APPLICATION OF A LONG-TERM EVOLUTION MODEL OF TIDAL INLETS TO THE DESIGN OF A NAVIGATION CHANNEL, THE NAVIA INLET CASE.

R. Medina[1], M. A. Losada[2], Member, ASCE, P. Lomónaco[1] and A. Baquerizo[3]

Abstract

The navigation channel of Navia is designed applying a long-term evolution model of tidal inlets. Navia is a port located on the North coast of Spain, and accessed by a narrow inlet, influenced by strong tidal currents, waves and a variable morphology. To define the design depth, the most important oceanographic processes are included in a probabilistic approach. The model allows comparing different scenarios, according to jetties length and maintenance dredging. In this way, optimum design represents a balance between capital costs and maintenance requirements. The long-term evolution model turns out to be an efficient tool for navigation channel design, and a must for optimum design.

Introduction

Tidal inlets are among the most active sedimentary units. Waves, tidal currents, river discharge, density currents and wind driven currents influence them. Sediments are continuously in motion, due to the strong hydrodynamics and the sediment size ranges from fine silt to pebbles. On the other hand, estuaries are generally used for port activities, since they provide naturally sheltered areas and allow inland navigation. The access to these ports is done through the estuary inlet.

The tidal inlet natural cross section is the result of a balance between sediment input, onset of motion and transport, tidal current patterns and tidal prism, among other factors. The result is a dynamically stable section, which tends to an equilibrium condition. Hence, a tidal inlet may be in equilibrium even though its morphology changes

[1] Ocean & Coastal Research Group, E. T. S. I. de Caminos, C. y P., University of Cantabria, Avda de los Castros s/n, 39012 Santander, Spain.
[2] Department of Civil Engineering, E. T. S. I. de Caminos, C. y P. University of Granada, Campus 'La Cartuja', Granada, Spain.
[3] Department of Hydraulic Engineering, Civil Engineering Faculty, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands.

continuously, since the latter is given by the current hydrodynamic conditions, but the mean condition is, in long-term, constant.

Therefore, two time scales are defined for the morphological variability of the inlet, the short-term variability (days, weeks), controlled by the time scale of waves, tides or river, and the long-term variability (months, years), controlled by the natural tendency towards equilibrium of the inlet. Several authors had proposed relationships between some estuary properties in equilibrium and the hydrodynamic conditions, e.g. tidal prism versus inlet cross section (O'Brien, 1930, Bruun, 1966), or tidal flats extension versus estuary area (Eysink, 1990). Any change in these properties will produce a different equilibrium condition, and the estuary morphology will tend towards a new stability state. Since the most active unit inside the estuary is the tidal inlet, one can find the strongest changes in it.

But the problem is that natural equilibrium conditions may not fulfil navigational requirements, at least during some time periods (at low tide or during storms). In most cases, it becomes very hard to achieve these requirements, particularly with respect to depths, and it is necessary to accept nature's conditions, or to pay a very high price in maintenance dredging.

As mentioned before, after dredging, the inlet will evolve and, after some time, will attain its equilibrium condition. In order to preserve the required depth, maintenance dredging must be performed and the time evolution of the inlet has to be assessed. A long-term evolution model can predict the inlet behaviour.

In this paper, a long-term evolution model will be applied to the Navia inlet, in the northern coast of Spain. The model is based on the work published already by several authors and will be presented here in detail. First, the physical environment within Navia will be shown and the navigation channel design principles will be defined. Then the long-term evolution model concepts and theory will be elucidated in order to apply it in the design of Navia's navigation channel and the maintenance works. With these results, an optimum balance between capital costs and maintenance dredging can be found for a particular channel geometry.

The Navia Inlet

The North coast of Spain consists of a series of pocket beaches and bays separated by pronounced rocky headlands. The coast in general faces North, towards the Cantabrian Sea, in the northern Atlantic Ocean. Depths here reach more than 4000 m far offshore and the continental shelf has an average width of 30 km. The mean tidal range is about 4 meters; spring tides reach ranges up to 5 meters and they are all semidiurnal.

