ARTIFICIAL SAND BYPASS SYSTEMS: FIXED, MOBILE, AND MIXED SYSTEMS

Ricardo Carvalho[1], Malcolm Pound[2], Cristina Afonso[3], Carlos Coelho[4], Paulo A. Silva[5], Tiago Oliveira[6], Márcia Lima[7], André Cardoso[8], and Celso Pinto[9]

This paper describes a feasibility study of large scale, sand bypassing solutions at Aveiro and Figueira da Foz tidal inlets, undertaken for the Portuguese Environment Agency (APA). Aveiro and Figueira da Foz are existing river ports where breakwaters constructed to maintain navigable entrances have resulted in excess updrift accretion and severe downdrift erosion. These entrances require ongoing dredging and cause dangerous navigation conditions, especially for smaller vessels. The study showed that large-scale sand bypassing systems can restore the stability of shorelines on high-energy coastlines, based on the success of fixed sand bypassing systems, such as in East Australia.

Keywords: sand bypassing, coastal erosion, fixed, mobile and mixed systems.

INTRODUCTION

This paper describes the main results of a feasibility study into large-scale, sand bypassing solutions at Aveiro and Figueira da Foz tidal inlets in northern Portugal (Figure 1), a study requested by the Portuguese Environment Agency (APA). Coastal sectors of Barra-Vagueira (Aveiro) and Figueira da Foz-Leirosa (Figueira da Foz) are high-energy, wave-dominated sandy coasts with long term erosion, with unstable and mobile bars and channels due to intense coastal processes.

These inlets were historically stabilized by breakwaters but have long-term disadvantages due to excessive sediment accumulation updrift of the breakwaters, and in deeper waters offshore from the inlets, causing downstream coastal erosion and dangerous navigation conditions at the inlets. The feasibility study investigated if coastal sediments management could be achieved by large scale artificial sand bypass systems (ASBP), even in energetic coastal zones.

The study showed that such solutions along the West coast of Portugal may be applicable, similar to the ASBP that have been implemented, for example, in Australia (Gold Coast) and France (Capbreton).

METHODOLOGY

The feasibility study focused on the technical feasibility of artificial sand bypassing systems at Aveiro and Figueira da Foz tidal inlets (Carvalho et al., 2021a and 2021b). Several configurations were studied considering three main types of systems:

1. “Fixed systems”, for example, based on a jetty supporting sand recovery equipment, and permanent pipelines with intermediate booster pumps to transfer recovered sand to discharge points;
2. “Mixed systems”, which combine mobile and fixed units, usually with mobile equipment to recover sand combined with permanent pipelines with intermediate booster pumps to transfer recovered sand to discharge points;
3. “Mobile systems”, based on mobile units for recovering sand, mainly dredgers, and floating and/or submerged temporary pipelines and booster pumps.

The main advantages of coastal protection using these types of ASBP systems are prevention of excessive updrift sediment accumulation, minimizing sedimentation at inlets and navigable channels, and downstream erosion control. There are also other benefits of these systems, including improved surfing conditions and beach amenity (Gold Coast City, 2015; Lazarow, 2008), which were discussed during the development of the study. Furthermore, principles for implementation of large-scale, sand bypass systems were defined and their applicability to the referred locations was studied. Finally, results

[1] OCEANING Engenheiros Consultores, Lda., ricardo.carvalho@oceaning.pt
[2] MALCPERL Engineering, malcolm@malcperl.com.au
[3] OCEANING Engenheiros Consultores, Lda., cristina.afonso@oceaning.pt
[4] RISCO & Department of Civil Engineering, University of Aveiro, ccoelho@ua.pt
[5] CESAM & Department of Physics, University of Aveiro, psilva@ua.pt
[6] CESAM & Department of Physics, University of Aveiro, toliveira@ua.pt
[7] R5 Marine Solutions, RISCO, University of Aveiro, Lusophone University of Porto, marcialima@r5engineers.com
[8] R5 Marine Solutions, marine@r5engineers.com
[9] APA – Portuguese Environment Agency, celso.pinto@apambiente.pt

of the ASBP feasibility study were presented to Portuguese Environment Agency in 2021 (UA-R5 et al., 2021).

Figure 1. Aveiro and Figueira da Foz inlets, both at the West coast of Portugal.

The material in the following sections is for Figueira da Foz ASBP as this system has the best economics and is most likely to be developed (Coelho et al., 2021d).

