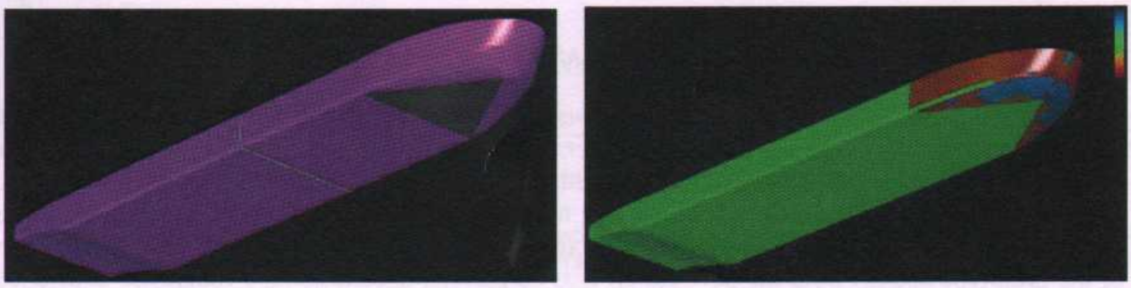
PRELIMINARY DESIGN AND HULL FORM MODELLING

A parametric study of the linear dimensions as shown in Table 4 with draft kept constant at 3.2m indicated that a barge dimension of 80m x 16m x 3.2m (LxBxT) will have a displacement of 3600 tonnes and resulting deadweight of approximately 3000 tonnes. This resulted in an additional 500 tonnes of deadweight capacity. The increase in dimensions is chosen solely based on loading conditions, unloading conditions and partly on the bathymetry of the navigation channel without considering the aspects on manoeuvring and propulsion. These are subsequently studied to check the operating viability of the proposed new design ore carrier.

To carry out the parametric study, CAD models of the hull form were generated. The lines plan of the ore carrier with length 80m and breadth 16m is developed in the CAD system. The hull form consists of double chine for ease of construction. To generate the CAD model, six surfaces are used viz. aft body, parallel middle body, upper fore body, chine, lower fore body, and fore body bottom surface. The fore body bottom surface is given curvature in longitudinal and transverse direction to reduce separation drag which is generally more in box shaped vessels. The middle body has no curvature whereas the aft body has single curvature for ease of fabrication. Figure 3(a) shows an isometric view of the new design barge CAD model with smooth shading. Figure 3(b) shows the same with colour codes depicting the Gaussian curvature values. As can be seen; from the curvature plots, there is a double curvature only in the forward bottom region of the vessel. Lines plan of the vessel is presented in Figure 4.

Table 4 : Parametric study of main dimensions and hydrostatic calculation

Vessel	Δ (t)	Light weight (t)	Dwt (t)	Length (m)	Breadth (m)	WSA (m^2)	Am (m^2)	C_B	LCB	TPCm	MCT 1cm t.m
8016	3685	626	3060	80	16	1644	51.04	0.878	-0.413	12.41	75.94
7916	3639	618	3021	79	16	1623	51.04	0.878	-0.408	12.26	73.31
7816	3593	610	2983	78	16	1603	51.04	0.878	-0.402	12.10	70.58
8015	3455	586	2868	80	15	1568	47.85	0.878	-0.413	11.64	71.35
7915	3412	579	2833	79	15	1549	47.85	0.878	-0.408	11.49	68.73
7815	3369	572	2797	78	15	1530	47.85	0.878	-0.402	11.35	66.17
8014	3225	547	2677	80	14	1493	44.66	0.878	-0.413	10.86	66.60
7914	3184	541	2644	79	14	1475	44.66	0.878	-0.408	10.73	64.14
7814	3144	534	2610	78	14	1457	44.66	0.878	-0.402	10.59	61.76



CAD Model of New Goa Barge Design

Figure 3(a) : Isometric view with smooth shading

Figure 3(b) : Isometric view with Gaussian curvature plot

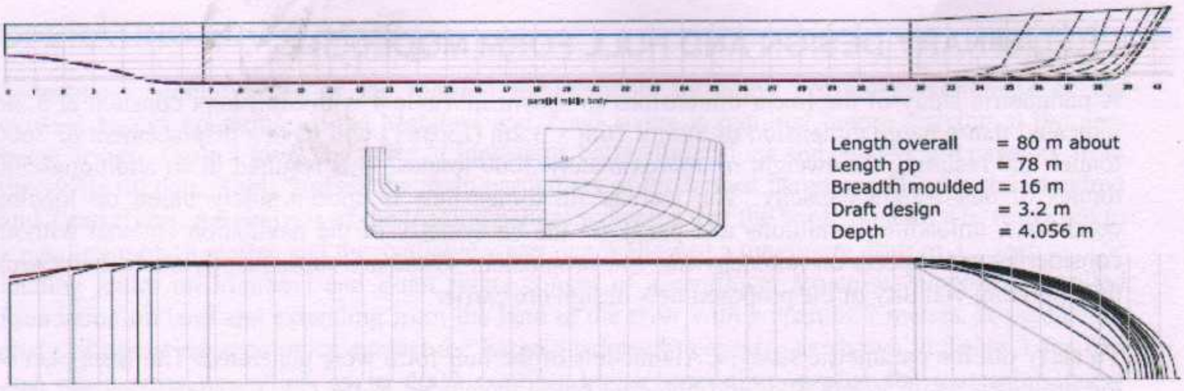


Figure 4: Lines Plan of Goa Barge (Design A)

GENERAL ARRANGEMENT, MIDSHIP SECTION AND STABILITY

The general arrangement of the parent vessel is considered to finalise the general arrangement of the new dimension ore carrier. Indian Register of Shipping (IRS) rules on "Construction and Classification of Inland Waterway Ship" are used to finalise the double bottom height, bulkhead and collision bulkhead positions [4]. The salient features of the space locations were as follows:

- Frame spacing = 600mm
- Collision bulkhead location = Frame 125
- Engine Room = Frame 11 to Frame 23
- Cargo Hold # 2 = Frame 50 to Frame 80
- Double bottom height = 900mm
- Aft peak bulkhead location = Frame 11
- Cargo Hold # 1 = Frame 80 to Frame 105
- Cargo Hold # 3 = Frame 24 to Frame 50

Tank compartmentalisation is done using the CAD software prior to stability calculations. Load cases considered for stability are fully loaded condition and ballast water condition. The initial metacentre (GM) and area under the static stability lever curve (GZ) are checked with the classification rules. The maximum GZ occurred at 23.9 degrees and above, which is acceptable for inland vessels. The inland vessel does not experience rough sea conditions and hence do not have rigorous stability criteria. The vessel is also checked for trim to ensure propeller immersion and for this additional aft tank is provided. Figure 5 gives the general arrangement drawing for the vessel.

