

The Orio Inlet: A Case Study from the North Coast of Spain

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ABSTRACT

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Results are presented from a one year study of Orio inlet on the north coast of Spain. The objective of this study was to design civil works which could solve navigational problems at the inlet entrance. Field measurement, physical models, and a mathematical transport model were used to achieve this objective. Three groins were planned in order to guarantee an established draught and a low wave energy along the inlet entrance.

ADDITIONAL INDEX WORDS: *Inlet entrance, navigational problems, wave-current, transport.*

INTRODUCTION

Most literature on tidal inlets only considers the gorge channel, defined as the cross section of minimum area, O'BRIEN (1931, 1969), ESCOFFIER (1940, 1972), VAN DE KREEKE (1985). However, if one is dealing with navigational aspects of tidal inlets, especially with harbour entrances, more appropriated theories are required, i.e. those where the overall stability of the tidal inlet is established, including all sections of a tidal entrance, their sediment transports, BRUUN (1986, 1978), and combinations of wave and current forces, GRANT and MADSEN (1979), FREDSSØE (1984). These kinds of theories give a proper idea of the morphodynamics of tidal inlets and can be deployed as adequate tools that indicate ways to solve problems within tidal entrances. Quantification of these solutions of requires physical and mathematical models. Accordingly, this paper presents the results of a one-year study of Orio inlet and the design of a new inlet geometry which alleviates navigational problems.

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ORIO INLET LOCALITY

Physical Setting

Orio Inlet (Figure 1), is a small inlet on the North coast of Spain ($43^{\circ} 17' N$, $02^{\circ} 08' W$), located about 80 km East of Bilbao and 10 km West of San Sebastián. This inlet is navigable for fishing vessels and has in Orio City, which lies about 2 km from the entrance, an important fishing-harbour. The region landward of Orio City is characterized by a tidal river of gentle slope (4×10^{-4}).

Tides, Waves and Sediments

Tidal data were obtained from a tide gage installed specifically for this study. Tides in Orio inlet are governed by the semidiurnal component M2. The average tidal range is about 2 m and the spring range is 4.5 m. Due to the configuration of Orio Inlet, storm surges are not a problem.

The wave climate along the northeast coast of Spain has an annual average significant height of 1 m, and a typical year winter storm of 4 m significant height. Significant wave periods range from 8 to 20 sc. Waves are normally from