APPLICATION TO FIGUEIRA DA FOZ

The adoption of ASBP systems at Figueira da Foz (and also at Aveiro) has been proposed since the 1960s, and it was also recommended by the Portuguese Coastal Working Group in its report, stating that implementation must be preceded by detailed analysis of solutions, cost-benefit and multi-criteria analysis and environmental studies based on coastal dynamics modeling (Santos et al., 2014).

The "Feasibility Study of Artificial Sand Bypassing of Aveiro and Figueira da Foz bars. Task T5 - Definition and Comparison of Technical Solutions", developed by UA/R5 Consortium, falls within the strategic guidelines of that referred report. It addresses various ASBP solutions, namely fixed jetties with jet pumps (type Gold Coast Seaway GCS and Tweed River Entrance TRE - Australia), motor-scrapers along the coastline (Adelaide- Australia), mobile cranes with jet pumps (Capbreton - France) or dredges operating in the active profile. These are all solutions that would be suitable for handling large volumes of annual bypassing. The paper discusses the options developed for Figueira da Foz.

An ASBP system, regardless of the type of sand collection, must have the capacity to recover and bypass the majority of the littoral sand transport (LST) to achieve a dynamic balance of upstream and downstream coastal sectors. Furthermore, in the initial years of operation, it shall allow the bypass of larger volumes, in order to retreat the accreted beach and create a buffer capacity for sand accumulation.

In the case of Figueira da Foz, the average LST net balance is estimated at 746,000 m^3/year in the N-S direction (Silva et al., 2021). Port dredging of approx. 300,000 m^3/year is carried out on the sandbar and in the entrance, with dredged materials deposition by a TSHD dredger in the active profile, at the downstream groyne field of Cova-Gala, a location well known for its erosion problems.

At Figueira da Foz, the beach has accreted 600m north of the breakwater and the study assumed that the accumulated beach north of the entrance will retreat ≈ 300m by the operation of the ASBP for all options, to minimize leakage into the entrance. The nominal ultimate annual sand transfer rate adopted for design has been set at 1,000,000 m^3, approximately 34% above the estimated average value.

DEFINITION

Sand bypassing can be defined as the "*artificial transport of littoral drift across tidal entrances to help prevent accretion, on the updrift side, control downdrift erosion and maintain navigation channels*" (Van de Graaff, 2020). This is compared to beach nourishment which is the periodic replenishment of eroded beaches with deposition generally onto upper levels of beaches.

The efficiency of an ASBP is defined as the percentage of the estimated total net littoral movement, bypassed by the ASBP. The proportion of the littoral movement not bypassed is considered a leakage.

The ASBP does not require a capacity to match the maximum value of the LST. If the layout allows temporary storage of sands not captured by the sand trap, i.e. behind the breakwater, the system can operate at a lower rate as those sands will be recovered later.

Sand bypassing requires a commitment to operate in perpetuity and is generally viable only when large community benefits are generated. In Australia, studies have assessed that a large capacity sand bypass in a beach resort community generates more than $20 million AUD annually in the local economy.

FIXED SYSTEM – GOLD COAST TYPE

The fixed system option is based on the large-capacity sand bypassing systems developed in Australia. The Gold Coast Seaway system (Figure 2) was commissioned in 1986 and the Tweed River system followed in 2001; both systems have operated successfully since completion. The Gold Coast system regularly bypasses more than 600,000 m^3 annually though the nominal annual capacity of both systems is 500,000 m^3.

Fears of blockages due to the accumulation of debris around the jet pumps in fixed systems have not eventuated due to the improved design of jet pumps to pass larger debris and the development of backwashing procedures to remove larger debris. During storms, debris loads can be high and can include timber, vegetation (kelp), shells, rock, and human debris (anything from bricks to flippers).

Figure 2. Gold Coast Seaway (GCS) or Southport Seaway, Queensland, Australia.

These fixed systems consist of the number of jet pumps (also called eductors) suspended under a trestle jetty (Figure 3) constructed across the active beach. The jet pumps run on vertical rails attached to vertical piles and are handled using a mobile crane. The jet pumps form sand extraction cones that merge to form a sand trap under the jetty; the sand trap captures the littoral movement as the breaking waves collapse over the deeper water allowing the sand to settle out. The jetty supports the jet pumps and pipework and provides access for operation and maintenance.