The scantling calculations are based on IRS "Rules for Construction and Classification of Inland Waterway Ship" [4] and the midship section drawing is shown in Figure 6.

MODEL TEST AND EFFECTIVE POWER ESTIMATION

At the preliminary design stage the bare hull resistance is calculated using model test results of published in SNAME model resistance data sheet, D-8 [5]. The prototype model dimensions chosen are as follows: Lwl = 5.813 ft (1.772m); Breadth = 1.094 ft (0.333m) Draft = 0.266 ft (0.081m); Displacement =1.507 ft3 (0.043 m^3). The model test results are then extrapolated to full scale using ITTC 1957 extrapolation method. Moor's correction [6] is then applied to account for the deviation of the prototype chosen from the new design Goa barge. The appendage and roughness allowance are added based on Holtrop and Mennen [7] to get the total resistance of ore carrier in deep water.

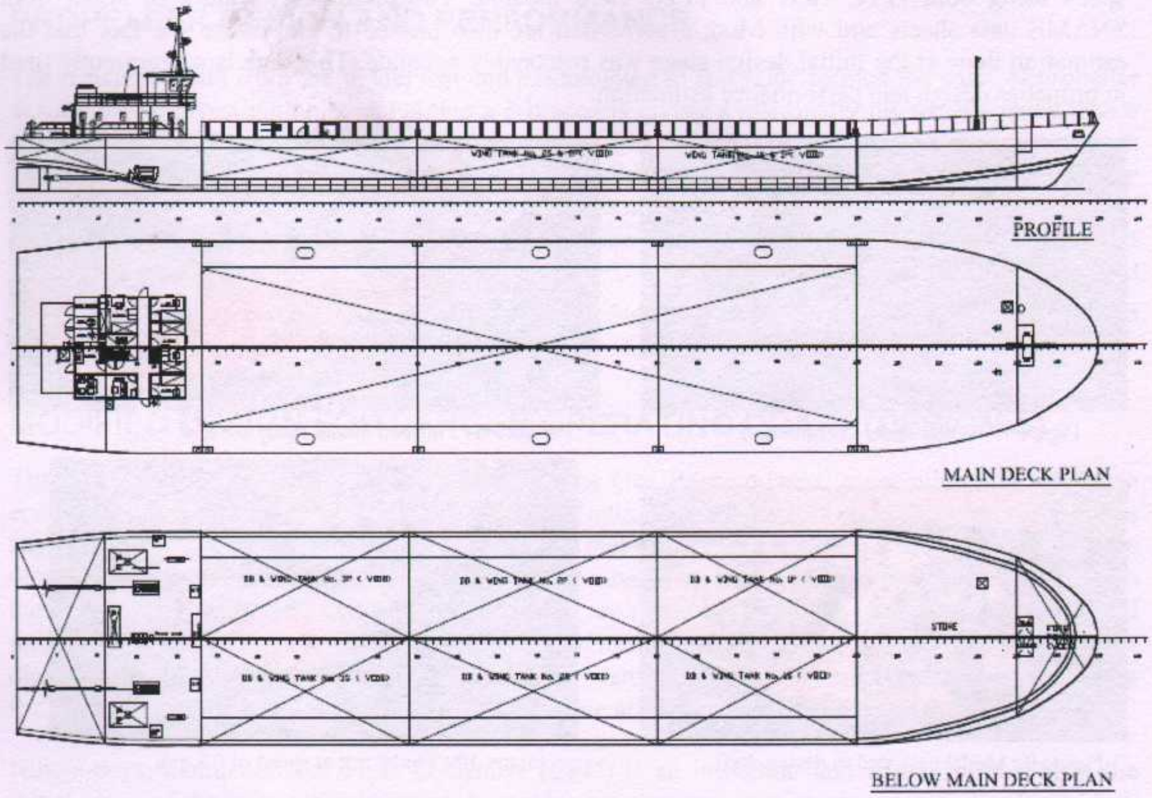


Figure 5 : General Arrangement of 3000 tonnes dwt ore carrier

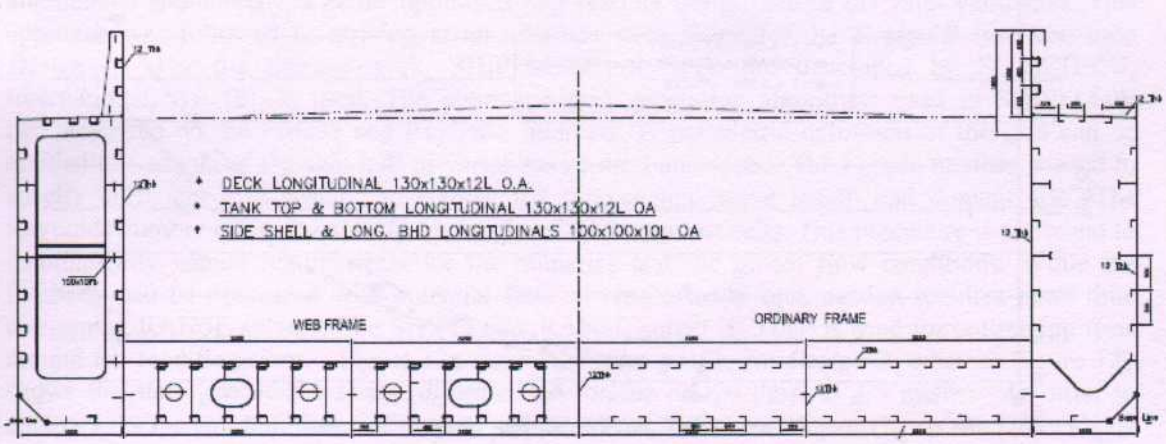


Figure 6 : Midship Section of 3000 tonnes dwt ore carrier

Once the lines plan is faired and frozen at the preliminary design stage, a 1:25 scaled model of the new Goa barge design is manufactured at the Hydrodynamics Laboratory of the Department of Ocean Engineering and Naval Architecture, IIT Kharagpur. Figures 7 and 8 show the model under construction and on completion, respectively. The model is ballasted to the draft corresponding to 3.2 metres at full scale (Figure 6). The model is then attached to the R47 dynamometer (Figure 9) and towed at over the complete range of corresponding Froude speeds by the Towing Carriage. Figure 10 shows the model being towed 0.8 m/s, which corresponds to the full scale speed of 7.8 knots. The model resistance values at corresponding speeds are extrapolated using ITTC 1957 method and also ITTC 1978 method. Figure 11 gives the extrapolated effective power versus ship speed using both ITTC 1957 and ITTC 1978 method. The preliminary values obtained from SNAME data sheets and with Moor's correction are also plotted to emphasise the fact that the estimation done at the initial design stage was reasonably accurate. This data is subsequently used in propeller design and performance estimation.

Figure 7 : Model under construction

Figure 8 : Finished model ready for test

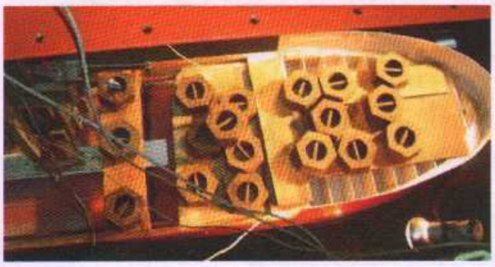


Figure 9 : Model ballasted to design draft

Figure 10 : Model test at speed of 0.8 m/s

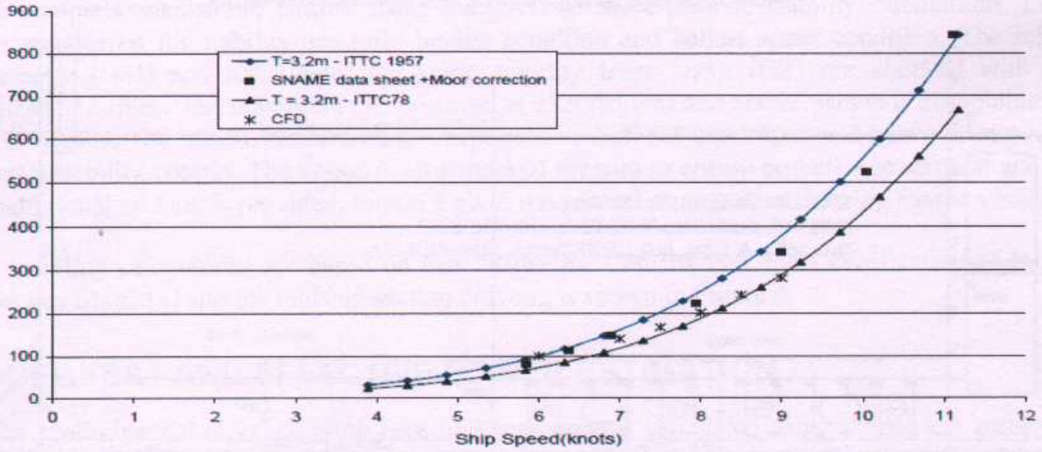


