Paper 13 -"Design of the Magdalena River Training Works for Navigation Improvement"

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ABSTRACT: The purpose of the project was designing the training works required to improve existing navigation conditions and extend Magdalena River navigation 256 km upstream the port of Barrancabermeja (Km 630) up to Salgar (Km 886) in central Colombia. Barrancabermeja is the main port on the Magdalena and is dedicated mainly to oil exports. Type of training works proposed consists of river bank rockfill revetments, rockfill training dikes, and partial closure structures of secondary channels, to stabilize the alignment of the navigation channel and reduce maintenance dredging. These works should guarantee the stability of the banks and sectors with extra-large width in order to prevent flows from going through various side channels in low water stages.

1. STUDIES, DESIGN AND BID PROCESSES

The work described in this article was carried out with the sponsor of a Colombian Government public entity and a private river transportation federation, which hired four engineering consulting companies, initially for the feasibility study in 2000-2001, and afterwards between 2006 and 2013 for the detailed design of the training works, along 460 km of river reach. The author was the Project Manager of all studies and designs.

Studies made since 1993 on cargo demand and the feasibility study 2001, showed the need to reactivate navigation upstream Barrancabermeja, and recommended revitalizing the river transportation system with a terminal port in Salgar, as an economically important inter-modal center only 180 km from Bogotá, the country's main cargo origin and destination center (Figure 1).

Figure 1: Magdalena River project area

The first training works design study in 2006 established the methodology for the Master Plan and detailed designs, according to guidelines provided by individual consultants who had participated with the United States Army Corps of Engineers - USACE in the planning, development, design, construction, and maintenance of similar river works done in various rivers. Their experience was instrumental, as the works designed for the Magdalena River are similar to works successfully done by USACE along the Mississippi River tributaries similar in size to the Magdalena River: Ohio River, Red River, upper Missouri, and Arkansas.

In October 2009 detailed designs were presented for the Berrío (Km 730) - Barrancabermeja (Km 630) sector over a 100 km reach; in October 2011 for the Salgar (Km 886) - Berrío (Km 730) sector over a 156 km reach. By the end of 2011 the Colombian Government had the detailed designs of training works required for opening an international tender and contracting process for the works on the Magdalena River.

However, the Berrío - Barrancabermeja sector had to be adjusted on account of significant morphologic changes brought by three very strong rainy and floods seasons of 2010 and 2011, caused by La Niña phenomenon. The new report, with the adjustments, was submitted in October 2012. Finally, the designs of the channeling works for the last sector between Barrancabermeja and Regidor (205 km) were presented in October 2013.

The FTA signed between Colombia and the United States three years ago, will result in an increase of transportation services and cargo demand from the central part of the country to the Atlantic coast, the Magdalena River becoming a significant multimodal transportation opportunity.

After a 20 months process, the tender was awarded in September 2014 to Odebrecht-Valorcon joint venture. It is a 13.5-year Public-Private Association concession created for the training works between Salgar and Barrancabermeja (256 km) initially, including river maintenance and dredging from Salgar to Barranquilla (886 km).

The contract value is US $2 billion, including financing, 63% being future resources from the central Government and the rest from the private sector.

2. TECHNICAL CHARACTERISTICS OF THE PROJECT

To begin, some basic features should be analyzed:

- A Master Plan to follow,
- Design vessel,
- Alignment of the navigation channel,
- Hydrology,
- Depth under reference level,
- Dimensions of the navigation channel,

2.1 Master Plan

Unlike structures designed for static environments, the ever-changing alluvial river necessitates a flexible vision and being very receptive from the conception of the project to these changing conditions.

As an alluvial river, the Magdalena has a dynamic nature, and before construction is completed, some adjustments should be done in order to accomplish the desired goals. The feasibility study along with the revised alignments and structure layout prepared for the different reaches can be defined as the Master Plan for the future development of the Magdalena river navigation project.

This Master Plan present a good guide to follow when preparing the definite drawings and specs for construction, and for programming construction logistics. As a matter of fact, the main contractor is actually updating and refining the design following the general criteria of the Master Plan to begin construction of the training works during the first semester of 2016.

According to the former USACE engineers that assessed this project, the Master Plan for a project that requires decades for completion, should be revised annually in areas where construction is scheduled for the next years, and an overall detailed review should be done in other sectors every 5 years or less, according to the dynamics of the reaches under consideration, to accommodate designs to changing river conditions.