Navia is a small inlet on this coast, in Figure 1 its location is indicated, and also can be seen the large fetch area to the Northwest, where strong extra-tropical cyclones generate wind and waves which make the Cantabrian Sea one of the roughest in the

world. Hence, waves arrive to Navia from the NNW and a typical winter storm has a significant wave height between 4-6 meters.

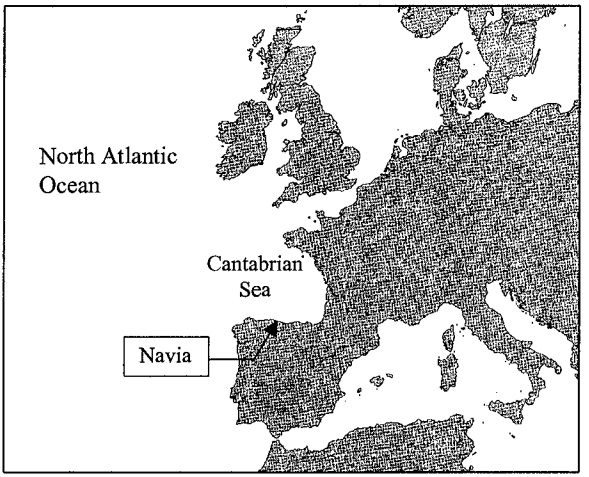

Figure 1. North Atlantic and the Cantabrian Sea. Navia inlet location.

Navia is an old port, meant for bulk cargo (iron ore) and fishing. In Figure 2 a 1786 chart is presented, where one can identify the original shape of the outer shoal, the river path and water depths. Comparing with recent charts, even though some differences are clear, it can be found that, in general, the shape and depth of the shoal are very similar. This means that the estuary is in equilibrium, and since the rocky headlands protrude quite offshore, the amount of sediment in the system is fixed and constant, no longshore transport occurs. Furthermore, several dams had been constructed along the river basin, stopping all sediment before it reaches the estuary and controlling the river discharge.

Nowadays, (Figure 3) Navia estuary presents a tidal prism of about $5*10^6$ m^3 and an offshore shoal that almost emerge in low tide. Human intervention in Navia's estuary starts at the end of the last century, with dredging, reclamation of tidal flats, shore protection along the river margins and the construction of two small jetties. Land reclamation was not very extensive, and the jetties become a lateral support for a beach east from the tidal inlet.

Recently, a new expansion project has to be made for the port, considering the possibility of maintenance dredging versus jetties enlargement. The outcome was a new approach for optimum design applying a long-term evolution model.

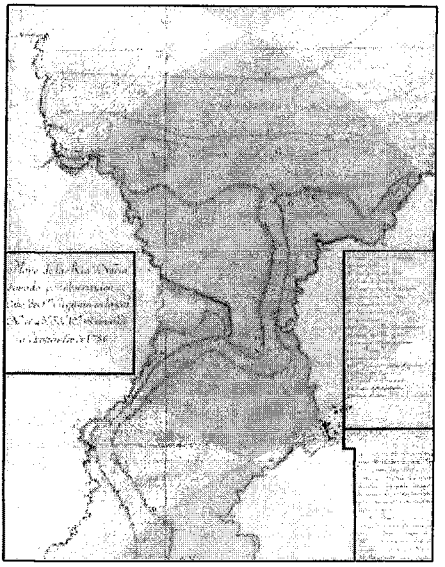

Figure 2. Navia inlet. Chart from 1786.

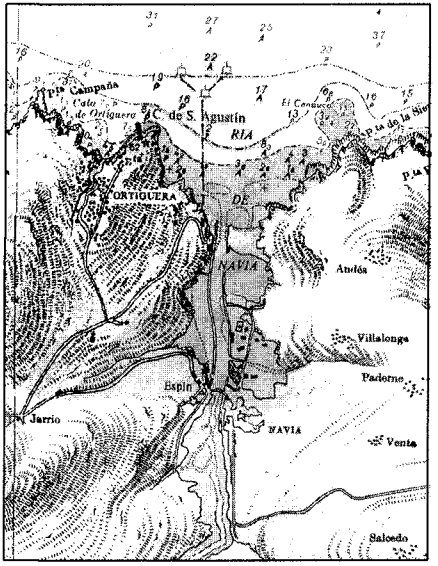

Figure 3. Navia inlet. Present day chart.