Figure 11 : Ship Speed vs Effective Power Goa Barge at T= 3.2m (using ITTC 1957 & ITTC 1978 method)

ENGINE AND GEAR BOX SELECTION

The engines used on existing ore carriers are in the range of 280-350 hp and have engine rpm of 1800 rpm. Gearbox of gear ratio (3.5 - 5) is being used in the industry so as to reduce the propeller rpm and obtain better propulsive efficiency. From their experience, Goa barge owners' association preferred Cummins 270 bhp of 1800 rpm for the new Goa barge design. The gearbox ratio options available were 4.9/4.5/3.8. A higher gear ratio results in a lower propeller rpm. This leads to a larger propeller diameter and higher propulsive efficiency. Therefore, the gearbox ratio is fixed at 4.9 and the resulting propeller rpm of 367. The propeller rpm was checked for hull resonance.

PROPELLER DESIGN AND PERFORMANCE

The resistance data from the model test and extrapolated to full scale formed the basis of propeller design. Initial investigation revealed that a 3-bladed is giving a marginally higher efficiency than a 4-bladed propeller. The 3-bladed propeller will be of less weight and easier to manufacture which should result in cost saving. The subsequent propeller design calculations are optimised for the *Design-A* with engine power of 2x270 hp for a 3-bladed propeller. The engine and the gearbox ratio being fixed by the Goa barge owners' association. The optimised propeller of diameter 1.6 m has a blade area ratio (A_E/A_O) of 0.4 and a pitch ratio (P/D) of 0.58. Performance calculations for load factor 1, 1.1 and 1.2 are carried out for this optimised propeller keeping in mind the increased resistance due to shallow water effects.

MODIFIED DESIGN FOR LARGER OPERATING DRAFT (*DESIGN-B*)

The present design (*Design-A*) was presented to the Goa Barge owners' association at a workshop convened by the Ministry of Shipping, Govt. of India. During the course of the workshop it was suggested that a design of shallow draft ore carrier that can operate at a design draft of 3.5 metres be developed as the Captain of Ports, Goa will allow vessels up to a draft of 3.6 metres to operate on these rivers. It was agreed that since these barges are made by small shipbuilders in Goa, the hull form will be kept the same with only the stern region suitably modified to accommodate a larger diameter propeller. The barge owners' association were keen on using Cumminns 2x530 hp engine for the design variant *Design-B* which was to operate at a draft of 3.5 metres to 3.6 metres.