The jet pumps are driven by high-pressure seawater, and this eliminates the need for high-voltage electrical equipment in the severe environment along the jetty. The jet pumps operate under high discharge heads, and the resulting severe duty requires robust abrasion-resistant units.

For Figueira da Foz, the jetty will be higher and stronger than the Australian examples due to the more severe wave climate and will support twelve jet pumps installed at a depth of -12m (ZH) (Figure 4).

A pump station and control building located at the base of the jetty would house the high-pressure pump to drive the jet pumps, a slurry hopper with trommel screen to remove debris, the slurry pumps to operate the transfer pipeline, the control equipment and facilities. Sand slurry would be delivered from the jet pumps through a pipe flume on the jetty. The slurry will be screened to remove debris and pumped through a transfer pipeline to the discharge points. The pumping would include two pumps in series in the pump station and booster pumps installed along the pipeline. The transfer pipeline will operate at a high slurry density under tight control for efficient pumping.

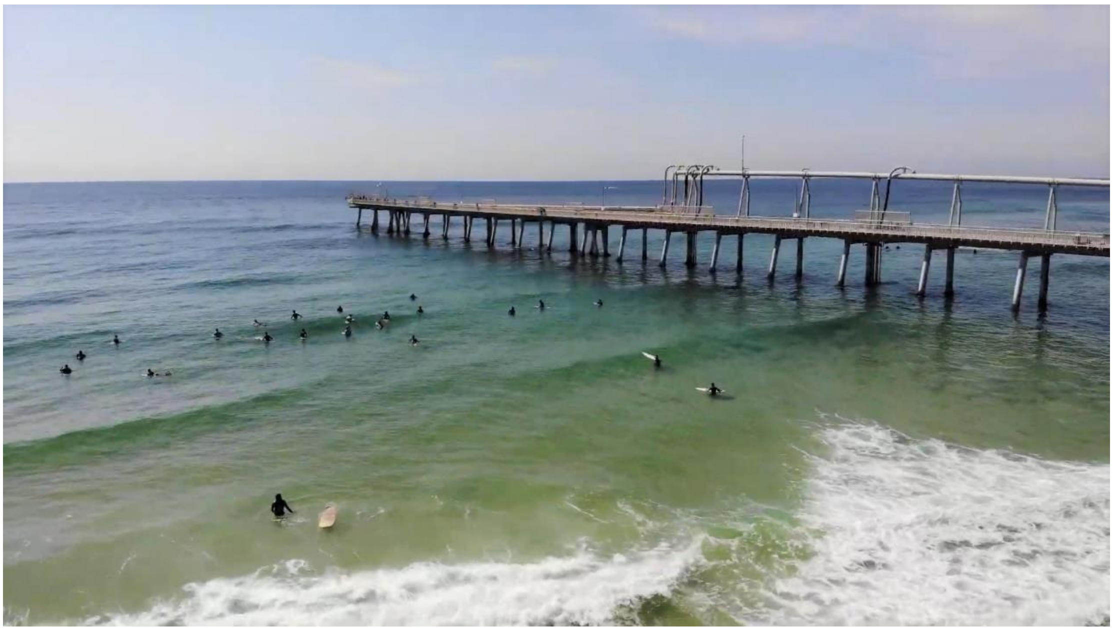

Figure 3. Tweed River Entrance Sand Bypassing Project (TRESBP), New South Wales, Australia.

The motive seawater will be supplied from a low-pressure pump station constructed in the Mondego River.

The proposed beach retreat will enable the required 450m long jetty to be constructed from the existing beach; this will simplify the jetty construction and enable the jetty span lengths to be increased; this will limit wave forces acting on the structure. The beach is underlain by limestone and some rock excavation will be required to form pits for the jet pumps; the jetty piles will mostly be grouted into bored holes in the rock.

The system will have a nominal pumping capacity of 650 m^3/hour. This capacity is delivered by 3, 4 or 5 jet pumps operating together, depending on selection of jet pumps along the jetty. The system will cycle through all jet pumps in each operating session to recover the available sand and maintain the sand trap. Ultimately, the system will operate about 30hours/week on average to bypass one million cubic meters of sand annually but will operate longer initially to retreat the beach.

