PAPER 81 - NAVIGATION CHANNELS DESIGN IN ARGENTINE INLAND WATERWAY

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ABSTRACT: The Paraná, Paraguay and Uruguay waterways in Argentine, have characteristics of an unregulated alluvial river with low slopes, significant morphological changes and an extensive floodplain in their middle and lower reaches. There are places called "critical zone" where the dredging works are necessary and inevitable. This usually occurs in the presence of bifurcations of two or more branches, widening of the river, bends and crossings. In these inland waterways, it is important to consider the criterion of maximizing the natural conditions to match the trace of the navigation channel with naturally deeper zones, and in the case of critical zones, procure channel designs that involve smaller volumes of dredging. This approach seeks to improve costs, as well as minimize the environmental impact of works.

1. INTRODUCTION

The Paraná-Paraguay Waterway in Argentine has a length of almost 2000 km and is divided into three reaches. The oceanic reach is 700 km long, from the Atlantic Ocean to the proximity to Rosario city. It has, at present, 34 feet of draft; and the typical vessel design is the Panamax bulk carrier which has a length of 230m and a width of 30m approximately. Then, it continues a river reach 130 km long, from Rosario city to the Santa Fe port inlet, with 25 feet of draft, where arrive vessels similar to those at the oceanic section but with lower load.

Figure 1: Paraná – Paraguay Waterway

Finally, to the north it develops the reach of barges with 10 feet of draft. In this case, the most frequent vessels are barges convoy formations, and the typical design barge called "Jumbo" is 60 m long and 11 m wide. At the confluence of the Alto Paraná and Paraguay rivers, this reach is divided into two branches: one reaches Puerto Iguazú along the Alto Paraná river, and the other reaches Corumbá along the Paraguay river.

The Paraná river, mainly on its middle and lower reaches, has characteristics of an alluvial unregulated channel with low slopes and an extensive floodplain up to 30 km wide. The channel is often divided into several branches that branch and merge, generating a main channel with widths up to 3 km and the presence of numerous banks and islands in constant motion.

Systematic morphological variations of the channel require the continuous move of the navigation channel axis to make it coincide with the thalweg of the river, looking for natural depths for navigation.

However, there are places called "critical zones", where dredging is necessary. This usually occurs in the presence of bifurcations, curves and crossings. In the case of crossings, the deep places are laying on the opposite banks; for this reason, the channel navigation must be dredged through the channel width.

In these cases, the design of the channel "on crossings", requires to contemplate the particularities of this unregulated river, where it is not possible to apply design methodologies of more developed waterways that contemplate regulated channels. The navigation channel axis presents a significant diference with respect to the flow direction, which implies to take into account a greater width to prevent sailing vessels with strong drifts from making contact with the channel edges.

In channel bends, greater widenings are also required due to relatively sharp angles. The design proposed, in these cases, includes the particularities of the Paraná river.

Moreover, in this waterway there are frequent bed shapes (dunes) of important dimensions, whose crests condition the navigation drafts; for this reason, they should be taken in special consideration.

Even though there is an extensive literature on the design of navigation channels (USCOE, PIANC, etc.), they do not contemplate all these features on the whole.

This work presents methodological contributions to the design of navigation channels in an unregulated river, with significant widths on the main channel and the alternating presence of banks, crossings and sharp curves, characteristic of the Argentinian waterway.

2. PROPOSED DESIGN METHODOLOGY

In sectors where channel depths and/or channel widths are detected insufficient, and dredging and deepening become necessary, it is essential to have studies to determine flow bifurcations in different channels, stream lines, speeds, among others. It is also necessary to have bathymetric surveys of the river at a length greater than the critical reach, either upstream or downstream of it.

Vessels characteristics such as dimensions, maneuverability, power, among others, are essential requirements for the design of the channel.

2.1 Alignment of channel axis.

To plot the channel axis, it is necessary to consider some practical rules developed according to experience and background, such as:

- Reaches as straight and long as possible.
- Look for natural depths to minimize dredging.
- In case of direction changes with angles less than 10 degrees, one may not make curves.
- Curves angles as smooth as possible.
- Channel trace located as far away as possible from areas of sedimentation.

Following these criteria, it should be drawn a line which represents the channel axis, locating the coordinates of its vertices and evaluating the need of curves, crossings or straight reaches.