Navigation Channel Design Principles

Water depth at the inlet is one of the factors controlling the access to a port. On one hand there is a minimum channel depth required for a given ship to enter safely, this depth is the result of considering ship's draft, the under keel clearance corresponding to cargo's characteristics and bottom material, and ship's dynamical response to waves and displacement, i.e. squat and heave. On the other hand, the real water depth at a certain moment is the result of minimum depth, astronomical tides and storm surge (see Figure 4). As one can see, some of these factors varies with time and, furthermore, a few are purely stochastic parameters. Thus, for a given vessel, there is a percentage of time where the channel can be accessed, in other words, to be operational. A combination of all these factors gives a curve for different dredged channel scenarios and a plot of percentage of time versus channel depth can be constructed for each vessel (Figure 5). In this curve, the minimum design water depth can be obtained given a desired functionality and vice versa.

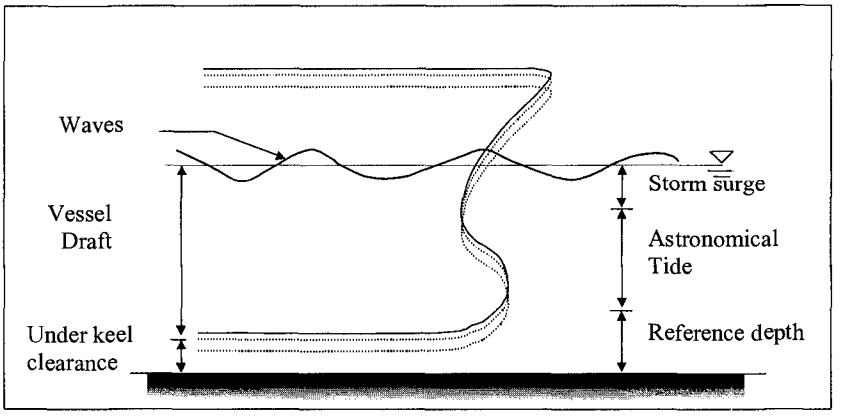

Figure 4. Real and required channel depth definition.

The obtained design depth corresponds to vessel requirements and has nothing to do with nature's equilibrium depth. Typically, both depths are different and the problem arises when the equilibrium depth is smaller than the required depth, thus the access channel is dredged. According to the preceding paragraphs, the inlet will try to recover the equilibrium immediately after changing its original condition, but this will take some time, depending on the strength of the hydrodynamic and morphologic processes, and sediment availability. Consequently, in order to warrantee the desired functionality, over dredging is commonly performed, as a sedimentation bulk capacity, delaying maintenance dredging. Thus, maintenance (m) should be done as soon as the inlet has evolved to the minimum depth, at least to fulfil the minimum requirement for functionality. Hence, three depths has been defined: the initial depth (i.e. over-dredged depth, h_o), the minimum depth for required functionality (design depth, h_L) and the final depth or equilibrium depth (h_f).

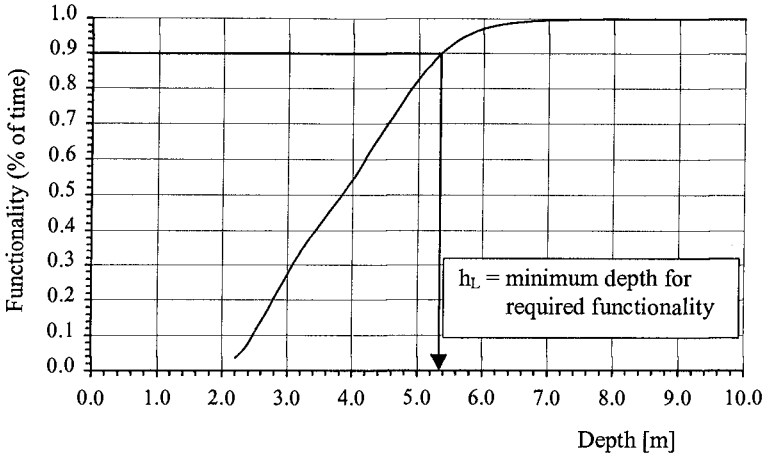

Figure 5. Functionality versus channel depth for the design vessel.