Now-a-days, Computational Fluid Dynamics (CFD) is an important and widely used tool in the initial stage of the ship design process. It enables the designer to evaluate a larger number of hull alternatives and thereby a better optimized and reliable design before the final validation. This approach was followed in arriving at an alternate stern shape for the *Design-B* from the base *Design-A*. For the present work, SHIPFLOW®, a CFD tool developed by FLOWTECH, International, AB [8], is used. The automatic grid generation algorithms used in SHIPFLOW parameterised on the Froude and Reynolds numbers. A parametric definition of the grid can be applied to variants of the ship hull or variations of draft and speed. The Froude number is used to specify sufficient grid spacing to resolve the fundamental wave length and domain size. The Reynolds number is used to specify the height of the innermost cells. This procedure is sufficient to automatically handle requirements for the numerics and the global flow conditions. While the forebody can be optimized with potential flow solvers, aftbody optimization requires more time consuming RANSE solvers. The SHIPFLOW RANSE solver XCHAP is used for optimizing flow around the modified stern. Figure 12a shows the stern profile for *Design-A*, whereas Figure 12b shows the stern profile for *Design-B* optimised for the design draft of 3.5 metres. In order to compare the the two hull forms of varying displacements, Telfer coefficient C_{TL} is used [9]. C_{TL} is defined as $\frac{R_T/\Delta}{\left(V/\sqrt{L_{WL}}\right)^2}$. C_{TL} values for *Design-A* and *Design-B* are plotted in Figure 13 on the basis of length Froude number. From of the plot of Telfer coefficient it is evident that *Design-B* is a relatively better hull form over the entire operating speed range. The wave height along the hull and free surface elevation for *Design-A* and *Design-B* are shown in Figures 14a and 14b respectively. The modified stern geometry allows for a propeller of up to 2 metres diameter to be accommodated. A 3-bladed propeller for the *Design-B* is designed. Propeller performance calculations, strength estimate, blade and hub geometry are also carried out.

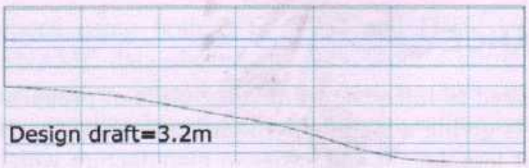


Figure : 12a Goa Barge Design (Design-A)

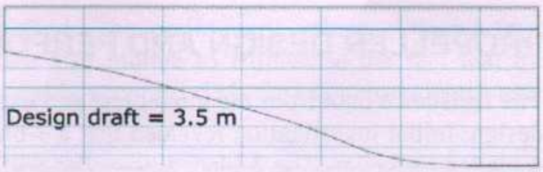


Figure : 12b Modified Stern Goa Barge Design (Design-B)

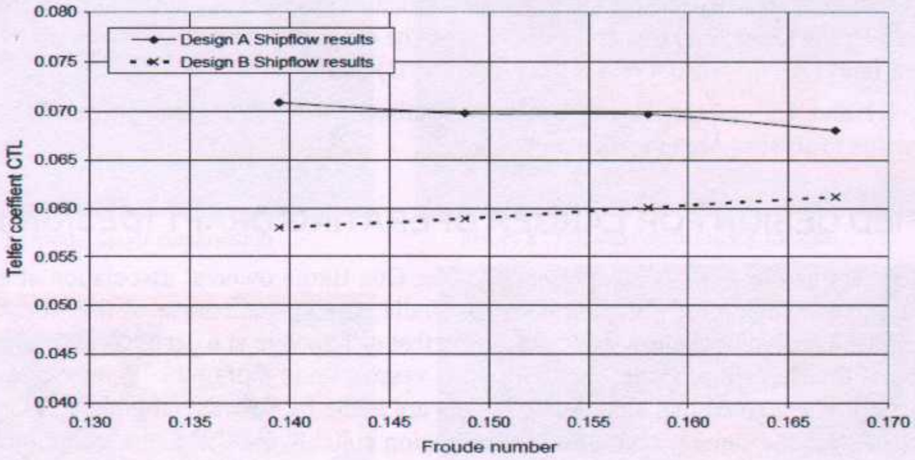
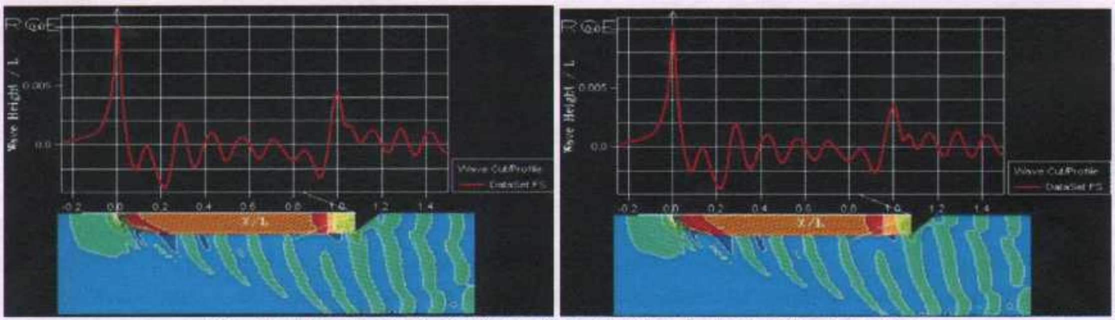


Figure 13 : Comparison of Design-A and Design-B using SHIPFLOW®



Wave height along hull and free surface elevation for design Froude number

Figure 14a : Design A

Figure 14b : Design B

SHALLOW WATER EFFECTS

The iron ore carrier operating in the shallow waters of Zuari and Mandovi rivers are investigated from the manoeuvring point of view for increased squat, sway forces and yaw moments due shallow waters (river depth ranging from 2.8 to 8 metres) and flow confinement (bank effects). These forces and moments are important as the proposed new Goa barge design is of increased length and breadth. The effect of increase in the length and breadth dimensions are likely to result in an increase of sway force and yaw moment, thereby affecting the directional stability. The performance of the designed propeller due to reduced fairway depth is also studied. The effects in shallow water [10] due to flow confinement and asymmetry of motion in navigation channel are summed up as:

- Increase in squat.
- Increase in resistance
- Increase in sway force and yaw moment

Increase in squat

The squat (relative sinkage when in motion) of the vessel is increased in shallow water due to flow confinement and asymmetry of motion. When a vessel moves from deep to shallow water, the water flow below it speeds up more than it does in deep water, with a consequent greater reduction in pressure and increased sinkage and trim [11]. If in addition the water is restricted laterally, as in river or canal, there is a further increase in squat [12]. The squat formula given by Millward [11] does not account for lateral flow confinement due to narrow channel which is accounted for in the Barass formula [12]. The type of river bottom is not considered in the present calculation. The Barass formula [12] for squat due to narrow channel is given by:

$$100\left(\frac{\bar{z}}{L}\right)=\frac{\frac{100}{L/h}\frac{A}{A_C}F_{nh}^2}{1-\frac{A}{A_C}-\frac{hW_O}{A_C}F_{nh}^2} \tag{1}$$

where $\bar{z}$ is the sinkage in m; L is the length of the vessel in m; h is the depth of water in m;
A_C is the cross section of the channel in m^2; W_O is the surface width of the channel in m;
A is the immersed midship area of vessel in m^2; F_{nh} is the depth Froude number;

The port starboard symmetry of the flow around the vessel is marred by presence of a sway or yaw component [10] in the ship speed vector or by the presence of a side of the hull and forcing the streamlines to curve around it. When the vessel moves parallel but offset from the centre line of a narrow canal, the squat of the ship will increase slightly. For the designed ore carrier the following are the conclusions related to squat from Figure 15:

- At grounding points the vessel speed should be reduced to 4-5 knots which gives at squat of 0.077m to 0.2m.
- The designed vessel of increased breadth and length further increases the squat by an amount 0.1 m as compared to existing vessels. Hence the masters on the vessel should add 0.1 m to the existing grounding tide levels.

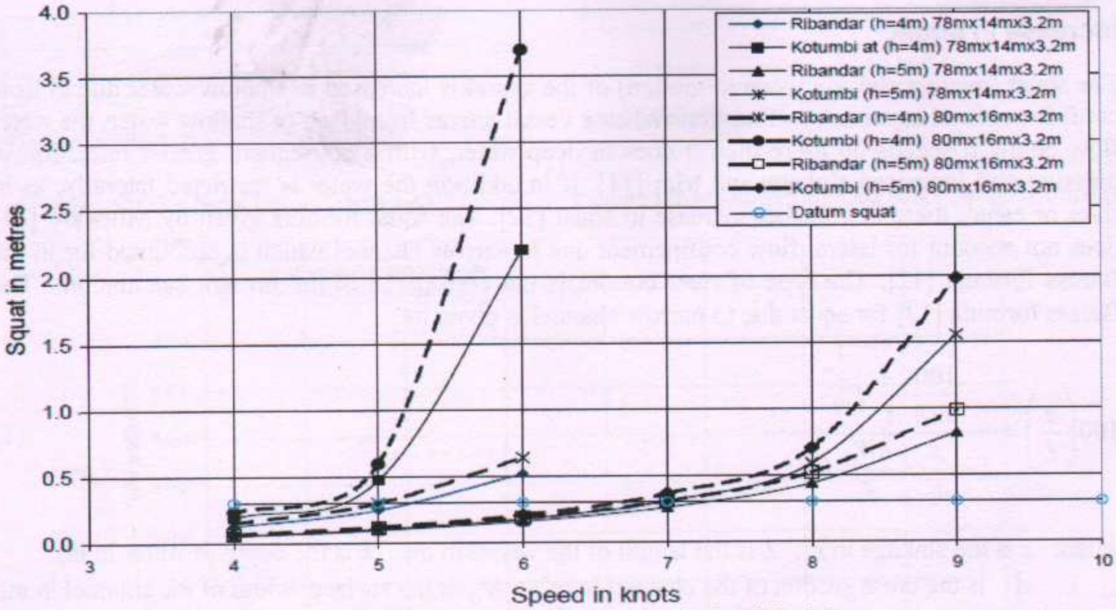


Figure 15 : Squat at narrow channels on Mandovi and Zuari rivers

Increase in resistance

The resistance of a ship is quite sensitive to the effects of shallow water. In the first phase there is appreciable change in potential flow around the hull. If the ship is considered at rest in a flowing stream of restricted depth but unrestricted width, the water passing below it must speed up more than in deep water, with a consequent greater reduction in pressure and increased sinkage, trim and resistance [13]. If in addition the water is also restricted laterally, as in river Mandovi and river Zuari, these effects are further exaggerated. The increase in resistance is determined by Schlichting method [14] and shown in Figure 16.