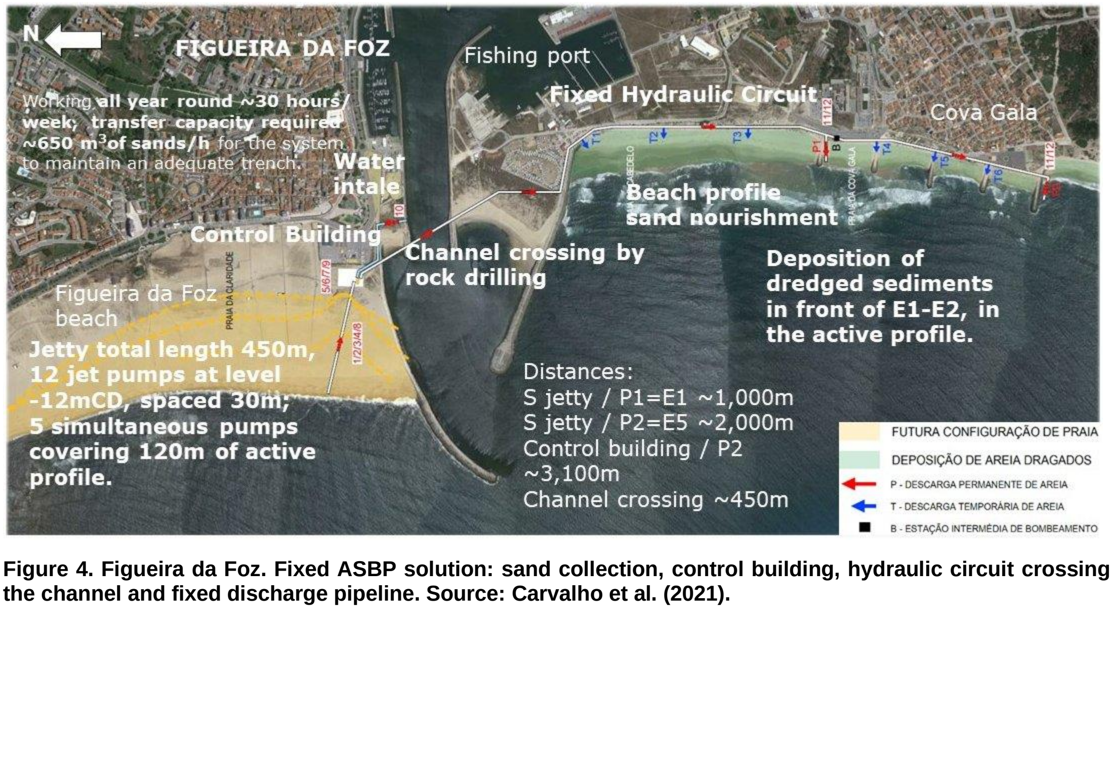

Figure 4. Figueira da Foz. Fixed ASBP solution: sand collection, control building, hydraulic circuit crossing the channel and fixed discharge pipeline. Source: Carvalho et al. (2021).

It is assumed the ASBP system will work throughout the year, whenever sufficient sand had accumulated in the sand trap.

The system makes the beach available for unrestricted public use and the operation has no adverse impact on the beach other than retreat of the shoreline and the presence of sand extraction cones under the jetty.

Advantages are:

1. No mobile plant operating on the beach,
2. Simple control – the beach will retreat to a point defined by the location of the inshore jet pump,
3. Following stabilization of the retreated beach, the monthly sand bypass rate will closely match the LST,
4. The initial annual sand bypass capacity will be more than 2,000,000 m^3 due to the availability of sand and early operations will generate a rapid retreat of the beach,
5. The bypass will operate unattended under automatic control and can operate 24/7 if required,
6. The system is always available and can be started with at the touch of a button,
7. The bypass can be operated in periods where cheaper electricity is available,
8. The bypass will operate whenever sufficient sand is available in the sand trap, regardless of weather conditions,
9. Not an essential infrastructure so there is no duplication of equipment to address equipment failures; System is offline during any repairs or maintenance as a long break is not relevant for the overall bypassing,
10. Provides a new attraction for tourists (if designed for public access),
11. Very safe for the public and beach users,
12. All electric operation,
13. Improved navigation conditions in and around the entrance,
14. Climate change adaptation, and
15. Low operating staff requirements.

Disadvantages are:

1. The jetty may be unacceptable to residents,
2. The initial high bypass rate may result in excess sand accumulation at the discharge points, and
3. High initial capital cost and lifetime energy and maintenance costs.

