Recent Evolution of Faro Channel and its Association to Dredging Operations (Algarve, Portugal)

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ABSTRACT

Uncontrolled dredging in complex environments such as barrier island systems can produce major changes in inlet conditions, current circulation patterns and modify channel margins, leading to silting or erosion. This paper presents a study of the evolution of Faro channel between 1927 and 2001, in the Ria Formosa barrier island system, taking into account the natural evolution and the impacts of dredging operations. Faro Channel, the only navigable channel providing access to Faro Harbour, is the largest inside the Ria Formosa and the most hydraulically efficient. An inlet was opened east of Faro Channel, and has forced a channel migration trend toward the east (axis and margins). Analysis of the evolution of the channel (width and axis) as well as the surrounding marsh areas was made. Results shows that the channel runs preferentially to the east and the axis displacement is being amplified by the intense dredge operations (specially after 1985 until present), resulting in loss of marsh areas in some areas. The continuous over exploitation of the channel could lead to its continuous deepening and can have consequences such as changing current circulation patterns and creating pronounced irregularities along the channel or loss of margins, as the channel is trying to achieve its natural equilibrium. This can not only affect the entire backbarrier area, but also cause significant problems for navigation security.

ADDITIONAL INDEX WORDS: Barrier island system, access channel, dredging, margin evolution, channel migration, bathymetric variability.

INTRODUCTION

The dredging of inlets and channels, needed to assure navigability and increase water exchange between lagoons and the ocean, can also be of economic significance, since the dredged material can be used for the construction industry. Barrier island systems are complex environments, with precarious equilibrium conditions, exposed to storm erosion, subsidence and sea-level rise (NUMMEDAL, 1983). Uncontrolled extraction of sediment within these systems can produce changes in inlet conditions, current circulation patterns and modify channel margins, leading to silting or erosion.

At present a number of ports are undergoing major changes to accommodate deep draft vessels, requiring an approach channel of larger dimensions in term of depth and width, therefore it is required to determine what would be the impact of maintenance dredging (GIORDI et al., 2001).

The present study is focused on the recent evolution of Faro Channel, in the Ria Formosa barrier island system (Figure 1), and its association to dredging operations. An inlet was opened and then stabilised between 1927 and 1955, with the purpose of creating an access to the main cities of the region. To accomplish this objective, an access channel (Faro Channel) was opened through a complicated pattern of tidal flats, marsh areas and sub-tidal channels, which implied intense dredging operations and therefore, subsequent modifications in the entire backbarrier system. Dredging operations in the channel have been continued in order to maintain navigation security. Since 1985 the dredging has been more intense due to the management policies of the Port Authorities that intend to enlarge the channel and manoeuvre area in order to increase the safety of the navigation conditions.

Although many authors have studied the system, these studies were focused on the general barrier island system (BETTENCOURT, 1994; PILKEY et al., 1989; ANDRADE, 1990; SILVA, 2001) or centred on the Faro-Olhão Inlet evolution (ESAGUY, 1986; TELES et al., 1997; SALLES, 2001, SILVA et al., 2002). Until now, the access channel, the subject of intense dredge operations, has been rarely studied. Background knowledge of inlet behaviour and channel evolution is needed to understand and predict the consequences of engineering actions, especially dredging activities.

The objectives of this work are to quantify dredge volumes and to identify dredged locations from the inlet opening to the present, as well as to analyse the implications for the evolution of Faro Channel (channel width, margins and axis).