2. 2 *Design of channel bottom widths*

In this waterway, at present, it is not necessary to consider a two-way navigation, since the critical zones are relatively short (from 2 to 4 km) and they are spaced along the length of navigation; in consequence, it is not appropriate to widen the channel to make ships overtaking in these places.

To calculate the bottom channel width, it is proposed to use the formula that provides the manual USCOE "Engineering and Design - Layout and Design of Shallow Draft Waterways" used for the Mississippi river. This formula is used contemplating a variable angle of drift for crossings, curves and / or straight sections.

$$A = M * \cos a + L * sena$$

where A is the Effective width, M is the Beam, L is the Lenght and α is the Drift angle.

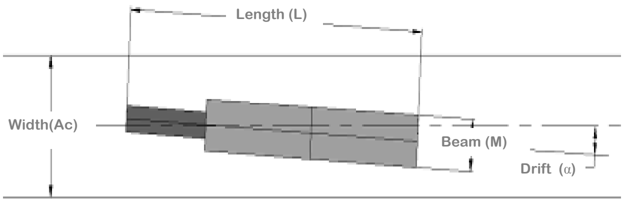

Figure 2. Scheme of navigation channel width.

As L is generally much greater than M and α is a small angle, this expression can be simplified:

$$A = M + L * sena$$

For the minimum channel width, it must be added an extra length of both sides, therefore:

$$Ac = (M + L * sena) + 2R$$

where Ac is the Minimum channel width and R is the Extra length.

2.2.1 *Straight reach*

It is proposed to use, in these cases, the formula provided by the manual USACE (United States Army Corp of Engineers " Engineering and

Design - Layout and Design of Shallow Draft Waterways") although that formula is mentioned for required widths in curves, it has also been adopted for straight reaches, changing only the drift angle.

The value of α depends on the size and configuration of the vessel, on the power and tow propulsion and government system, on channel dimensions and wind conditions and currents, among others. Typical values (for straight reaches) are on the order of 4 to 5 degrees.

2.2.2 *Crossings*

Generally, natural depths in the Paraná river are located on one of the margins but then, downstream, the deep areas are located on the opposite margin.

This fact creates a “crossing zone" which is characteristic of this waterway. To design the navigation channel taking advantage of the natural depths, vessels must move across the river where the current direction is different from the navigation direction, affecting their trajectory and position.

To cross the channel, the vessel must navigate with a different direction, making an angle called drift angle. This drift angle depends on the direction and speed of the flow and on the vessel speed. In these cases, the drift angle is very important in relation to that taken into account when designing the width on straight reaches.

From a vector composition arises:

$$Ve * sen\alpha = Vc * sen\delta$$

where Ve is the Vessel speed, α is the Drift angle, Vc is the Flow velocity and δ is the Flow direction.

Figure 3: Example of navigation on a crossing zone (Entre Ríos).

2.2.3 Curves

On the curves, a lateral displacement of the vessel occurs, which mainly depends on the depth/draft ratio (D / d).

To make a turn, the stern of the vessel moves laterally in the opposite direction. This causes the vessel to move producing a sidescan of the channel, occupying a space wider than the width of the vessel.

The following table lists the minimum requirements to be applied to vessels without the assistance of tows at a speed of 10 knots or, to avoid widenings by taking advantage of the curve.

Table 1: Curves radiuses

Curvature radiuses in navigation channels	
Angle	Curvature radius
< 25 º	3 L
25º - 35º	5 L
35º - 55º	8 L
> 55º	10 L

where L is the Vessel length.

Smooth curves with radiuses larger than 10 L are considered as straight reaches and do not require widening of the curve. For two consecutive curves, it is recommended a straight reach between them of at least 5 L to avoid widening.

The angle between the axis of the vessel and the alignment of the channel is called the drift angle. To calculate the widening, in this case, there are several methodologies. The one proposed here determines the drift angle by a set of graphs obtained from results of studies on physical models (United States Army Corp of Engineers “Engineering and Design - Layout and Design of Shallow Draft Waterways").

From these graphs, the drift angle is determined by the size of the vessel, radius and angle of the curve, flow velocity and if it is navigating upstream or downstream. With this drift angle, the channel width in curves (Ac_{curve}) and, then, the widening are calculated

$$S = Ac_{curve} - Ac_{straight}$$

where *S* is the curve widening.