MIXED SYSTEM – ADELAIDE TYPE

This option is based on the sand transfer infrastructure developed for Adelaide beaches in Australia. The Adelaide System consists of a mobile sand slurrying unit (Figure 5) which can be placed at four sand recovery points along the beaches. The unit is supplied with sand using a 15 m^3 modified scraper (Figure 6) that recovers layers of sand from the adjacent beach. The unit is supplied with motive seawater from an adjacent seawater pump station and the slurried sand is delivered into a permanent pipeline with booster pump stations and numerous discharge points behind the beach.

The Adelaide system has a nominal capacity of 200 m^3/hour and is operated in the off season to minimize disruption to beach users.

Due to the much greater required bypassing capacity, the option proposed for the Figueira da Foz ASBP would utilize 3 or 4 modified scrapers operating over a 600m length of the beach. The scrapers would recover sand across the active beach extending down to the low tide level. The scrapers would dump their loads directly into a single buried semi-permanent sand collection hopper located at the back of the active beach to avoid double handling. The hopper would be moved back as the beach retreated to maintain short haul distances to the hopper. The tracked deck of the hopper would screen out oversize material for separate removal and disposal. Water jets would be provided in the deck to rapidly sluice dumped sand into the hopper.

The sand would be slurried in the hopper by two or more jet pumps and pumped to a shore-based pump station and control building, located inshore of the final beach line. The pipelines to the pump station and control building would be flanged PE pipes that would be shortened as the beach retreated and the hopper was relocated. The slurry would be screened at the pump station to remove debris and pumped through a transfer pipeline to the discharge points. The transfer pipeline will operate at a high slurry density under tight control for efficient pumping.

Figure 5. ASBP mixed system – Adelaide Beaches, Australia – mobile sand slurrying unit.

The motive seawater will be supplied from a low-pressure pump station constructed in the Mondego River.

The operating time would be limited by weather, working hours and beach access requirements, requiring an increased nominal capacity of 800 m^3/hour. Even so, extended operating hours would occur during the period of beach retreat.

Figure 6. ASBP mixed system – Adelaide Beaches, Australia – scraper recovering sand.

Advantages of an Adelaide type system are:

1. After each operation, the beach is left in a public-safe condition,
2. There is no permanent infrastructure on the beach.

Disadvantages are:

1. Operations can only occur in restricted hours and the bypass rate will not match the littoral transport rate,
2. All operations require mobilization of equipment and labour,
3. There will be continual beach changes depending on difference between the actual sand littoral movement and the volume of sand bypassed by the ASBP,

4. The retreat can be managed only by monitoring the annual volume of sand bypassed and adjusting the future operating hours,
5. The system may be unable to retreat the beach to the proposed extent due to insufficient operating hours in adverse conditions,
6. The beach retreat necessary to minimize leakage into the entrance may take many years to achieve and leading to public perception that the ASBP is ineffectual,
7. Public beach access must be controlled when sand recovery operations are under way,
8. High operating staff requirement, and
9. Lifetime energy and maintenance costs (increased capacity increases costs).

MIXED SYSTEM – CAPBRETON TYPE

This option was included at the request of the client based on the sand transfer system developed at Capbreton, France which is the only mixed sand bypassing system in Europe.

This system at Capbreton uses a single jet pump suspended from a tracked crane operating on the beach to recover sand (Figure 7). Temporary PE pipelines connect the jet pump to the pump station. A permanent pump station supplies high-pressure seawater to drive the jet pump and pumps the sand slurry delivered from the jet pump to the discharge points. This system has a nominal capacity of 180 m^3/hour to pump 100,000 m^3 annually.

For Figueira da Foz, three jet pumps suspended from tracked cranes are proposed to operate together to recover a nominal 800 m^3/hour of sand. The three jet pumps would be supplied with motive water from and deliver sand slurry via a separate set of temporary flexible pipelines for each jet pump, to a pump station and control building located inshore of the final beach line. The slurry will be screened to remove debris and pumped through a transfer pipeline to the discharge points. The transfer pipeline will operate at a high slurry density under tight control for efficient pumping.

The seawater motive seawater will be supplied from a low-pressure pump station constructed in the Mondego River.

Figure 7. ASBP solutions through fixed systems: Capbreton-France – Jet Pump Arrangement and Discharge System.