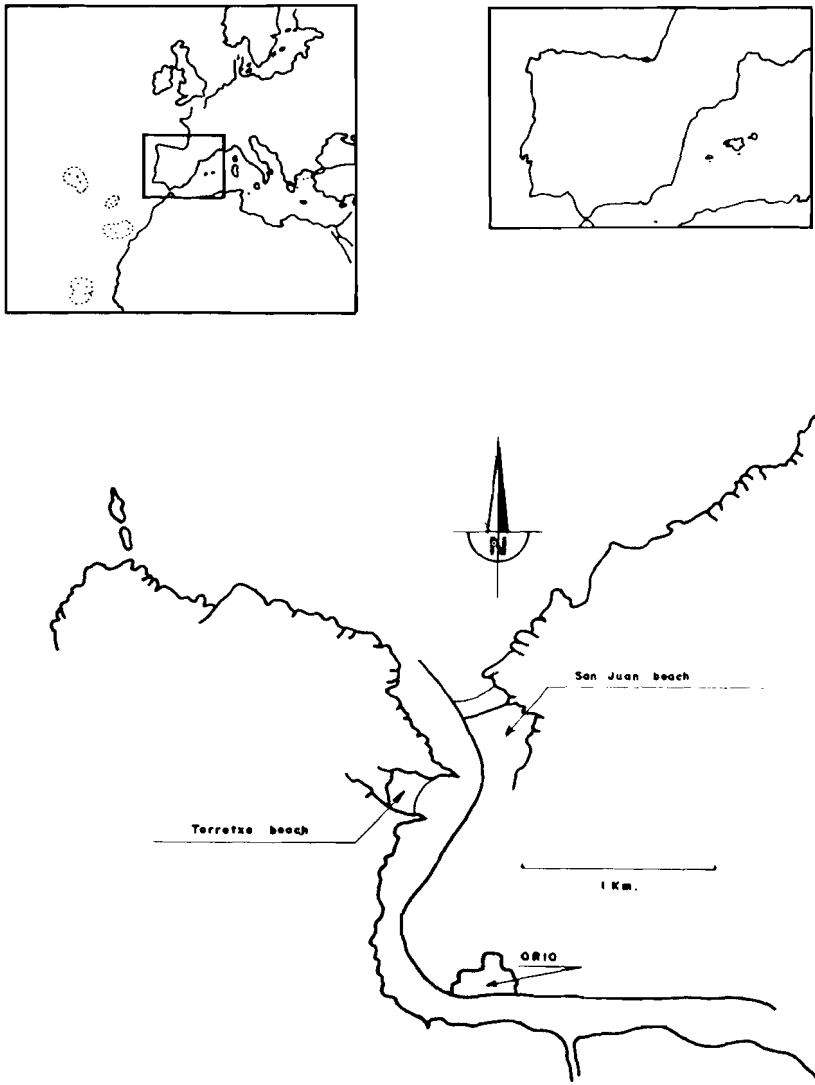


Figure 1. Location of the study area.

the north-northwest. Figure 2 shows the deep water annual significant wave height (H_s) regime.

The continental shelf in the front of the inlet has a slope of 1:100 and is sandy up to the forty meter depth contour. In most of the zone sand thickness averages about five meters. Orio is a sandy inlet with sand ranging between 0.20 and 0.30 millimeters in diameter; muds and silts are found only up the Oria River. Dams and bridges stop most sediment transport by the river. The average river discharge is about

$10 \text{ m}^3/\text{sec}$ and is not significant relative to the maximum tidal discharge ($300 \text{ m}^3/\text{sec}$ for spring tide). Floods are controlled by dams and the expected maximum flow in one hundred years does not reach $100 \text{ m}^3/\text{sec}$.

Inlet Geometry

The actual Orio Inlet entrance geometry is determined by the east side jetty and the west side cliff. The east side jetty acts as a beach barrier and the beach San Juan de Orio may be con-