2.2 Design vessel

According to the feasibility study, CMG - CORMAGDALENA (Government Agency owner of the project) defined a barge tow in a 2x3 formation as the design vessel. Barges are 65 m length, 13 m beam, 1.80 m draft (6 feet), with a 1,200 ton cargo capacity. Thus, the design tow transportation capacity is 7,200 tons, and tow size is: length 240 m, beam 26 m, draft 1.8 m. This design vessel is valid along the overall length of the project, from Salgar (Km 886) to Barranquilla (Km 0), for the capital dredging, the maintenance dredging and the training works design (Figure 2).

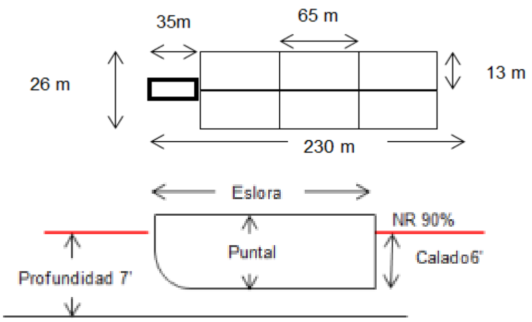


Figure 2: Design tow, plan view and profile

Although there are 8 and up to 10 barges tows navigating the Magdalena River downstream Barrancabermeja, CMG has decided that the navigation project should progress step by step, because nowadays there is no navigation to Salgar. The Master Plan allows to adequate the channel dimensions and training works to a larger vessel if future conditions demand it.

2.3 Alignment of navigation channel

Design was divided into two components: i) the design of the proposed navigable channel layout, and ii) the design of the training structures as such.

The navigable channel layout was defined based on geomorphology along river valley, river dynamics of the last 20 to 30 years, and river thalweg location during the past 8 years, with special consideration for the most recent channel surveys during the last 2 years.

However, it is much more important to insure that the cannel to be developed is along a smooth sinuous alignment that is self-maintaining rather than follow a particular sailing line that is not along a very good alignment and may be in state of change (Figure 3).

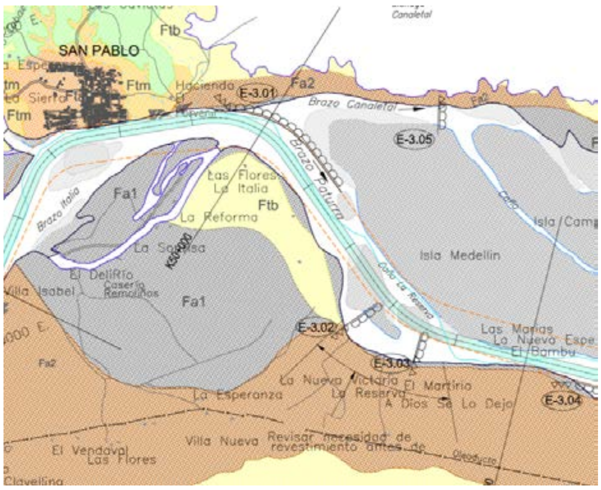


Figure 3: Typical alignment of navigation channel

Training structures are designed to keep the navigation channel within the defined alignment.

The channel surveys depict the bathymetry of all river channels, sandbars and bank lines. This information is necessary for the contractor to determine transportation and placement logistics.

2.4 Hydrology

Magdalena river drainage area exhibits a bimodal hydrograph, with two periods of low water levels and two periods of high water levels that are called “summer” and “winter” respectively. Summer months are January to March and July to September; winter months are April to June and October to December (Figure 4).

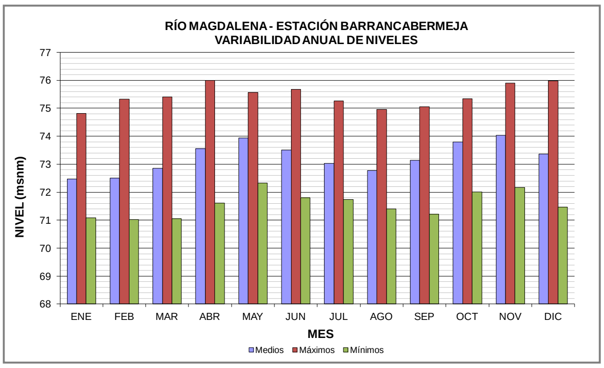


Figure 4: Variation of water levels at Barranca

Mean water discharge in Salgar is 1263m^3/s, in Barrancabermeja is 2950 m^3/s, 2,3 times larger. Water level variations are fairly similar along the reach under consideration. In Salgar the difference between maximum and minimum levels is 5.26m; in Barranca is 4.98m.