Advantages of the Capbreton option are:

1. There is no permanent infrastructure on the beach.

Disadvantages are:

1. Very industrial operation when operating with three cranes and six temporary pipelines on the beach,
2. Major task to mobilize and demobilize the equipment and pipelines for each campaign,
3. All operations require mobilization of equipment and labour,
4. Operations can only occur in restricted hours and the bypass rate will not match the littoral transport rate,
5. The operation of the jet pumps may be impacted by the rock underlying the beach due to limited depth of sand. Rock pick-up by the jet pumps may be an issue,
6. The retreat can be managed only by monitoring the annual volume of sand bypassed and adjusting the future operating hours,
7. The system may be unable to retreat the beach due to insufficient operating hours due to adverse conditions,
8. The beach retreat necessary to minimize leakage into the entrance may take many years to achieve and leading to public perception that the ASBP is ineffectual,
9. Public beach access must be prevented when sand recovery operations are under way,
10. The beach is not left in a public-safe condition after operations due to the presence of extraction pools,
11. Very high operating staff requirement, and
12. Lifetime energy and maintenance costs (increased capacity increases costs).

MOBILE SYSTEM – DREDGING

In addition to the sediment bypass solutions mentioned earlier, the conventional mobile ASBP solution using only dredges is also considered. Moreover, this solution has the potential to fulfill not only the needs of the port but also to supply beaches located to the south.

This purely mobile system would have to bypass up to 1,000,000 m^3 of sands annually, which is about three times the current volume dredged in the sandbar and main navigation channel of Figueira da Foz port (Figure 8). The sediment deposition in this method is intended to occur primarily in the active zone of the LST, in front of the Cova Gala spur field as it presently occurs.

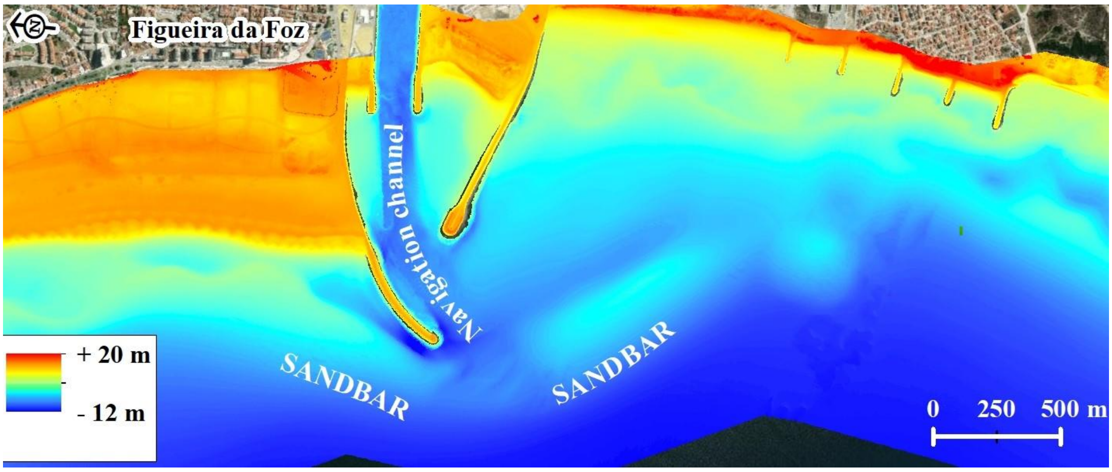

Figure 8. Figueira da Foz. North beach (Claridade), port navigation channel, sandbar and south beaches with groyne field (Cabedelo and Cova-Gala).

This solution requires additional dredging in front of Figueira da Foz beach, in line with sediment bypass strategies previously proposed in the past. Over two decades ago, Oliveira (2001) first proposed that dredging in the port of Figueira da Foz should prioritize securing maritime access to the port. These dredging operations should begin with the access channel, as ensuring safe navigation conditions in that area is of immediate concern.

Once essential port dredging is secured, additional dredging should be carried out in the area immediately north of the N breakwater, in front of Figueira da Foz beach, to create a "retention box". The dredging efforts in that area should progress from higher to lower levels, such as from -4.0 to -8.0 m (ZH). The range of elevations is naturally determined by the size and maneuverability of the dredger, as well as the sea conditions in which it operates.