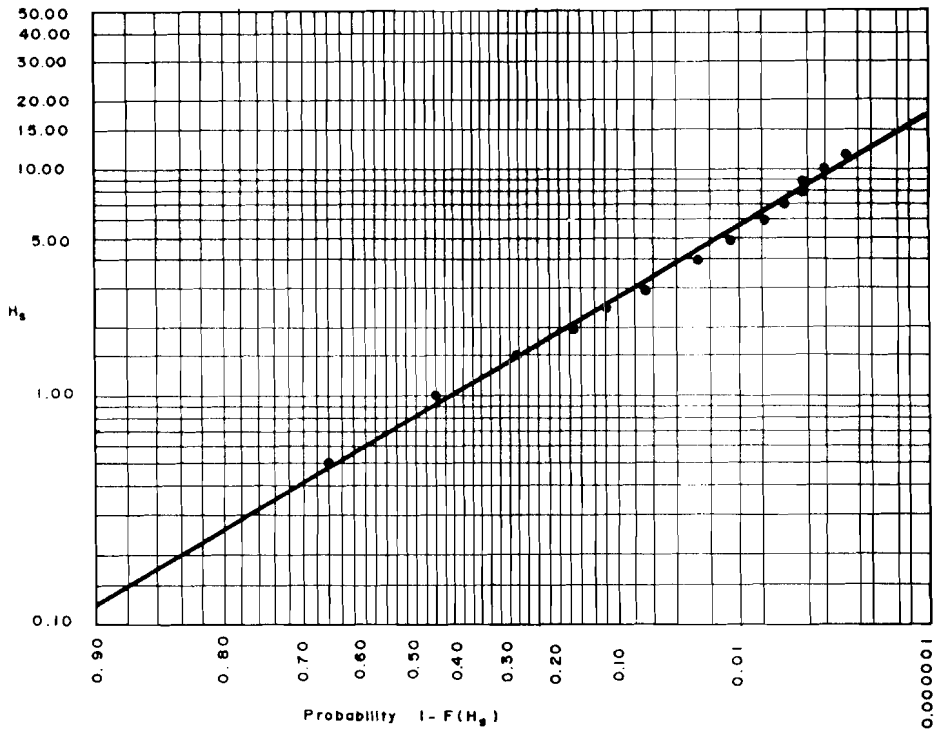


Figure 2. Deep water significant wave height regime.

sidered a pocket beach. Two bends of approximately 70° and 40° are the most conspicuous geometrical characteristics. Since the entrance orientation is NNW, storm waves reach it almost orthogonally and propagate along the inlet axis.

Civil Works History

Navigational improvements in Orio Inlet began in 1533. By that time, the beach was closer to the city, the entrance depth was about 2 m and the entrance width was adequate for any known vessel. From 1533 to 1920 all civil works were focused in the construction of a wall along the river between Orio and Torretxe beach (see Figure 1). In 1910 (Figure 3a), the construction of a primary east side jetty was finished. This jetty was supposed to wash out the dangerous ocean shoals. In 1935 (Figure 3b), the jetty was lengthened and a beach (San Juan de Orio) emerged between it and the east cliff. The jetty length was not enough for solving the

shoals problem. The east jetty was lengthened afterwards in 1960 and in 1984 (Figure 4a,b) with similar results. This last enlargement placed the jetty head in water six meters deep and beyond a hypothetical line drawn between rocky headlands.

Navigational Problem

The navigation channel in Orio Inlet is modeled by waves and tidal currents. It can be divided into two different zones: an internal zone and an exposed zone. The internal zone, which extends from Orio City to Torretxe Beach (Figure 1) (about 1500 m length), is well protected against wave action by the last bend near Torretxe Beach. The dynamic equilibrium is thus basically defined by tidal ebb and flood currents. Sediment movements and hydrodynamics features of this zone are well established by the geometry and results in a quiet and stable navigational channel. The exposed zone, which extends from Torretxe Beach to the entrance