According to the compilation of data for the major rivers of the world (Schumm et al, 1994) the Magdalena River ranks 29 in respect to water discharge (7000 m^3/s), but it ranks 12 with respect to sediment discharge (172 million tons/yr). That amount of sediments is the biggest challenge for this project.

2.5 Depth under reference level

Available depths were established under a low water reference level exceeded 90% of the time for the reach Barrancabermeja – Pto Salgar. Downstream of the first port, the reference level is the one which is equaled or exceded 95% of the time. The difference is due to the fact that upstream Barranca there is almost no navigation nowadays.

The water level duration curve in Barrancabermeja shows that the 90% time exceded level is only 1,10m below the mean average level, which indicate that the level variations are not very large in the middle part of the curve.

2.5 Dimensions of navigation channel

The channel layout complies with navigation standards for a two way channel (widths, radii of curvature, and depths), as defined by USACE.

The navigable channel will have the following characteristics for the design tow:

- Navigable channel width (two-way)=150m
- Minimum radius of curvature = 900 m.
- Summer channel depth = 7 feet (2.10 m).
- Vessel draft = 6 feet (1.83 m).

3. DESIGN CONSIDERATIONS

Project scope was to conceive training works for controlling river width between Puerto Salgar and Barrancabermeja. The works should be designed for restricting summer flows to a main channel adequate for navigation within the boundaries of the training works, avoiding flow dispersion through secondary channels in sectors with extra wide cross sections, assuring bank stability, but allowing high water discharges to flow over the structures and occupy the whole river bed.

As mentioned before, training works design was adapted from the procedures followed by

USACE for a similar scope in the Mississippi River system and tributaries, under the supervision of Environmental Protection Agency (EPA). Training works objective is to stabilize main navigable channel, with a combination of structures including trench fill revetments to prevent lateral erosion of river banks, stone fill revetments for the same purpose, channeling stone fill dikes to direct flow towards the center of the main navigation channel avoiding dispersion of flow through secondary branches in summer time, bank connections and closure dikes over secondary and minor channels.

However, dikes elevation should be below high water stages and floods, allowing the river to occupy the whole width of the river bed for the transit of high discharges. While the river works proceed, dredging is the only mean to maintain the river depths required for safe navigation.

This combination of works has been lay down consistently in practice in the U.S. since the 50’s and has demonstrated to be the most effective in economic terms, as dredging costs have lowered at the same time as river works have been built.

Determination of required area for channeling summer flows, is based on the estimation of the predominant numerical value of the Conveyance Factor in cross sections that don’t need channeling works, at full bank conditions, whose water discharge is considered dominant and the most representative for the river bed dynamics and morphology (Petts, Calow, 1996).

Manmade modifications to the cross section geometry by means of dikes and/or dredging looking for the creation of a main navigable channel shall respect the original value of the conveyance in the new geometric cross section for the particular reach under consideration.

Manning’s formula,

$Q = 1/n*A*R^{2/3} * S^{1/2}$ (metric system)

can be re-expressed as,

$A* R^{2/3} = n *Q/S^{1/2}$

In alluvial rivers, where the width is much greater than the height, the hydraulic radius becomes equal to d, the height of the water flow.

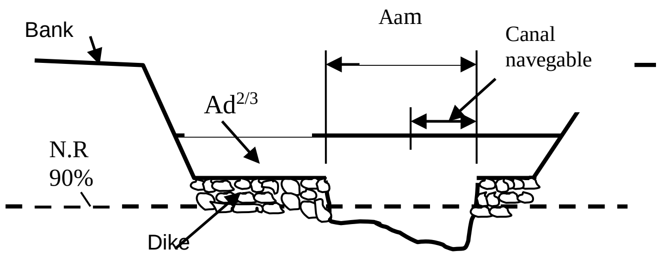
The term $A* d^{2/3}$ is then the Hydraulic Conveyance or Section Factor. Ven Te Chow explains this factor stating that it depends on the geometry of the wetted perimeter and that the equation shows that for a given condition of **n, Q** and **S**, it exists only one possible depth to maintain uniform flow.

Engineering cannot make significant changes in **n, Q** or **S** (building dams with locks is not the case), but engineering can modify the geometry of the cross sections. By building training structures, the cross section area can be reduced in width and the river will seek to compensate that loss in area by deepening the cross section to re-establish the conveyance factor and then improving available depth for navigation.

What design has to do in this case is to determine the cross area that should be blocked or made ineffective, which is equivalent to determining the elevation of the structures within the river bed.