As a result, it is required to know the depth evolution time history at the inlet. A long-term evolution model will provide this information. Figure 6 shows an example of channel depth time evolution, indicating the initial, design and final depths and defining the maintenance interval. Here two approaches can be followed: to dredge and maintain the inlet or to modify the evolution trend by constructing jetties, or changing any of the main parameters that control the time evolution. In any case, the long-term evolution must be determined. The theory behind, concepts and how it was applied to Navia will be presented in the following paragraphs.

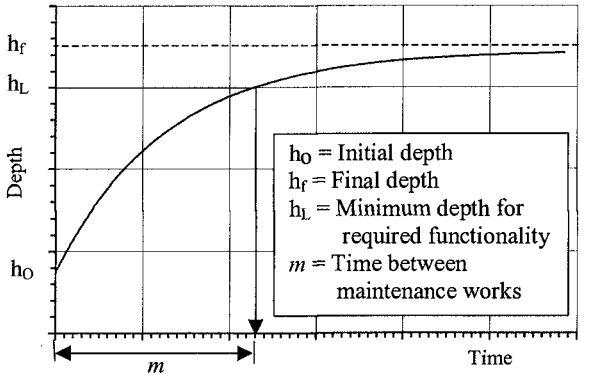

Figure 6. Time evolution example of channel depth.

Long-Term Evolution Model

As mentioned before, a long-term evolution model is based on the assumption that the estuary, and its elements, will tend to a known natural equilibrium condition. The dynamical stability, with a mean morphology, is a feature of tidal inlets measurable all over the world. Several researchers had studied these mean morphologies, and found empirical relationships between the morphology and some parameters representative of the estuary.

Hence, if any estuary parameter is modified, there will be a change in the morphology accordingly, or if the inlet cross section is altered, it will recover its original shape (van Dongeren, 1992).

The main approaches for modelling long-term inlet morphology are:

1. To use small scale physics and to integrate the results over larger time scales. This is known as aggregated scales and can only be used when the process modelled is dominated by a linear behaviour.
2. To use empirical relationships, i.e. those mentioned before which relate an estuary parameter with hydrodynamics.
3. To use a hybrid model (van der Kreeke, 1996).

In the present paper, a hybrid model has been developed to evaluate the long-term evolution of Navia inlet. Following de Vriend, *et al*, 1994, the proposed model is based on the assumption that the system, which consists of four interacting elements (the tidal basin, the outer shoal, the offshore shelf and the adjacent coast, see Figure 7), will try to attain the equilibrium after a human work (dredging and/or jetties).

The model describes the transition of the outer shoal from the initial disturbed position to the equilibrium. It uses physics as well as empirical relationships. In particular, the along-shore and cross-shore transport are calculated using physics based models. Tidal basin sediment transport and outer shoal equilibrium is calculated by means of empirical relationships.

Basically, the evolution model performs a sedimentary balance at the inlet, from the input and the output volume of material. It is assumed that the output volume is inversely proportional to the degree of instability of the inlet, in other words, the closer is the inlet to equilibrium, the more sand is exported to the adjacent morphologieal units.

In a long-term time step (months/years), the inlet organises the input volume in the shoal, thus some part will be under the waves and currents influence and will be transported back to the beach or inner estuary. The volume of sediment, which actually remains is, therefore, a fraction of the originally deposited (Losada, *et al*, 1997):

$$\Delta V_I = k_1 (Q_O + Q_R + Q_B) \Delta t \qquad (1)$$

Where V_I is the volume of the outer shoal, which includes the inlet, and is proportional to the inlet depth (Eysink, 1990). k_I is a constant and represents the fraction of sand volume, which remains at the inlet. The value of k_I is obtained from the wave incidence pattern (Hicks and Hume, 1996) and is also calibrated from adjacent inlets. The rest of parameters are defined below.