In the design of the navigation channel for large rivers (eg. the Paraná river) it is proposed a different widening in developing the curve, being maximum at its vertex and decreasing towards the beginning and the end of the curve.

This widening should be incorporated on the inner side, trying to smooth the curve. In figure 5 the curve widening process is observed: the inside shoal curvature is drawn with a higher radius, so that the channel vertex has the width of the curve.

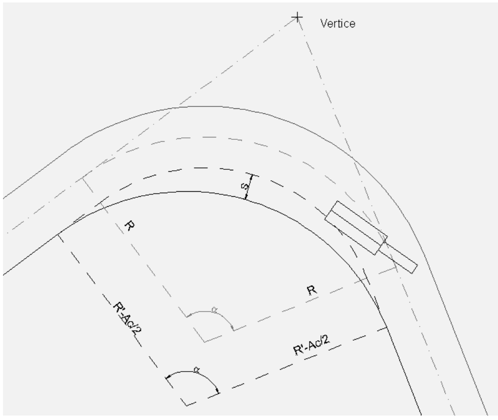

Figure 4: Diagram of widening on curve.

$$d = C + S$$

$$C = \sqrt{R^2 + E^2} - R$$

$$R' = \frac{d * sen(\alpha/4 + 90)}{sen(\alpha/4) * tg(\alpha/2)}$$

$$E = R * tg(\alpha/2)$$

Where S is the Widening, C is the space, R y R’ are the Curves radiuses and α is the Drift angle.

Figure 5: Widening of curve in Paraguay river, in front of Formosa city.

2.2.4 Depth of the channel

The depth of the channel is determined from a reference water level, which must be defined uniformly for the whole route of navigation. It arises from the statistical treatment of a hydrometric data series.

The reference level of a route segment is defined as an imaginary polygon formed from the union of the heights of water (from hydrometers), which have the same probability of being exceeded.

This reference level may vary depending on the adopted statistical series, since there are wet periods and dry periods, thus the drained water volumes are different each year.
It may also vary due to the regulatory effect produced by the reservoirs operation in the basin, causing the minimum values being higher and, therefore, the maximum being lower.

The graph shows the monthly mean heights registered in the hydrometer at Paraná port (at 603 km trunk route), from the year 1905 to 2009 (in green line), and the average of all the series and, the mean values of two different periods (1935-1955: dry (in red line) and 1970-1990: wet (in pink line)). It can also be seen that minimum heights are greater in recent years, partly due to the regulatory effect of the reservoirs located on the upper basin of the Paraná river.

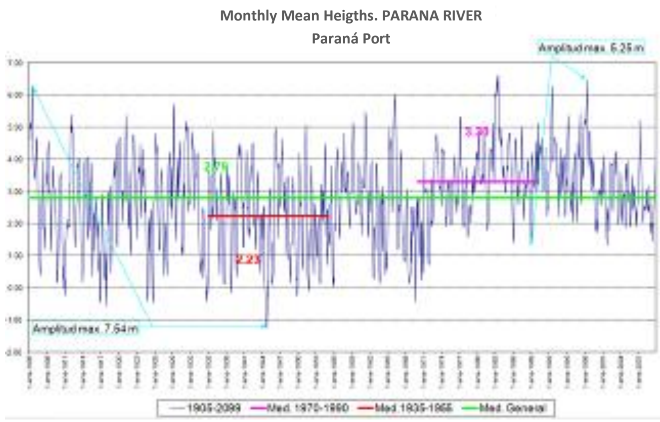

Figure 6: Monthly mean Heights Puerto Paraná - series 1905 -2009.

The depth of design (D), taken from the reference level of a navigation channel, is a function of several components such as: draft, settlement, stowage, pitch, tide and water density, among others. In the case of the critical zones on the Paraná river, it should be added a space to allow the sedimentation that occurs between one dredging and another. Sedimentation over the time can be estimated by mathematical modeling.

The main effects which cause decrease in navigation depths on the channels of these waterways are:

- Decreasing of transport capacity in the longitudinal direction due to expansions and/or bifurcations of the channel.
- Bias effect, when the channel is not aligned with the flow; in this case the channel bed acts as a trap of the sediment transported on its bottom.
- Contribution of the channel lateral slopes in beds of loose materials and velocities of flow.