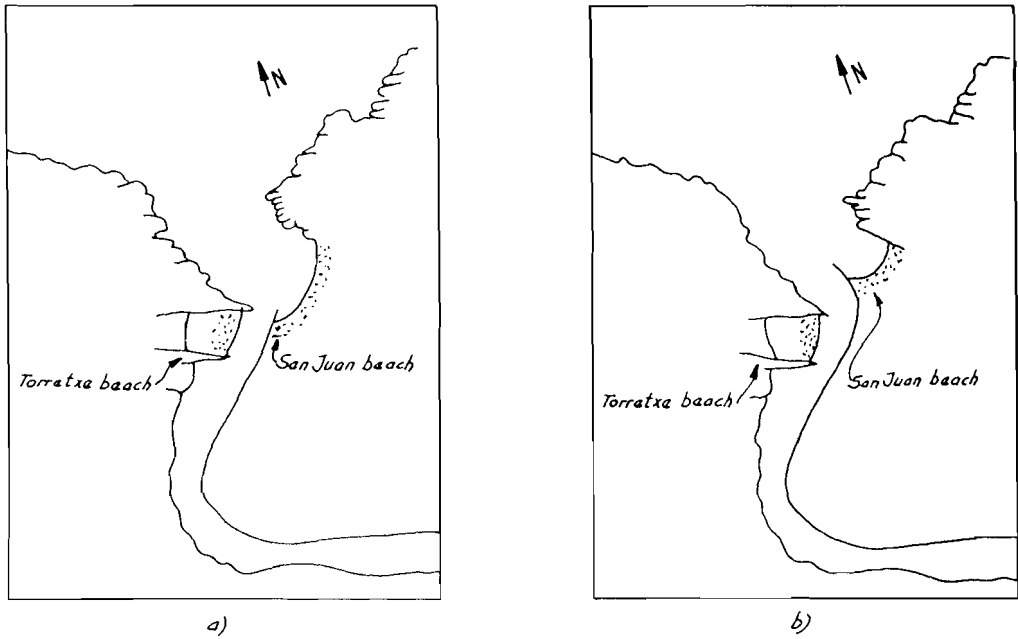


Figure 3. Historic jetty positions (a) 1910, (b) 1935.

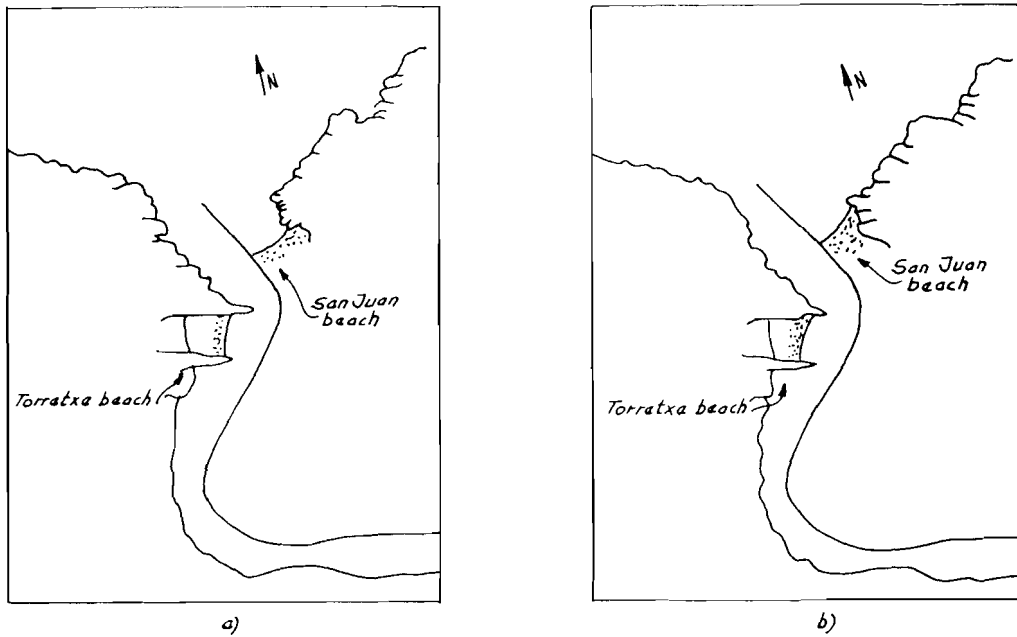


Figure 4. Historic jetty position (a) 1960, (b) 1984.

due to the combination of waves and currents, has a dangerous movable channel where waves may break.

The bed morphology of the exposed region, described in Figure 5, results from the strong interaction between waves, currents and inlet geometry. Due to the jetty bend, ebb currents increase their velocity in zone 1 causing a deep and narrow channel. It deflects to zone 4 where waves are low. Zones 2 and 3 correspond to sedimentation or bay shoals, mainly due to the variation of the wave action. The equilibrium of the exposed zone is established by the combination of waves and currents so the seasonal changes modify the geometry of the channel. The bathymetry of the inlet shows these seasonal changes. In winter, when waves are higher, the channel becomes deeper and the sand of zone 2 is transported to Torretxe Beach. Waves breaking on ocean bars and the beach introduce sand into the inlet increasing sedimentation in zone 3. In summer, under a mild wave regime tidal currents predominate and the channel loses depth. In conclusion, waves

not only break on outer and inner bars but the navigation channel morphology changes continuously during the year.