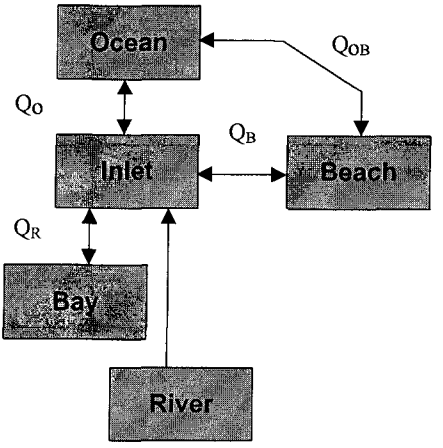

Figure 7. Morphological units of a tidal inlet.

In Figure 7 also the sediment transport flux between each unit is shown. Q_O is the cross-shore transport, mainly induced by waves. Q_R is the estuary sediment input and output due to tidal oscillatory currents and river discharge. Q_B is the longshore transport from the adjacent beach produced by oblique wave incidence, set-up and tidal currents, and Q_{OB} is the cross-shore transport from the outer shoal to the adjacent beach. Hence, two different processes has been defined, the process within units, based on empirical relationships and formulations, which is considered to be instantaneous, and the process among units, defined by the continuity of sediment flux between units.

Notice that in each time step, the value of the fluxes depends on the inlet condition, the farther the inlet is from its equilibrium condition, the larger is the sediment input. With this approach, each unit is modelled in a different way, according to its morphological response.

The estuary will contribute with sediment linearly according to the degree of instability of the inlet:

$$Q_R = k_2 (V_I - Ve) \quad (2)$$

Where: Q_R is the sediment flux from the estuary,
V_I is the volume of sediment in the inlet,

Ve is the tidal inlet equilibrium volume, and
k_2 is a constant based on empirical models (Eysink, 1990) and calibrated from adjacent inlets.

The river input is independent to the inlet condition; therefore its flux is assumed to be constant. The ocean unit can endow or receive sediment from the inlet. The ocean-inlet flux is an exponential function of inlet degree of instability:

$$Q_O = Q_{OE} \exp(-k_3(h-h_f)) \quad (3)$$

Where: Q_{OB} is the ocean-beach sediment flux,
Q_O is the ocean-inlet sediment flux,
Q_{OE} is the ocean-inlet sediment flux for equilibrium conditions,
h is the inlet water depth,
h_f is the inlet equilibrium water depth, and
k_3 is a constant based on empirical data and calibration.

Finally, the beach will supply sediment to the inlet according to the incident wave field. If there is no jetty, the wave will approach to the spit of the sand bar with an angle, which will create a longshore current and sand transport. If there is a jetty, the shoreline position, relative to the tip of the jetty, will indicate the percentage of sand flux from the beach to the inlet.

$$\begin{aligned} Q_B &= Q_{B(MAX)} && \text{if } D_L = 0 \\ Q_B &= k_4 D_L && \text{if } 0 < D_L < D_{L(MIN)} \\ Q_B &= 0 && \text{if } D_L > D_{L(MIN)} \end{aligned} \quad (4)$$

Where Q_B is the beach-inlet sediment flux,
$Q_{B(MAX)}$ is the long-shore sediment transport, computed with the overall incident wave climate,
D_L is the distance from the shoreline to the tip of the groin,
$D_{L(MIN)}$ is the surf zone width, where long-shore transport mainly occurs, and
k_4 is a constant based on equation (4) requisites.

The sand transport, $Q_{B(MAX)}$, is computed using one of the several formulae available from the literature, and the actual flux is computed using a multi-line model of the beach profile, which in turn depends on the total volume of sand at the beach.

The beach behaves as a special sedimentary unit in this case, since the total amount of sand in it will define the shoreline position. The actual volume of sand is a balance from the output flux towards the inlet and the input flux from the ocean (or any other source, e.g. sand by-passing, wind transport, nourishment, etc). The model assumes that the ocean-beach flux (Q_{OB}) will be exactly all the sand volume exported by the inlet during its sedimentary balance, thus:

$$Q_{OB}=(1-k_1)(Q_O+Q_R+Q_B) \quad (5)$$

The sand volume and distribution at the beach is based on accurate bathymetry and charts. The shoreline position and cross-shore profiles are based on empirical formulations and similar beaches formed on inlets along the North coast of Spain (e.g. Zumaya, Orio, Suances, among many others).