2.2.5.1 Dunes effect

In many cases, the determinant depth for navigation (shallow zone) in a critical zone is given by the crest of a dune. Bed shapes, though are eliminated with dredging works, are then regenerated in a relatively short time, so it must be added extra deep to the design depth.

In the Paraná river, the dunes have rounded peaks with mean shape coefficients of about 0.65. For this reason, the mean bed level is a horizontal plane located closer to the crest than to the valley of dunes; so that the necessary extra-space added due to dunes is 35% of the value of the expected dune height.

There is a considerable information of dune heights obtained from field measurements in representative areas of study and many critical zones in the Argentinian waterway. Based on these measurements, it has been possible to develop a calculation methodology (ML Amsler et al. 2000) to estimate the expected heights of dunes after the deepening of the navigation channel by dredging works.

The mean heights of dunes on the barge route (10 feet) of Argentinian waterway are generally variable, between 1 and 2 meters. In the case of the deep navigation route (34 feet), the mean heights can reach 4 meters. This shows the importance of considering a significant value as extra-space due to dunes effect.

In some critical zones, it is common to find extraordinary heights of dunes that can double the mean height of the reach. Dunes of extraordinary dimensions close to 7 meters high have been measured in the critical zones called "Canal de Muelles" and "Borghi" in Argentinian waterway, near Rosario city. In such cases, to keep the drafts of navigation, specific dredging works are used, which "shave" or "cut" the crests of these extraordinary dunes. This requires having adequate dredging equipment, readily available in the area.

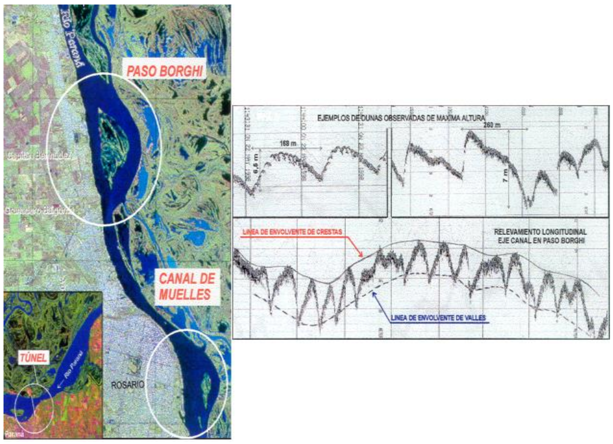

Figure 7: Bottom shape in "Paso Borghi" and "Canal de Muelles".

3. ANALYSIS OF WIDENING IN CURVES

The particularities of our waterways Paraná, Paraguay, Alto Paraná and Uruguay are not common in the world. The hydrodynamic of flow and the ships route, looking for the deepest parts, are typical of a natural system without regularization works. This fact forces to resort, sometimes, to curves with radiuses and angles which require special ship maneuvers.

Taking advantage of the execution of a navigation channel project for the reach called Concepción del Uruguay – Fray Bentos, on the Uruguay river, it has been made a comparative analysis of widenings obtained by using some of the generated methods for other waterway systems.

In this work, it was considered to be important taking into account the criterion of maximizing the natural conditions offered by this river. To achieve this, it should be matched the navigation channel trace with the naturally deeper areas; and in the case of critical zones, it should be looked for channel designs, keeping safe navigation maneuvers, involving lower volumes of construction, dredging and maintenance works.

3.1 Design vessel

On the reach from Km 0 until km 187.1 on Uruguay river, the project was performed for a design vessel type Panamax (of approximately 224 m long and 32 m wide) to navigate with 23 feet (7.01 m) draft and 2 feet (0.61 m) of tolerance or rematch security under keel. The adopted channel width in straight reaches was of 100 meters.

3.2 General Design of the Navigation Channel

The recommendations of PIANC-ENGINEER MANUAL EM 1110-2-1611 (COE U.S.A.) AND PORTS AND WATERWAYS LOUISIANA STATE INSTITUTE U.S.A. were used to determine the widenings on bends. However, after these calculations, widenings in curves were recalculated using alternative methodologies available in the CARU / CTMSG-European Union (2003) and in the manual "Hydraulic Design of Deep Draft Navigation Project" (USCOE, 2006), which are described below.