MORPHOLOGICAL AND NAVIGATIONAL STABILITY ANALYSIS

Bars and shoals, *i.e.* their locations and configurations, dominate the Orio entrance problem. According to BRUUN and GERRITSEN (1969) the coastal geomorphological condition of the entrance may be described by the Ω/M_t ratio (Ω = tidal prism, M_t = the total amount of material carried to the entrance). Good conditions for navigation are guaranteed if $\Omega/M_t > 300$. The conditions for navigation at Orio Inlet are very bad. Comparing the actual morphology of Orio Inlet with stability conditions given by BRUUN (1986), the parameter Ω/M_t may be evaluated as large as 40. Taken in account that $\Omega = 4 \times 10^6 \text{ m}^3$, the total amount of material carried to the entrance is $M_t = 10^5 \text{ m}^3/\text{yr}$.

Today, it is impossible to obtain an increase

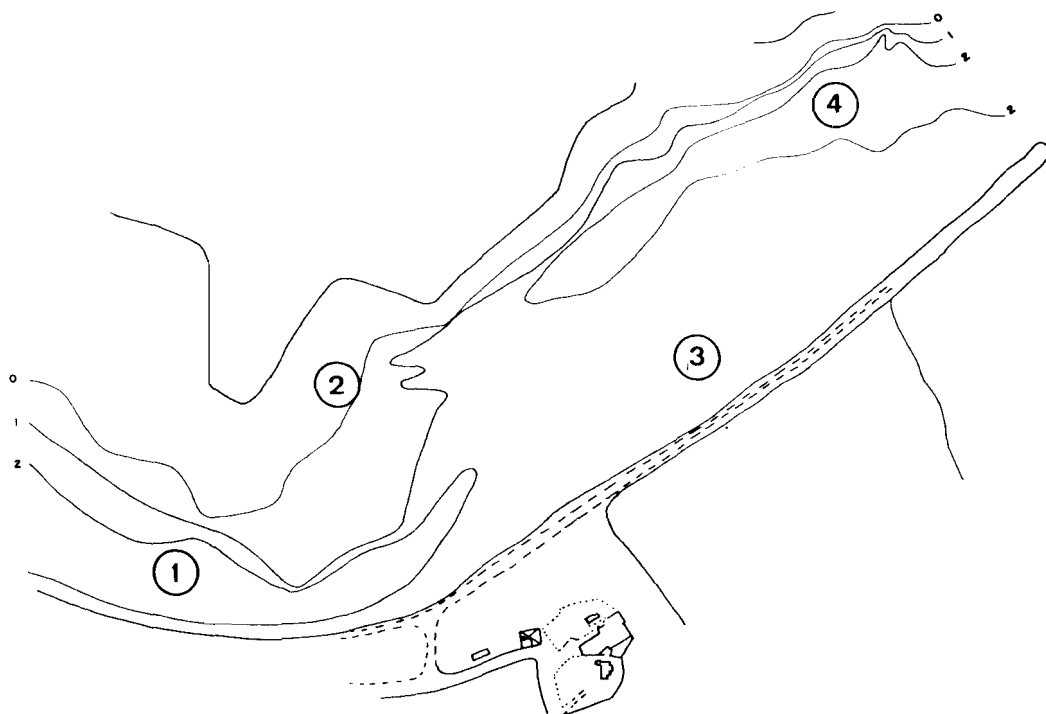


Figure 5. Entrance bathymetry.

of Ω and inlet improvement calls for a reduction of M_t . The source of material computed in M_t and carried to the entrance can be divided into: bay shoal material, ocean shoal material and beach material. A reduction of M_t may be achieved by (1) dredging, (2) extending the east jetty, (3) improving the flushing ability of ebb currents (Venturi Effect). In this case, the later solution was selected. This objective was to design a Venturi system in the exposed zone that consists of three hydraulic barriers (Figure 7). Two physical models were constructed for the evaluation of the flushing ability of ebb currents and the modification of wave action. One distorted hydraulic model was for the inlet while another undistorted wave model was for the entrance. Once the hydraulic model confirmed the efficiency of the solution, it was tested in the wave model. Several postulation and feedback mechanisms were needed before a final solution could be achieved.