Each morphological process, for every sedimentary unit, has a stochastic character. Thus a probabilistic approach is used to include individual strong events, such as a storm or high runoff discharges. The first case, linked with high wave energy, will try to close the inlet, moving sediment from the outer shoal and the adjacent coast. The second case will wash off the sediment from the inlet, due to the related high velocities. Each situation will delay or shorten the evolution time.

Introducing for each process a mean value and its standard deviation, the procedure is repeated several times to assess the overall trend and confidence intervals (Montecarlo simulation). To attain the mean values and deviations, historical data is collected from Navia and adjacent inlets, similar in behaviour and configuration. Some of these inlets have been modified in the same way as planned for Navia, so detailed surveying of medium and long-term evolution has been undertaken to calibrate the model.

In this way, knowing the sediment flux for each unit, the sedimentary balance at the inlet is performed, as mentioned above. The relationship between the inlet sand volume and depth will provide its time evolution.

Next, the model will be applied to Navia's inlet and a relationship between percentage of operational levels, jetties length and mean maintenance requirements will be studied, leading to an optimum design procedure based on capital and maintenance costs.

Results

The long-term evolution model, combined with the percentage of operational time data, has been used to determine the maintenance requirements at Navia inlet for different scenarios of jetty construction. The optimum solution is somewhere in between two extremes:

1. No jetty construction and maintenance of functionality purely with dredging, and
2. Extremely long jetties, reaching a depth such as the inlet becomes independent of the adjacent sedimentary units. This includes an initial dredging of the whole inlet up to the closure depth.

In the first solution, continuous dredging has to be undertaken, and the solution is more sensitive to individual events like storms or high river discharges. The second solution is extremely expensive, and might have tremendous effects on the environment, not only the estuary under consideration, but also to the neighbouring coast.

Two different scenarios will be presented as possible solutions. One with two short parallel jetties (240 m) and an initial dredging depth h_O = -2 m, the other with two long parallel jetties (600 m) and dredging up to h_O = –6.5 m. All levels are referred to chart datum, which is at MLWS. The required data and computed parameters to apply the long-term model are given below.

Equilibrium depth at the inlet, h_f:	1.1 m
Equilibrium volume of the inlet, V_e:	420,000 m^3
Initial estuary and river sediment flux, Q_R:	5,000 m^3/yr
Ocean sediment flux for equilibrium conditions, Q_{OE}:	10,000 m^3/yr
Maximum long-shore transport, $Q_{B(MAX)}$:	15,000 m^3/yr
Surf zone width, $D_{L(MIN)}$:	680 m
Constant k_1:	0.5
Constant k_2:	$(h_O-h_f)/Q_R$
Constant k_3:	0.35
Constant k_4:	$-Q_{B(MAX)}/D_{L(MIN)}$

The equilibrium depth is obtained from O'Brien, 1930 and Bruun, 1966 formulations. Also this depth is compared with present and old data from charts (Figures 2 and 3). The equilibrium volume is computed following Hicks and Hume, 1996 and the estuary and river sediment flux are based on comparisons with similar inlets in the neighbourhood. The ocean-inlet flux for equilibrium conditions is also based on adjacent inlets and the maximum long-shore transport is computed as in the Shore Protection Manual, 1984. The surf-zone width was assumed to be the same as the active profile at the beach, measured and observed in several beaches along the Cantabrian Sea coast. The constant k_1 was proposed by a simple geometrical consideration, from the wave incidence pattern and the inlet characteristics. The constant k_3 was defined arbitrarily; in order to have half of the volume flux when the actual depth is the equilibrium depth plus 2 metres.

In Figure 8 the time mean evolution of the inlet is shown for the long groin scenario, as can be seen the fastest changes occurs at the beginning and the equilibrium is attained in less than, say, 40 years. Also, in Figure 9 the sediment fluxes between units are presented. Notice that these curves are not given formulations, but the output of the model for each time step according to inlet demands and morphological evolution.