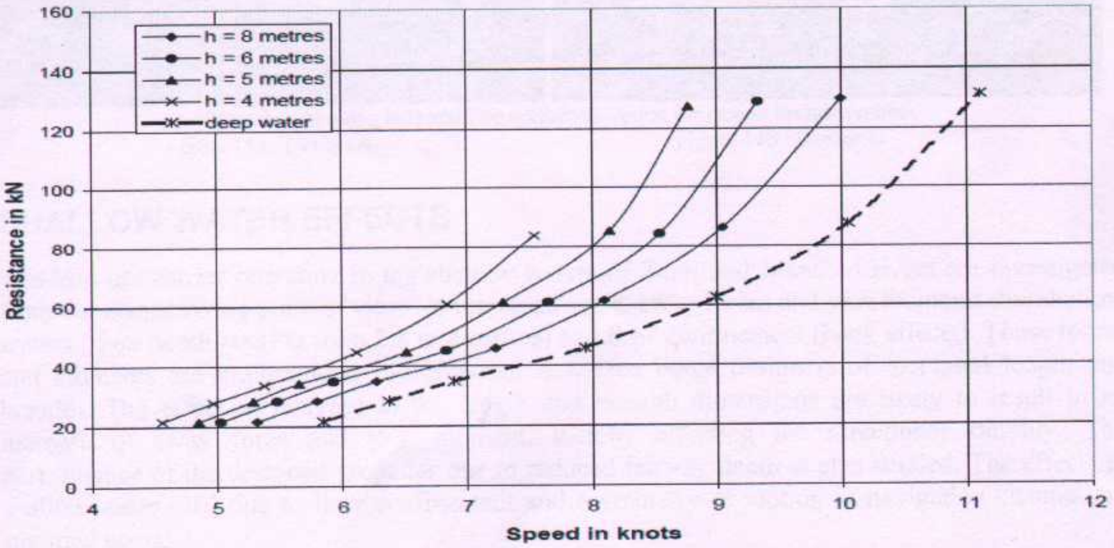


Figure 16 : Resistance in shallow waters at different water depths

Increase in sway force and yaw moments

When a vessel proceeds along a bank in shallow water a lateral sway damping force (Y) between ship and the side bank and a yawing moment (N) turning the bow away from the bank acts on the vessel i.e. the resulting force usually has its centre of pressure somewhat aft of midship. The increase of damping derivatives with reduction in underwater clearance is closely associated with simultaneous added masses, and these are sensitive to breadth of vessel (B). These sway force Y and moment can be countered by rudder angle (δ) and ship side-slip (β) required to maintain a steady state passage along a track parallel to and at a distance from the bank.

The largest vessel operating on Mandovi river and the new design are equal in fullness and form except for difference in breadth ($B_1 = 14$ m and $B_2 = 16$ m) and length ($L_1 = 77$ m and $L_2 = 80$ m). It is assumed that the vessels are moving at the same speed and equal centreline distance from long bank. The acceptance of a common value for the force derivative $0.5Y''_{uun_S}$ as well as the moment derivative $0.5N''_{uun_S}$ now implies that $Y_2/Y_1 = B_2^2/B_1^2$ and $N_2/N_1 = L_2/L_1$. The sway force for the new vessel will be $Y_2 = 1.3Y_1$ and the yaw moment for the new vessel will be $N_2 = 1.04N_1$.

CFD INVESTIGATION INTO HYDRODYNAMIC FORCES ON THE BARGE

Due to the layout of the river transportation network, it is observed that barge have to manoeuvre continually during their voyage. In open oceans, vessels usually cruise at steady speed for long duration of time with very little rudder movements. However, in river navigation, rudder movements are continuous and the operator has to be very alert since no advanced navigational aids are available. The hydrodynamic forces on the *Design-B* of the barge are investigated using SHIPFLOW®, since this design was optimized for the river navigation from resistance and propulsion point of view. The principal particulars of *Design-B* are given in Table 5.

Table 5Principal particulars of Design B

L_{WL} (m)	L/B	B/T	xG/L	Yp/L	C_B	A_R/LT	Rudder AR	Prop dia (m)
78	4.875	4.571	1% fwd	0.245	0.87	0.014	1.4	2.0

Due to high block coefficient of the barge, the hydrodynamic forces on the barge during manoeuvring are expected to be high. For twin propeller twin rudder vessels, the asymmetry in propeller plane wake during manoeuvring becomes significant. This asymmetry may induce sway force and yaw moment on the barge at the propeller plane. In open oceans this disturbing forces could be easily countered by rudder action, however in a narrow canal the continuous rudder action can exhaust the helms or the navigator. This may cause accidents/ navigational problems etc. In river navigation, the drift angle may go up to 20°. The vessel does not have enough area for performing turning manoeuvres, etc. In large ocean going vessels, the rudder is actuated by hydraulic machinery through an autopilot control system. However, in the subject river barge, the rudder actuation is manual through, pulley and wire rope arrangement. This changes the steering dynamics of the vessel as compared to an autopilot driven vessel.

We first investigated the hydrodynamic forces acting on the barge during deep-water condition. The variation of sway force and yaw moment acting on the vessel is shown in Figure 17. The variation observed was similar to other twin-propeller twin-rudder vessel available in literature [14].

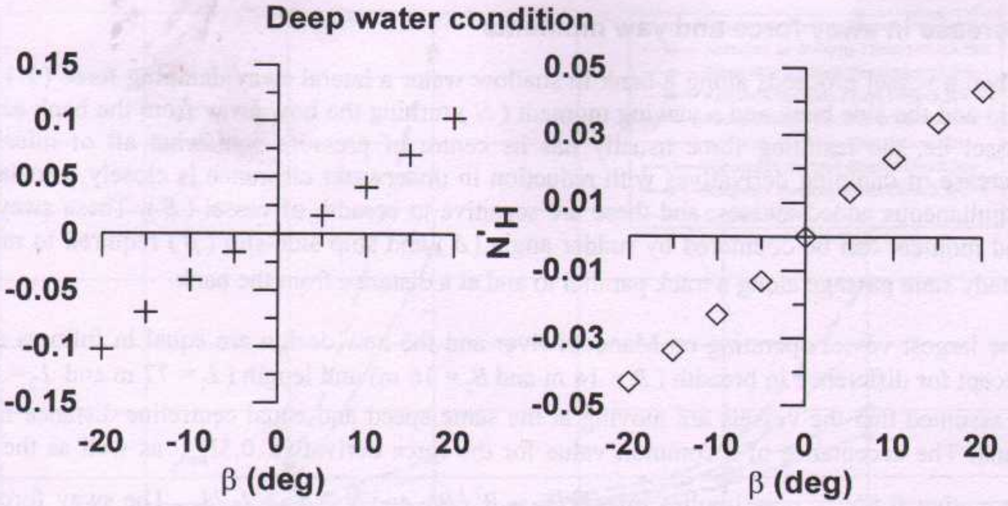


Figure 17 : Hydrodynamic force coefficients Y'_H and N'_H

For optimization of the propeller design, the propeller wake in way of propeller plane is investigated. The propeller wake in the straight running condition of the vessel is shown in Figure 18. The wake is higher near the hull therefore; the flow velocity is greater at the bottom of the propeller than at the top. As a result, the blades are at a larger angle of attack and so produce more thrust (and torque) when they are above the hub [15]. Besides above, the port and starboard propeller rotate in opposite direction. This may result in transverse force acting on the hull at the propeller disc position during straight running condition. For manoeuvring in narrow rivers, such transverse forces though of lower magnitude become important. These transverse forces are usually proportional to propeller torque, Lewandowski [15]. It may be noted here that propeller plane wake is influenced by shallow water condition. Yoshumira and Sakurai [14] showed that average effective propeller wake in straight running condition can increase by 10% for twin-propeller twin-rudder vessel when they go from deep to shallow water. The subject vessel has similar principal particulars as the conventional twin hull vessel considered by Yoshimura and Sakurai [14]. Additional transverse forces and moments are generated when the propeller is in an oblique flow. Glauert [16] has given an expression for the side force acting on a propeller that is inclined to the direction of motion.