The hydraulic model was a distorted fixed bed model with $n_x = 1/150$, $n_y = 1/45$, $n_y/n_x = 3.3$. Flood and ebb currents were evaluated for different tidal conditions. Two field measurements (winter and summer) were conducted to calibrate the model. Maximum ebb velocities for spring tide conditions are presented in Figure 6. It is possible to distinguish three different areas: Entrance-Torretxe beach with current magnitudes about 0.35 m/sec, Torretxe beach with currents about 0.45 m/sec, and Torretxe-Orio City with currents about 0.6 m/sec.

All the regions have the same sediment

transport rate, that is all the regions have the same flushing ability (dynamic equilibrium) although they have different velocity magnitudes. That gives an idea of the relative importance in stability conditions of wave action in each region. A similar example can be found in BRUUN (1968) in relation to the case of Thyboran Channel. Consequently, wave action must be reduced in the region of the entrance-Torretxe beach and accompanied by an increase in current velocity to maintain the flushing ability of the zone.

The final solution, shown in Figure 7, is composed of three groins almost perpendicular to the east jetty with curved heads. Hydraulically, the main ebb current flows between groin heads and the east jetty; two eddies are formed in the space between the groins. The distance between the groins was established so that eddies develop and avoid the interchange of water between eddies and main flow. The groin system works as a hydraulic barrier. Finally, it was ascertained that the distance between the groin heads and the east jetty were sufficient for admitting adequate navigational conditions for fishing vessels. The maximum ebb velocity for spring tide conditions with the new configuration is presented in Figure 8.

The objectives of the entrance wave model were to determine (1) the wave propagation along the navigational channel, (2) the geometry of the groins (interacted with hydraulic model), and (3) stability of groin slope. With the configuration of the groins (shown in Figure 7) and overall reduction of wave height was deter-

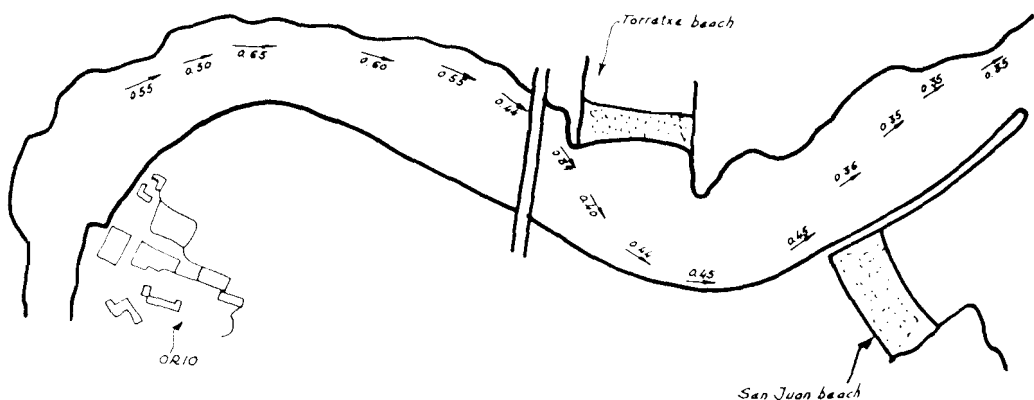


Figure 6. Current velocities with actual geometry.