BACKGROUND KNOWLEDGE

The Ria Formosa is a multi-inlet barrier island system (Figure 1) located in Southern Portugal, that presently has 6 inlets. The inner part is formed by a complex pattern of tidal flats, salt marshes and sub tidal channels, covering an area of 8.40x105 m2 (ANDRADE, 1990). According to SALLES (2001), the Ria Formosa system can be divided into three hydrodynamically quasi-independent sub-embayments: (a) the western sub-embayment including Ancão, Faro-Olhão and Armona inlets; (b) the central sub-embayment, including Fuzeta and Tavira inlets; and (c) the eastern sub-embayment, including Lacém Inlet. The Faro-Ólha Inlet is the main inlet of the western sub-embayment as it traps 60% of the tidal prism (SALLES, 2001). It was artificially opened and stabilised with jetties between 1929 and 1955 (ESAGUY, 1986), and is an ebb-dominated inlet (SALLES, 2001, SILVA et al., 2002).

The area chosen for opening Faro-Ólha Inlet was located 2 km East of Santa Maria Cape (Figure 1) in a place where another inlet had existed before. The configuration of the jetties was conceived to protect the access channel from the prevailing west to east littoral drift and to improve some aspects concerned with navigation, namely the depth required and channel orientation (ESAGUY, 1986).

The objective of the inlet opening was to assure the self-maintenance of proper depths in the access to the navigation
channel, leading to Faro Harbour and to the two main cities of the region, Faro and Olhão. However, time showed that the distance between the two jetties was too narrow and, as a consequence, an erosion process took place, leading to local depths of about 40 meters in the inlet throat, due to the intensification of the ebb currents (ESAGUY, 1986; SILVA et al., 2002). Furthermore, due to the jetty configuration, the channel was not in equilibrium. Consequently, a meander in the currents in the channel was set up due to the east jetty, which created an extra difficulty for navigation (ESAGUY, 1986).

The opening of Faro-Olhão Inlet had important effects on the littoral physiography of the Ria Formosa, as well as on the hydrodynamic behaviour of the lagoon (ANDRADE, 1990; SILVA et al., 2002). The major global effects were the drastic reduction of the downdrift sediment budget, making barriers more vulnerable to erosion and decreasing the sediment supply to the eastern inlets (SALLES, 2001). VILA-CONCEJO et al. (2002) showed that the width of Armona Inlet (situated E of Faro-Olhão Inlet), which had been decreasing since the end of the 19th century, started to decrease at much higher rates, thus losing some of its hydrodynamic efficiency. GARCIA et al. (2002) stated that the opening of the Faro-Olhão Inlet was responsible for significant changes on Culatra Island (east of Faro-Olhão Inlet). The changes included an acceleration of the natural eastward elongation of the island and increase of the shoreline retreat in the western half of the barrier (due to the interruption of the eastward directed longshore drift). On the other hand, it is believed that the consequences of the opening and stabilisation of Faro-Olhão Inlet were not greater because it was performed in a former inlet position (VILA-CONCEJO et al., 2002).

Faro Channel is the largest inside the Ria Formosa and the most hydraulically efficient. The channel has a general orientation NE-SE and a length of 9 km, covering an area of 337 km². The channel width is not constant, ranging between less than 175 m to a maximum of 625 m. Typical depths for the channel range between 6 m and 12 m (below MSL) (SILVA et al., 2002). Currents near the inlet can reach maximum values of 2.22 m/s, during ebb conditions, and 1.59 m/s, during flood conditions (IT, 2000; SILVA et al., 2002). Tides in the area are semi-diurnal, average ranges are 2.8 m for spring tides and 1.3 m during neap tides. However maximum ranges of 3.5 m can be reached. Predominant wave directions are from the W-SW, approximately 68% of time, whilst waves coming from the SE only account for 25% of the observations (COSTA, 1994). Therefore, littoral drift is from W to E with values that range...
from 900x103 m\(^3\)/year (ANDRADE, 1990) to 3000x103 m\(^3\)/year (CONSULMAR, 1989 in BETTENCOURT, 1994).

Due to the morphology of the channel, there are some restrictions related with channel navigation. The longer ships are not able to enter completely loaded. Therefore many studies are being undertaken in order to correct the inlet jetties. Dredge operations to assure navigability and sand mining for construction purposes have also been performed.