The first thing to consider when designing a reach is what structures are required to control the channel alignment. This is accomplished by the channel and structures layout described above in section 2.3. The next step is to determine the most economical structures that will accomplish this task using standard sections that are going to be described in a later paragraph. The third step is to compute the conveyance over the structures below the bank full stage, particularly in multi-channel braided reaches. If this value is larger than that allowed by the conveyance, the elevation of the structure would have to be raised accordingly.

The different elements that participate in numerical calculations are indicated in Figure 5. The central idea is that the area that is reduced from lateral cross section because of the dikes and rockfill structures, be recovered by the natural work of the river to preserve the same numerical value of the hydraulic conveyance. At the beginning, to accelerate the process, it is recommended to carry on an induction dredging on the channel to be deepened, that the river itself will maintain.



NR = Reference level (exceded 90% of time)
Aam = River width in controlled low water condition > navigation channel width.

Figure 5. Typical cross section in navigable channel with controlled width.

Selection of Conveyance Factor (CF) as design parameter was based in studies by Anding (1970), who demonstrated the consistency of CF in channel crossings and curves for dominant discharges, and in studies by Biedenharn et al (1987) who demonstrate that the majority of total sediment load is transported in full bank stages or less.

This can be stated in other words: for a given water discharge, the CF will be approximately the same in all sections. If enough time is allowed for a given discharge to equilibrate the river bed, all cross sections will adjust to that condition. Field studies have shown that main effects of erosion and siltation in a particular section, have a tendency to occur in areas occupied by the main channel, whilst the areas with secondary channels exhibit much less dynamics.

The training works so designed not only control low water stages, but they neither obstruct don't alter the flow during floods or high water stages.

3.1 Determination of river channel width to be stabilized (Aam)

To determine the river channel width to be stabilized, a conveyance analysis of the reach should be done as described previously. The idea is to develop a design curve valid for certain reaches, plotting the hydraulic conveyance against the depth of the navigation channel for several cross sections. As sections are analyzed and points are plotted, a definite pattern develops showing a clear relationship between the conveyance and the navigable depth. A design line can then be drawn which encompasses the majority of the points plotted to insure that a navigation channel will be available. That design line shows the conveyance that can be allowed outside of the controlled channel for different navigation depths (Figure 6).

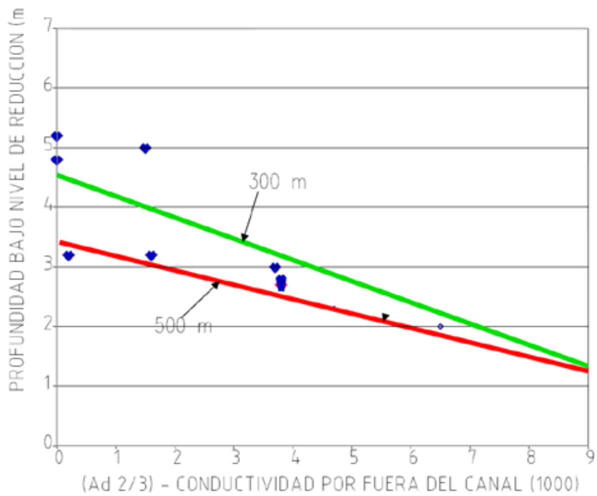


Figure 6: Conveyance analysis design curve

According to such analysis, a summer river channel width was determined for the selected design vessel, as follows:

- Salgar – Berrío reach = 300 m.
- Berrío – Barrancabermeja reach = 500 m

3.2 Characterization of training structures

As mentioned before, the structures were classified under four categories:

First one is Trench Fill Revetments where flow is essentially parallel to the structure and the trench must be designed to provide sufficient rockfill material to launch to the maximum anticipated scour along it (Figure 7).

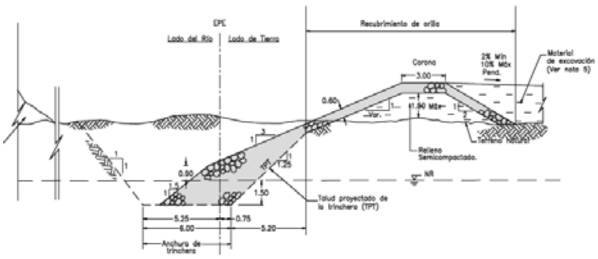


Figure 7: Trench fill revetment

The second category is Stone Fill Revetment where flow is along the structure as well as across the structure. This requires that the trench be designed to provide sufficient stone for launching, as in category 1, and the upper portion be designed to withstand the hydraulic head that develops across the structure. In addition, the section must provide sufficient riprap for launching to stabilize the scour hole that can develop downstream from the structure.