Finally, it was made a comparative analysis of the results and the final adoption of the widenings included in the project. The following methods were considered:

1) Method 1: ENGINEER MANUAL EM 1110-2 -1611 "Layout and Design of Shallow Draft Waterway" (COE U.S.A.) AND PORTS AND WATERWAYS LOUISIANA STATE INSTITUTE U.S.A.

$$\Delta W = \left(sen\alpha_d * L\right) + B + 2C - A_r$$

where *ΔW:* bend widening.
- α_d: maximum drift angle of the vessel, sailing downstream, at the most unfavorable condition.
- *L*: vessel length.
- B: vessel beam.
- *C:* free space between the vessel and the channel limit.
- A_r: width in straight reaches.

The α_d value is a function of the curvature radius and the length and width of the vessel.

The Corps of Engineers of the United States recommend drift angle values corresponding to different configurations of barge convoys that regularly navigate the Mississippi waterways.

These values emerged from a large set of physical model tests carried out for this purpose. The tests were conducted for convoys navigating upstream and downstream, maneuvering in the presence of curves with different radiuses, angles and flow speeds. The results were summarized in design graphics, corresponding to the different considered convoys, where the drift angle "α" proves to be a function of the aforementioned variables.

For the purpose of this study, the curves corresponding to a barge convoy sailing downstream were selected; it had the following dimensions: Length: 183 m, Length plus tow (total 223 m), Width: 32 m and Draft: 8 feet.

Flow speeds of 3 ft/sec and curves angles assigned according to options for 0°, 30° and 60° were considered. To perform calculations, mathematical functions were adjusted to the graphs provided by the method.

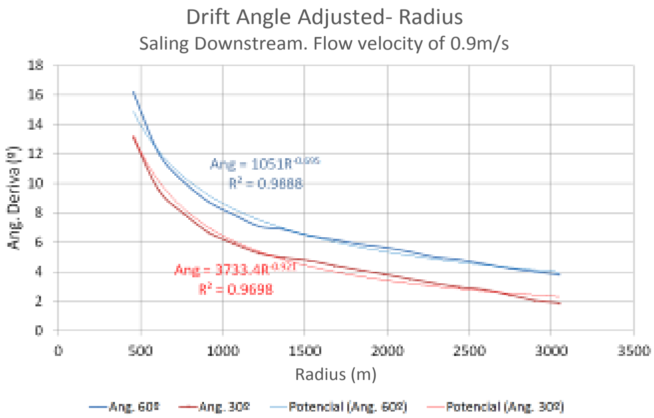

Figure 8: Curves adjusting.

2) Method 2, (Alternative Method): "Canadian Coast Guard"

Analysis through studies on physical models allowed developing an equation that evaluates the curves widening. The suggested expression is the following:

$$\Delta W = (0.9144\ f\ Vs2\ L2\ F) / (Rt\ Cc\ S)$$

where *ΔW*: bend widening (m).
- f: curve angle (degrees).
- Vs: relative vessel speed to the bottom (knots).
- L: vessel length.
- Cc: coefficient of maneuverability.
- S: unobstructed distance from the bridge of the vessel.

Rt: curve radius(m); F= 1 for single hand.

3) Method 3, (Alternative Method): Kiel Formula.

It is an expression adjusted empirically from radar images. The proposed equation to estimate the widening "Δw" is the following:

$$\Delta w = L \ sen \ \alpha + R - ((R + (2/3)L)\ (R - (2/3)L))^{0,5}$$

where R: curve radius.
L: vessel length.
α: drift angle.

To calculate the drift angle three alternative methodologies were used:

a) Physical modeling of the Vuelta de San Antonio (Paraná de las Palmas river) performed by the Laboratorio de Hidráulica Aplicada (LHA - INA).

Considering that the present case has as design ship an oversea vessel, it was considered as appropriate to incorporate in the comparative analysis, the resulting expression for the drift angle obtained from the navigation study performed at the Vuelta de San Antonio. The calculation equation is as follows:

$$\alpha = 23{,}5° - (19{,}5°/2440)\ R$$

where R is the curve radius.

b) INSA - Hartung Formula

It is an empirical formula for calculating the drift angle (α)

$$\alpha = arctg\left(\frac{L}{2R - \left(\frac{L^2}{2R + B}\right)}\right)$$

where R is the curve radius, *L is the vessel length and B is the vessel beam.*

c) Use of physical models, that is to say, the same method used for Method 1.