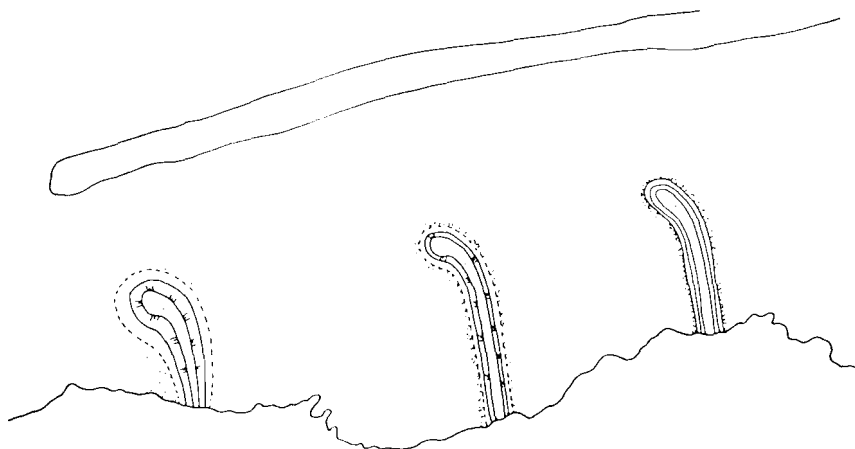


Figure 7. Proposal.

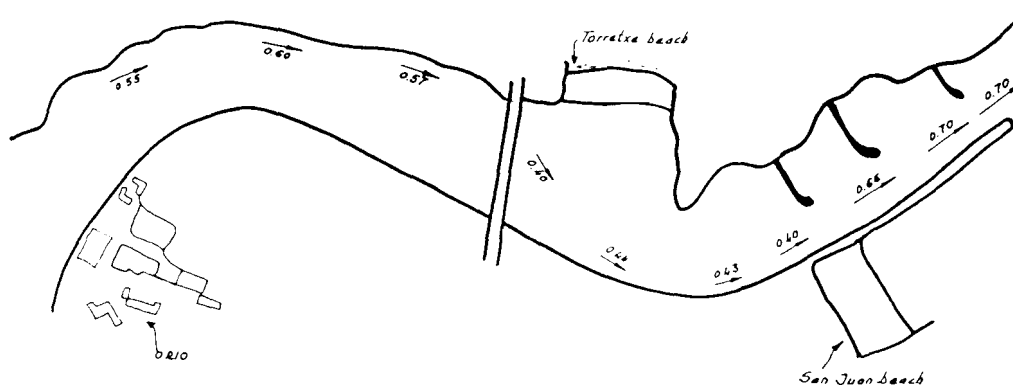


Figure 8. Current velocities with modified geometry.

mined to be 26% after the first, 55% after the second, and 85% after the third groin.

As both hydraulic and wave models were fixed bed models, changes of the bottom geometry were calculated using a system of numerical models. It included models for tidal induced currents, wave propagation, wave-current velocity profile and sediment balance. The tidal induced-currents model solved the vertically integrated equations of continuity and momentum using an Alternating Direction Implicit difference scheme. The model included lateral turbulent shear stresses in the vicinity of the groins. Details of this model can be found in the work of Falconer *et al.* (1986). The parabolic

approximation of the mild slope equation was used in the wave propagation model in order to include the diffractive effects of the groins. The model followed the approach of Ebersole *et al.* GRANT and MADSEN's (1979) theory was used for the wave-current velocity profile model. Their theory describes the combined motion of waves and currents in the vicinity of a rough bottom and the associated boundary shear stress. The theory accounts for nonlinear interaction between two flows and gives solutions for wave and current kinematics, both inside and outside the wave boundary layer as well as a solution for the wave-current friction factor used to define the bottom shear stress.

The velocity profile can be found as:

$$u = (u_c^*/\kappa) (u_{wc}^*/u_c^*) \text{Ln}(30z/k_b) \quad z < \delta_w$$

$$u = (u_c^*/\kappa) \text{Ln}(30z/k_{bc}) \quad z > \delta_w$$

where:

- u_{wc}^* wave-current friction velocity $(\tau_{wc}/\rho)^{1/2}$
- u_c^* current friction velocity $(\tau_c/\rho)^{1/2}$
- k_b bottom roughness (2D)
- k_{bc} bottom roughness $(k_b(24u_{wc}^*A_t/u_bk_b)^{1/2})$
- β parameter $(1 - u_c^*/u_{wc}^*)$
- δ_w wave boundary layer thickness
- κ Von Karman constant
- τ_c current shear stress
- τ_{wc} wave-current shear stress.