$$Y_P = \rho U_A^2 D^2 f \left\{ \frac{K_q}{J} - \frac{1}{2}\frac{dK_q}{dJ} \right\} \alpha_P \tag{2}$$

where α_p is the flow angle at the propeller. The factor f accounts for the distribution of torque along the blades. For the subject twin-propeller twin-rudder vessel, the variation in propeller plane wake during maneuvering was investigated in deep water condition. The variation in axial wake is shown in Figure 19. It is noted that the wake becomes asymmetric for port and starboard propeller. The asymmetry is different for port and starboard propeller. The asymmetry becomes more severe for tangential and radial wake for the same condition. The tangential and radial wake variations are shown in Figure 20 and 21 respectively. This may induce a side force of higher magnitude on the propeller, thereby impairing vessel's course stability. Additionally, the increase in axial and tangential wake variation will influence propeller vibration, cavitations, etc. This is being further investigated by CFD studies. The wake in shallow water condition for the subject vessel is being investigated. It may be concluded that, for a twin-propeller twin-rudder vessel, the vessel maneuvering is impaired not only by increased hydrodynamic hull forces, but also by side forces induced by propeller. These may become significant if the vessel is maneuvering in confined waters.

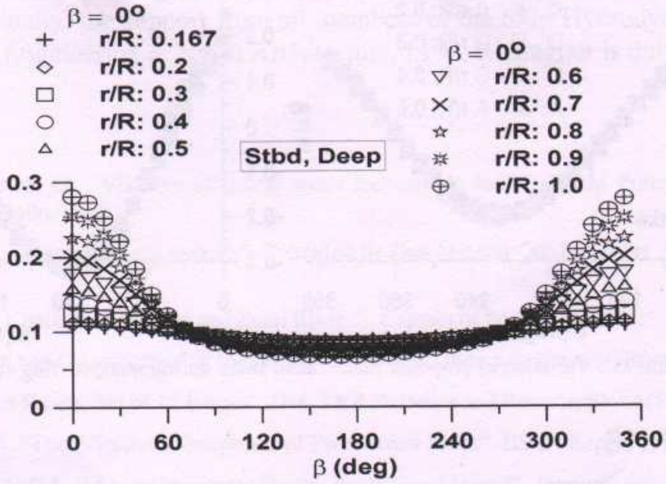


Figure 18: Variation of propeller plane axial wake during straight running condition. Deep water condition

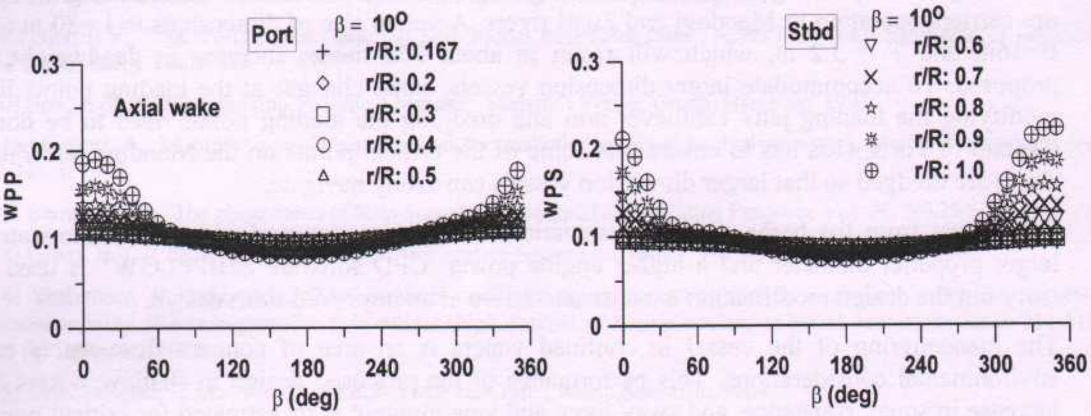


Figure 19 : Variation of propeller plane axial wake during manoeuvring condition.

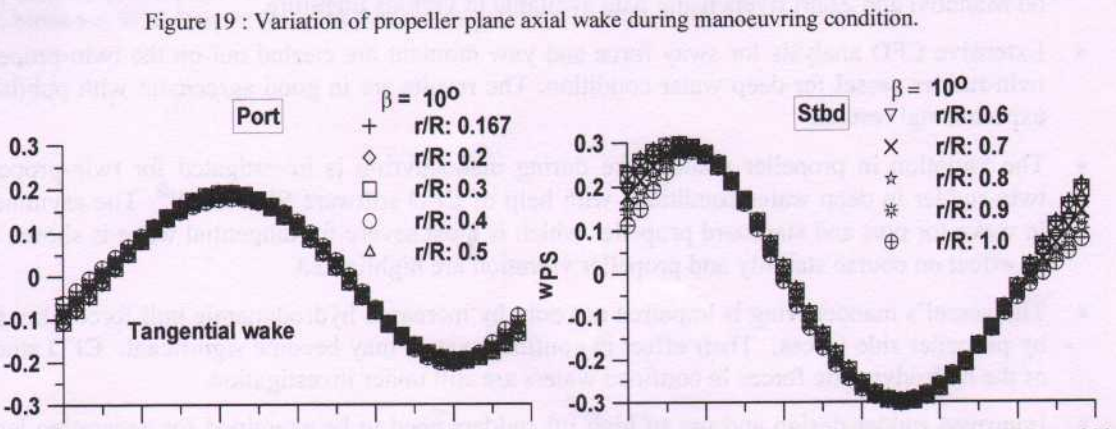


Figure 20 : Variation of propeller plane tangential wake during manoeuvring condition.