4) Alternative Method (Method 4): U.S. Army Corps of Engineers Manual EM 1110-2-1613 "HYDRAULIC DESIGN OF DEEP DRAFT NAVIGATION PROJECT" approved in May, 2006.

This method determines the widening in curves of a navigation channel for vessels in general, depending on relations between the radiuses of the curves and the length of the ship.

From Figure 8.3, Manual EM 1110-2-1613, the widening curves are obtained graphically. To expedite the calculation, it was adjusted to a mathematical function.

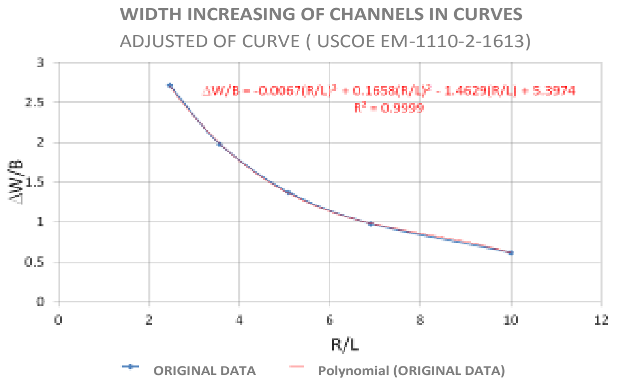

Figure 9: Mathematical function adjusted (Uscoe 1110-2-1613).

Using the 4 methods described, in the case of Method 3, and also considering the variants a), b) and c), 6 values of widening were determined; the one proposed and other 5 more, on a comparative basis.

3.3 *Analysis of results obtained for widening of curves*

Figure 10 summarizes the results of the calculations performed. The widenings have been plotted as a function of curves radiuses. It may be noted that the results obtained with the method of Kiel (with drift angle obtained at Vuelta de San Antonio, Method 3), differ markedly from the rest of the discussed methods, overestimating the widenings.

The Method 2, "Canadian Coast Guard", has very similar values to those obtained with the method proposed (Method 1 - MANUAL EM 1110-2 -1611).

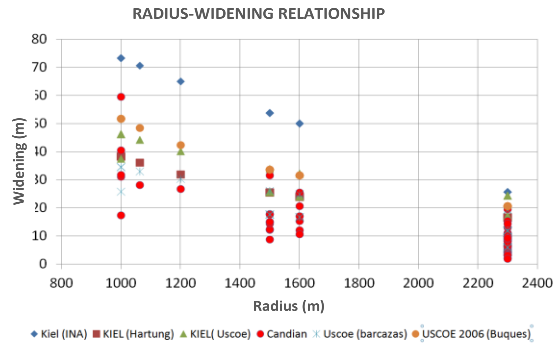

Figure 10: Comparison of methods.

In general, the methods 3b, 3c and 4 have relatively limited variations; for example, for higher radiuses adopted (10 lengths), the widening variations range from 10 to 20 m; on the other side, ie. in the case of small curves radiuses (1,000 m), variations range from 35 to 50 m.

The values obtained with the methodology 1 are located on the lower middle zone of the comparative graph, minimizing volumes of work.

Furthermore, the methodology 1 allows obtaining a safe widening backed up by the experiences and backgrounds of application at Mississippi waterway (USCOE).

4. CONCLUSIONS

It should be adopted widening curves obtained by Method 1 - MANUAL EM 1110-2 -1611. These ones, unlike the others, take into consideration calculation elements as current speed and navigate direction; variables considered critical in turning maneuvers due to their effect on drifts caused by the ships movements. Their adoption ensures the choice of widenings and generates projects that economically optimize volumes of work.

Due to the characteristics of the Paraná river, mainly in its middle and lower reaches, the main works for fluvial navigation, in addition to navigation signals, are the deepening, the widening and the periodic maintenance of the navigation channel by dredging.

This work proposes methodological elements for the design of a navigation channel on lowland rivers, obtained from considering the particularities of the Argentinian waterway. They would also apply to other similar waterways (large reaches of unregulated lowland rivers).

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