Figure 10 presents the time evolution of the inlet for the short groin scenario; also the evolution sensitivity is presented as a function to process variability. In this case the inlet will attain the equilibrium in 4 – 6 years, depending on the environmental conditions present. The sensitivity analysis was not presented for the long groin scenario, since it becomes almost negligible, due to the relatively long equilibrium period.

As shown before, each scenario will present a different evolution pattern. Hence, fixing the minimum depth for a given required functionality (h_L), the maintenance interval (m) is obtained from the time evolution curves. Including all scenarios, a curve can be constructed with the groin length on one axis, and the maintenance interval, on the

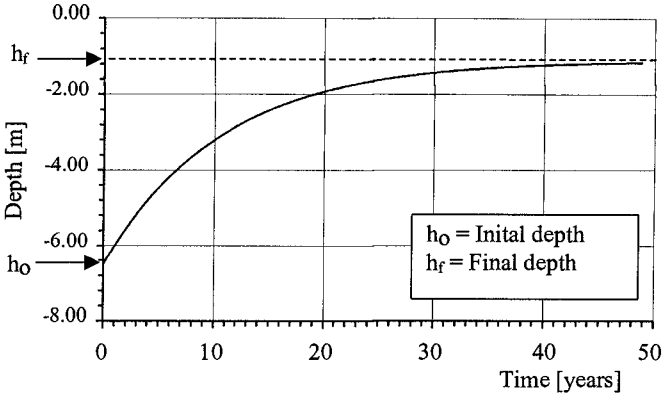

Figure 8. Time mean evolution for the long groin scenario (600 m).

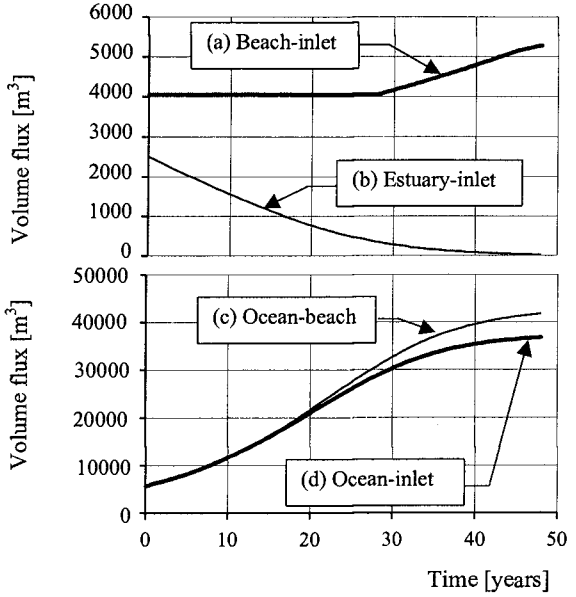

Figure 9. Sediment fluxes for the long groin scenario. Beach-inlet flux (a), estuary-inlet flux (b), ocean-beach flux (c) and ocean-inlet flux (d).

other, for a given functionality, as presented in Figure 11. Here, the short groin scenario implies maintenance dredging every 6 months and the long groin scenario a maintenance dredging every 5 years. Both scenarios presented are meant to allow the entrance to the port 90% of the time for the design vessel. Nowadays, Navia's inlet functionality is less than 30%.

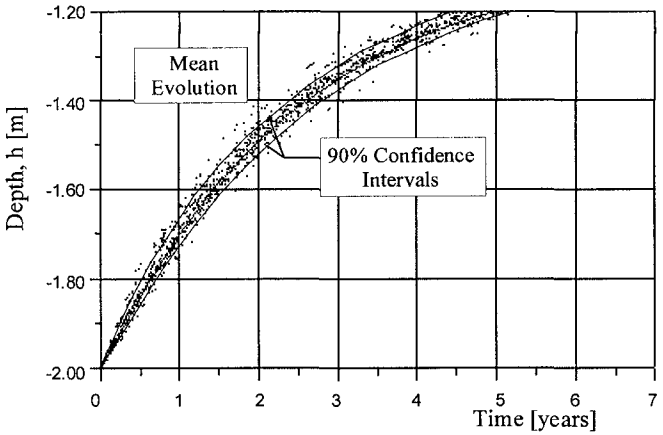

Figure 10. Time mean evolution for the short groin scenario (240 m) and 90% confidence intervals.