**METHODS**

To evaluate the consequences of dredging within the study area, an integrated analysis was performed. This involved dredge volumes determination, aerial photo studies of channel width and marsh areas and study of the channel axis by recent bathymetric evolution. For a correct and detailed comparison, the channel was divided in three major sections (Section A-Faro Harbour, Section B central zone and Section C inlet zone) (Figure 2).

The period of study was from 1927 until 2001. Data used for the analysis included vertical aerial photos and bathymetric charts, as well as data from other authors (Table 1).

**Quantification of Dredging Volumes**

Determination of historical dredged locations and volumes between 1927 (inlet opening) and 2001 was made taking into account the technical reports and bibliography from the Harbour Authorities (IPS-IPTM) and the Ria Formosa Natural Park (PNRF).

**Aerial Photograph Analyses**

A set of aerial vertical photographs covering the period 1947-1997 were analysed by standard procedures, briefly consisting of scale determination, qualitative interpretation and consecutive measurements of channel width and margins. The smallest possible measurement on each photograph was considered to be 0.5 mm, which corresponds to accuracy between 7 m and 17 m, depending on the photograph scale. Nine cross-sectional segments and 25 marsh areas were defined within the three different sections (Figure 2). Channel width evolution was obtained from measurements made of the cross-sectional segments for each set of photos. For the evolution of the marsh areas, east/west margin areas were defined for each section in order to determine accretion or erosion. The measurements were made considering the marsh area extensions along the channel, delimited by the main channel (Faro Channel) or by any other secondary channel. The years of data, equivalent for the three sections, were 1958, 1991 and 1997. The results obtained are presented as average values to each section.

**Recent Bathymetric Evolution**

Three bathymetric maps from FARO CHANNEL (1985, 1994 and 2001) were digitised using GIS software. Topographic software was used to obtain digital maps. Comparison between maps allowed the identification of sectors between the two periods defined (1985-1994 and 1994-2001). Volumetric calculations were used to quantify the evolution of the study area. The values obtained where then compared with the values from the dredging activities undertaken in the study area given by IPS (2001). Additionally, cross-sectional profiles (Figure 2) were calculated using the digital bathymetric maps, allowing the study of channel axis displacement, channel deepening and margin evolution.

**RESULTS**

**Quantification of Dredging Volumes**

The period between 1927-1947 corresponds to the opening of the Faro-Olhão Inlet and to the first dredging of the Faro Channel, and therefore shows significant dredged volumes (>2.5x10\(^6\) m\(^3\), ESAGUY, 1986 and SNPRCN, 1986). The engineering works related with the inlet opening included the opening of an access channel, beach nourishment and construction of the jetties.

Between 1947-1985 the volume dredged was about 2.0x10\(^6\) m\(^3\) (ESAGUY, 1986 and SNPRCN, 1986). However, the accuracy of this value is not very high because there is a lack of information between 1956 and 1974 and therefore dredged values are likely to be higher. The works undertaken between 1945 and 1985 were made to improve the depth of Faro Channel, preventing the silting up of this area. Intense erosive processes occurred in the inlet during this period leading to channel depths of about 40 m. The distance between the two jetties and their configuration was responsible for the occurrence of high current values, mainly under the ebb conditions, leading to the erosion (ESAGUY, 1986; ANDRADE, 1990; SILVA et al., 2002).

![Figure 3. Channel width evolution based on aerial photography measurement.](image-url)

![Figure 4. Evolution of channel marsh areas for the three sections defined. Percentage relative to the marsh area value on 1958.](image-url)
The period 1985-2001 had the most intensive dredge operations with a volume of about 4.6x10^6 m³ (IPS, 2001). This increase was mainly related with management policies, since the Port authorities were especially concerned with reaching 10.0 m depths in the channel (below MSL) and undertaking sand mining for construction purposes.