In order to obtain the wave-current velocity profile for an initial wave and current, an iterative procedure was used. Assuming an initial value for the velocity at a height $\partial(u_b)$ above the bottom, the equations for wave current interaction can be solved (GRANT and MADSEN, 1979) and the velocity profile obtained, including the assumed u_b . The sediment concentration profile is needed for the sediment balance model. Similar approach as NIELSEN's (1986) can be achieved to determine the suspended sediment concentration profile:

$$\bar{C}(z) = f(z) \cdot C_0$$

Consequently the rate of transport, \bar{q} , can be found as:

$$\bar{q} = \int_0^h \bar{C}(z) u(z) dz$$

The variation of the bottom geometry can be obtained solving the continuity equation:

$$(\partial h/\partial t) + (\partial \bar{q}_i/\partial x) = 0$$

The continuity equation was solved using a finite difference scheme. Field measurements of actual conditions (velocities, sea level) were used to calibrate the models. Model measurements of wave penetration coefficients and currents were used as initial conditions to determine future geometry. Different wave climates were computed in order to establish bottom geometry changes.

The increase in transport rate due to larger

current velocities exceeded the decrease due to reduction of wave height in the entrance. A new dynamic equilibrium with an average increase of 1.5 meter depth in the navigational channel all along the area affected by the groins was obtained for annual average conditions of waves and tidal range. Once the dynamic equilibrium was reached the new velocities were compared with actual velocities (no groins). An average increase of 30% was found. The navigational channel was stable with minor depth changes due to wave climate variation, even in storm conditions. Depth variations were only important in an area close to the groin located more seaward. A storm condition combined with spring tide conditions was tested in order to study this groin foundation. A maximum increase of 3 meter depth was achieved for 4.5 meters tidal range and 4 meters wave height.

SUMMARY AND CONCLUSION

(1) The increase in flushing effects of ebb currents (Venturi effect) is an efficient way to improve tidal entrances.

(2) The combination of field measurements, physical models, and mathematical models is an acceptable technique for designing protection works at inlet entrances.

ACKNOWLEDGEMENTS

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□ RESUMEN □

En este artículo se presenta el conjunto de trabajos realizados durante un año en la Ría de Orío. El objetivo del trabajo era el de diseñar las obras necesarias para solucionar los problemas de navegación de la ruta de entrada. Para conseguirlo se realizaron una campaña de campo, construcción de un modelo físico de corrientes y un modelo físico de oleaje así como un modelo matemático de transporte de sedimentos. Como resultado se obtuvo una configuración de diques que garantizan un calado mínimo así como unas condiciones de baja energía de oleaje.

□ RÉSUMÉ □

Présente les résultats d'un an d'étude du goulet de l'Orío. Cette étude visait à concevoir des ouvrages civils susceptibles de résoudre les problèmes de navigation à l'entrée du goulet, à partir d'études de terrain, de modèles physiques et d'un modèle mathématique du transport solide. Trois épis ont été prévus pour garantir une dérive stable et une faible énergie des vagues à l'entrée du goulet.—*Catherine Bressolier (UA 910 CNRS, EPHE, Montrouge, France)*.

□ ZUSAMMENFASSUNG □

Vorgestellt werden die Ergebnisse einer Untersuchung des Orío Inlets an der Nordküste Spaniens. Ziel der Studie war die Ermittlung von Entwurfskriterien für die Lösung von Navigationsproblemen in der Einfahrt des Inlets. Lösungsansätze wurden aus Feldmessungen, Modellversuchen und einem mathematischen Modell erarbeitet. Geplant wurden 3 Buhnen, die eine vorgegebene Wassertiefe und geringe Wellenhöhen im Einfahrtbereich des Inlets gewährleisten sollen.—*Reinhard Dieckmann, Wasser- und Schiffsamt Bremerhaven, West Germany (FRG)*.