Third category is Stone Fill Dikes where all the flow is across the structure. They must be designed to withstand the hydraulic head across the structure as well as providing sufficient stone to launch and stabilize the downstream scour hole (Figure 8).

The fourth category is bank connections for Stone Fill Dikes. For all four categories there are a number of subtypes, depending on the topography of the banks and bathymetry details.

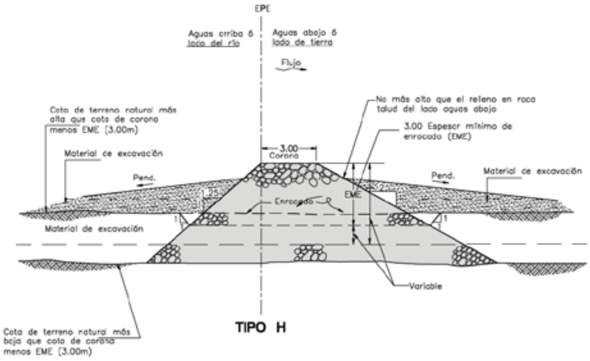


Figure 8: Stone fill dikes

3.3 Typical designs

For the 456 km length, 265 structures were designed and 697 detailed plates were drawn.

Figure 9 outlines a plan view for the structures, with indication of type or types of structure (one structure could encompass several different structures depending on site conditions), reference points for locating and defining the work ready for construction, elevations, and location of signaling devices for navigation purposes.

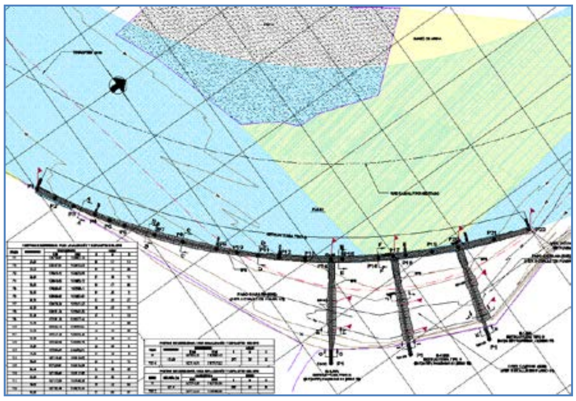


Figure 9: Plan view of structure with tie-backs

The profile of structures together with cross sections are essential to define clearly structure types, elevations, and varying conditions at field. Figure 10 shows a typical drawing of a structure profile and cross sections.

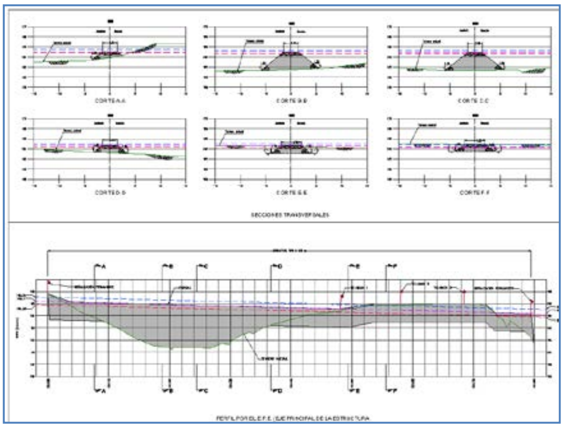


Figure 10: Typical profiles and cross sections

3.3 Materials for the structures

Main material for the structures is quarry rock. An overall volume of nearly 4 million m^3 was estimated for the structures.

Twenty possible quarry areas were studied, with a capacity of more than fiftyfold the requirements of the project.

The size and gradation of rock was determined from the reference studies and field tests done for the Red and Arkansas rivers of similar size to the Magdalena, verifying that the size of stone required from the scour depth calculations were well inside the gradation bands.

The contractor that won the bid for the construction of the river works (Joint Venture Odebrecht – Valorcon) is presently analyzing the possibility of replacing the rock for geo-containers of different sizes or a combination of sizes in order to reduce costs and ease the construction logistics. Geotubes, geobags, geosacs, etc, are being analyzed together with four of the largest geo-textiles providers worldwide, like Flint, Tencate, Huesker and Pavco.

4. CONCLUSION

After a 15 years period of studies and analysis, the Colombian Government finally awarded the construction of river works to improve the navigation in the Magdalena River. The detailed and careful elaboration of field investigations, studies, analysis, reports, detailed construction drawings and the assessment given by individual consultants, former engineers with the USACE, were instrumental in the decision making process that allowed the development of this project.

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