**Aerial Photgraph Analyses**

Figure 3 shows the channel width evolution, based on the average results of the cross sectional profiles made for the three channel sections defined. Figure 4 shows the evolution of east and west channel marsh areas for the three sections.

According to these results (Figure 4), channel enlargement occurred in all sections, being more significant adjacent to Faro-Olhão Inlet (Section C), with strong reductions in area seen on both margins from 1958 to 1997.

For Section A and B, the east margin shows erosion and the west margin accretion, leading to a possible displacement of the channel (Figure 4). Section C experienced drastic erosion of the east marsh area (Figure 4). However, Section C also showed reductions on the west margin, especially between 1991 and 1997, resulting in a considerable enlargement of the channel width (Figure 3).

In general, the major reductions took place on the east margin, while on the western margin some accretion was observed. This suggests a tendency for channel displacement toward the east.

**Recent Bathymetric Evolution**

Figure 5 shows the cross sectional profiles made for each of the three defined sections, based on the bathymetric surveys undertaken in the system (1985, 1994 and 2001). Two different periods were considered: 1985-1994 and 1994-2001. The arrows represent variations in depths and in the channel axis. Table 2 shows the volume variability for each section, obtained by bathymetric comparison.

The results show a general deepening common to all sections, although some differences can be found. In Section A, a total of approximately 1.22x10^5 m³ was removed. However, in some places (i.e. Figure 5A) some accretion was found, namely in the centre of the channel (channel axis).

Section B had the highest values of recorded sediment removal. A total of 3.10x10^6 m³ was removed between 1985 and 2001. From the cross sectional profile (Figure 5B), it is possible to note significant deepening of the channel, channel enlargement and a major eastward displacement of the channel axis.

In Section C, approximately 3.2x10^6 m³ of sediment was removed between 1985 and 2001, with some accretion occurring during the 1994-2001 period. Observing Figure 5C it is possible to notice an eastward channel displacement, affecting not only the channel axis but also both margins, being more significant on the east margin. This also caused the occurrence of channel enlargement.

In general, between 1985 and 1994, the channel was found to be deeper in all sections, with average vertical changes ranging from 0.1 to 1.9 m and with a total sediment loss of about 1.90x10^6 m³ (1.75x10^7 m³/year of sediment removal). From 1994 to 2001, there was general erosion of the channel, with differences from section to section. It was possible to distinguish three different zones: Section C, in accretion; Section B, with strong sediment removal and, finally, Section A, with no significant variations.

**DISCUSSIONS**

Since the opening of the Faro-Olhão Inlet, important modifications of the channel have occurred. Intense dredging operations were undertaken in order to accomplish the required depths for navigation and to construct the two jetties. The channel underwent some readjustments to the new conditions.

Between 1958 and 1991 the variability was high in all sections, probably related with dredging operations but mainly as a response to the inlet opening and stabilisation. The major changes observed in Faro Channel took place between 1991 and 1997, when intensification of dredged operations occurred.

According to the results obtained, it was adjacent to the inlet (Section C) where the main modifications occurred. In terms of channel width, it was seen that the enlargement was related primarily with the erosion observed on the east margin. This aspect was first pointed out by ESAGUY (1986) who showed that the currents in the channel started to flow preferentially next to the east margin and this was responsible for the creation of a pronounced meander in the channel entrance, which is an extra problem for navigation. This was because the channel was not in equilibrium as a result of the configuration of the jetties (ESAGUY, 1986; SILVA et al., 2002). However, this factor was intensified by the extreme dredge operations that occurred between 1985-2001 (Table 2).