Translating these results to economical meaning is straightforward, and depending on each case and budget availability, one solution might be better than the other might be. The financial and environmental best solution was beyond the scope of this paper, but it was clear that, to give the port authority a better forecast for the investment, based on technical foundation was, for the first time, an improved approach for optimum design.

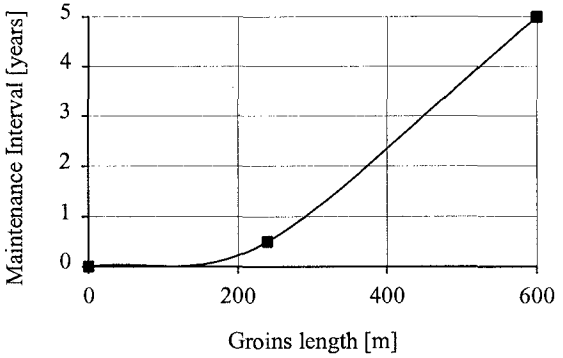

Figure 11. Groins length versus maintenance interval for Navia inlet (Functionality: 90%)

Conclusions

In order to attain an improved methodology for optimum design of Navia's navigation channel, a long-term evolution model of tidal inlets is applied. The special

features of Navia coast and oceanographic process are presented and the navigation channel design principles lead to require the knowledge of the long-term evolution in the inlet.

Thus, an aggregated scales model was implemented and used in Navia inlet, where the sedimentary units were modelled in a simplified way, employing historical data and surveying from adjacent inlets. The time evolution was found to be in the order of decades and the obtained information was not old enough to ensure the morphologic response. Therefore a sensitivity analysis was performed to study the variability of each process leading to a relatively more sensitive solution for shorter evolution periods.

The long-term evolution model was then applied for different scenarios and, by means of a minimum required functionality for the port, a maintenance period was obtained. As a result, a relationship between groin length and maintenance dredging was obtained. The economical impact is evident and a financial study for optimum groin length and periodic maintenance will provide, for the first time, a long-term evolution forecast and better budget planning.

Acknowledgements

This study was partially supported by the Spanish CICYT (Comisión Interministerial de Ciencia y Tecnología), as part of the projects MAR95-1845 and MAR95-1896.

References

- Bruun, P., 1966. Tidal inlets and littoral drift. Stability of tidal inlets, Vol. 2.
- de Vriend, H.J., Bakker, W.T., Bilse, D.P., 1994. A morphological behaviour model for the outer delta of mixed-energy tidal inlets. *Coastal Engineering, 23*, pp. 305-327.
- Eysink, W.D., 1990. Morphologic response of tidal basins to changes. *Proc. 22nd Coastal Eng. Conference, Vol. II,* pp. 1948-1961.
- Hicks, D.M. and Hume, T.M., 1996. Morphology and size of ebb tidal deltas at natural inlets on open-sea and pocket-bay coasts, North Island, New Zealand. *Journal of Coastal Research, 12(1),* pp. 47-63.
- Losada, M.A., Medina, Raul, Baquerizo, A., Lomonaco, P., 1997. Estudio de la Canal de Navegación de la Ría de Navia (in Spanish), *Fundación Leonardo Torres Quevedo*, Universidad de Cantabria, Spain.
- O'Brien, M.P., 1930. Estuarine tidal prism related to entrance areas. *Coastal Engineering 1,* pp. 738-739.
- Shore Protection Manual, 1984. Coastal Engineering Research Centre. U.S. Army Corps of Engineers.
- Van de Kreeke, J., 1996. Morphological changes on a decadal time scale in tidal inlets: Modelling approaches. *Journal of Coastal Research, 23*, pp. 73-81.
- Van Dongeren, 1992. A model of the morphological behaviour and stability of channels and flats in tidal basins. MSc Thesis. TU Delft, The Netherlands.