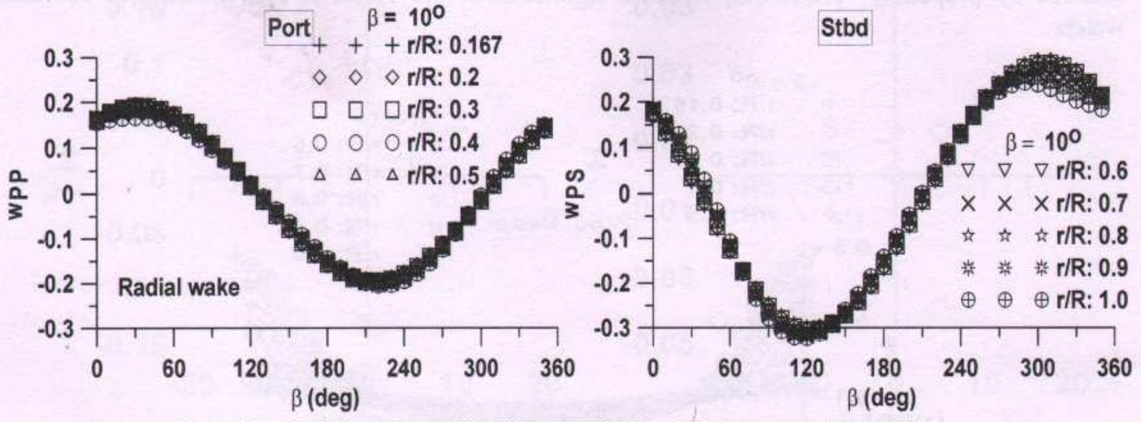


Figure 21 : Variation of propeller plane radial wake during manoeuvring condition.

FINAL REMARKS

Following are the broad observations arising out of the current study :

- The analysis of operating economics show higher profits with increase in the deadweight of the ore carriers operating in Mandovi and Zuari rivers. A vessel size of dimensions to L=80 m and B=16m and T = 3.2 m, which will result in about 500 tonnes increase in deadweight, is proposed. To accommodate larger dimension vessels, some changes at the loading points like modifying the loading jetty cantilever arm and dredging the loading points need to be done. Captain of Ports, Goa has to ensure that some of the critical points on the Mandovi and Zuari rivers are dredged so that larger dimension vessels can safely navigate.
- On request from the barge owners' association, the design was modified to accommodate a larger propeller diameter and a higher engine power. CFD software SHIPFLOW® is used to carry out the design modification exercise and arrive at an improved stern design.
- The manoeuvring of the vessel in confined waters is an area of concern from safety and environmental considerations. This performance of the proposed design in shallow waters for increase in squat, resistance, and sway force and yaw moment is investigated for critical points on Mandovi and Zuari rivers using data available in various literature.
- Extensive CFD analysis for sway force and yaw moment are carried out on the twin-propeller twin-rudder vessel for deep water condition. The results are in good agreement with published experimental results.
- The variation in propeller plane wake during manoeuvring is investigated for twin-propeller twin-rudder in deep water conditions with help of CFD software SHIPFOW®. The asymmetry in wake for port and starboard propeller which is most severe for tangential wake is shown and its effect on course stability and propeller vibration are highlighted.
- The vessel's manoeuvring is impaired not only by increased hydrodynamic hull forces, but also by propeller side forces. Their effect in confined waters may become significant. CFD studies of the hydrodynamic forces in confined waters are still under investigation.
- Improved rudder design and use of high lift rudders need to be examined for generating larger control forces and better manoeuvring ability.

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REFERENCES

[1] Rangaraj, N., Raghuram, G., "Viability of Inland water transport in India", INRM Policy Brief No. 13, Asian Development Bank, New Delhi, 2007.

[2] "Selected Statistics – Goan mineral ore exports", Compiled by Goa Mineral Ore Exporters Association (GMOEA), 2009.

[3] "Hydrographic Survey Charts for Mandovi and Zuari Rivers"., Captain of Ports, Goa India.

[4] "Rules for Construction and Classification of Inland waterway Ship", Indian Register of Ships, 2008.

[5] "Model Resistance Data Sheets, Set of 12 Barges", D-8, T&R Bulletins and Reports, SNAME, 1966.

[6] Moor, D.I., Small, V.F., "The Effective Horsepower of Twin Screw Ships", BSRA Report 192, 1968.

[7] Holtrop, J., Mennen, G.G.J., "An Approximate Power Prediction Method", International Shipbuilding Progress, Vol.29, No. 335, July 1982.

[8] SHIPFLOW® Users' Manual, Ver 5.0, Flowtech International, Gothenburg, 2013.

[9] Telfer, E.V., "The Design presentation of Ship Model Resistance Data", North East Coast Institution of Engineers and Shipbuilders, Trans. Vol. 79, 1963.

[10] Brix, J. (Ed), "Manoeuvring Technical Manual", Seehafen Verlag, Gmbh, Hamburg, 1993.

[11] Milward, A., "A preliminary Design method for prediction of Squat in shallow water", Marine Technology, Vol. 27, No. 1, 1990.

[12] Barrass, C.B., "The phenomena of Ship Squat", International Shipbuilding Progress, Vol. 26, N0.294, 1979.

[13] Lewis, E.V. (Ed), "Principles of Naval Architecture Second Revision, "Vol. II, SNAME, 1988.

[14] Yoshimura, Y., Sakurai H., "Mathematical model for the manoeuvring motion in shallow water (3rd report) – manoeuvrability of a twin-propeller twin rudder ship", Journal of Kansai Society of Naval Architects, Japan 211:115–126 (in Japanese), 1989.

[15] Lewandowski, E. M., "The Dynamics of Marine Craft", World Scientific, 2004.

[16] Glauert, H., "Airplane Propellers, Miscellaneous Airscrew Problems", Vol. IV of Aerodynamic theory, Div. L, Ch. XII, Series 5-6, W. F. Durand, ed. Berlin: Julius Springer, 1935.