Between 1991-1997, important erosion occurred on both margins of Section C, being more significant on the eastern one (Figure 3 and 4). Simultaneously, a significant eastward displacement of the channel axis to the east occurred in Section C (Figure 5C). Nevertheless, when compared with the dredged volumes for Section C, results from Table 2 show some accretion, which is mostly related with the entry of sediment into the system, allowed by the formation of the flood tidal delta (SALLES, 2001). PACHECO et al. (2003) determined that the amount of sediment entering the system is about 1.40x10^6 m³/yr in Section C. Thus, channel enlargement was not higher, because of this significant amount of sediment entering the system, allowing the formation of the flood tidal delta and reconstruction of the margins, despite the dredging operations undertaken. Therefore, it is necessary for the Port Authorities to undertake dredging operations in this area in order to maintain the navigability of the channel. However, the volumes to be
dredging should only be those needed to avoid silting up of the channel and to maintain navigability. Furthermore, according to the reports of IPS (2001), dredging in the area has been undertaken not only to maintain the navigability of the channel but also with economic purposes (i.e. sand mining).

In Section B, the engineering works undertaken were mostly related with dredging operations in order to obtain the required depth for navigation purposes. It is possible to notice a gradual channel enlargement (Figure 3), which corresponds to erosion on the east margin (Figure 4), as well as a displacement of the channel axis (Figure 5). Since 1958 until 1997, some accumulation was observed on most of the western margin areas and erosion of the eastern margin (Figure 4), which confirms the observed channel displacement tendency seen in Section C (Figure 3). The intense dredge operations undertaken between 1985 and 2001 in this section (3.10×10^3 m³), had important effects in changing channel depths and possibly led to important reductions of the eastern margin, with loss of marsh areas. Since the sediment supply from the inlet (Section C) is retained in the flood tidal delta, Section B does not receive a direct sediment contribution from the inlet. The intensification of dredge operations will lead to its continuous deepening. As a result the channel axis will tend to move towards the east margin, causing erosion in the east margin and accretion in the west margin. Consequently, the currents in the channel will start to flow preferentially on the eastern side, thus increasing the channel displacement.

In Section A (Faro Harbour), channel enlargement is also observed as well as erosion of the eastern margin. The period 1947-1991 shows erosion on the east and accumulation on the western margin (Figure 3), related to the construction and maintenance of anchorage depths. However, between 1991 and 1997, erosion is also observed on the western margin. This can be related with channel axis displacement to the west, which is probably caused by a realignment of the main current transport. The sediment observed on the western marsh areas is possibly related with the axis displacement identified in the other sections, raising the hypothesis that dredging operations along the channel can have the effect of changing channel alignment.

CONCLUSIONS

The evolution of a navigable tidal channel was studied using an easily implemented technique. Both natural evolution and impacts of dredging activities were taken into account for the integrated analysis of the evolution of the channel. The Port authorities needed to undertake dredging operations in order to establish and maintain a safe maritime pathway for the vessels that use the Faro Harbour. However, different management policies led to a situation of over exploitation of sediment removal by dredging operations inside the channel limits.

Reductions found on the east margin caused global channel enlargement for the majority of the channel. Because Faro-Olhão Inlet was opened east of Faro Channel, this had the effect of forcing a tendency for channel migration to the east (axis and margins). Subsequently, dredging operations were responsible for amplifying this migration, especially for the channel axis displacement. It also contributed to the observed enlargement, since the currents in the channel started to flow preferentially on its eastern margin. The continuous dredging, taking place on both sides of the channel, did not allow the reconstruction and growth of the west margin and, subsequently, whenever channel displacement is not observed, enlargement occurred with losses on both margins. The external sections, located near the inlet underwent the strongest changes.

The uncontrolled sand extraction can lead to changes in channel hydrodynamics and inlet conditions, by changing the current circulations patterns and modifying channel margins. All these factors can cause important security problems for the navigability of the access channel and changes in the entire backbarrier environment. The improvement of the Faro Channel hydrodynamics by dredging can have important impacts in a multi-inlet system. Dredging operations produce an increase in the hydrodynamic efficiency of the inlet, thus, capturing more tidal prism from the sub-embayment and producing loss of efficiency and silting up in the neighbouring inlets that are hydrodynamically connected (i.e. Armona Inlet).

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LITERATURE CITED


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