Nevertheless, suitable conditions for dredging in front of the beach are limited to months between May and October because of sea states. Tide levels in relation to the draught of the dredges mobilized for the operation shall also be taken into account. In these circumstances, about 1-3 dredges would be required for 3-9 months to bypass large sand volumes each year. In these circumstances, this solution presents disadvantages related namely to long periods of dredging inoperability and the consequent costs.

It is recommended that a pilot experiment is carried out before its implementation, for a limited period of time, in which the dredging operation, technical aspects of the dredging cycle, downtime, and dynamic response of the beach profile are monitored, before undertaking a large-scale intervention.

Advantages are:

1. Low initial capital costs,
2. No mobile plant or equipment operating on the beach.

Disadvantages are:

1. Operations can only occur in restricted hours and the bypass rate will not match the littoral transport rate,
2. All operations require mobilization of equipment and labor,
3. There will be continual beach changes depending on difference between the actual sand littoral movement and the volume of sand bypassed by the ASBP,
4. The retreat can be managed only by monitoring the annual volume of sand bypassed and adjusting the future operating hours,
5. The system may be unable to retreat the beach to the proposed extent due to insufficient operating hours in adverse conditions,
6. Difficult to collect large volumes of sand from the front of the north beach as dredgers will not be able to operate in depths between level -4,0 m(ZH) and the shoreline, where most of the coastal sediment transport occurs,
7. Dredging occurs in large unsheltered areas with varying depths and poorly defined limits, thus without the operational advantages of common port dredging,
8. Lifetime fuel cost of dredges (increased capacity increases costs),
9. Frequent dredging operations in front of the north beach maybe unacceptable to residents.

DISCHARGE POINTS

Two types of discharge points are proposed for installation on the beaches south of the mouth of Mondego River, which may be common for different types of sand collection systems (Figure 9):

1. Permanent sand discharges are placed in areas where a large volume of sand is intended to be released continuously over an extended period. These main discharges involve a supported pipeline that deposits the pumped sand slurry directly into the active wave zone. The pipeline can be supported on piles or installed on an existing groyne. No adjustments are needed for these discharges during operations.
2. Temporary sand outlets are used to discharge small amounts of sand for beach nourishment, typically for a limited number of days, and for initial use before the shoreline has stabilized and permanent discharges can be constructed. These outlets consist of a pipeline laid on the beach with portable supports. Ongoing adjustments are necessary for these discharge points during operations.

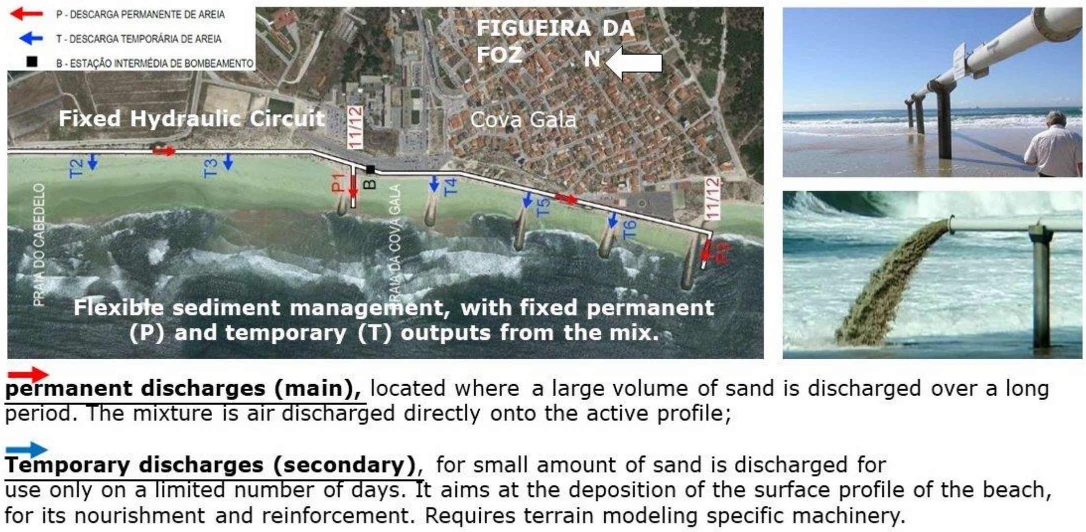

Figure 9. Figueira da Foz. Sediment discharge solution based on permanent discharges and temporary outlets. Source: Carvalho et al. (2021).

Based on mathematical modeling of shoreline evolution, the studies found that the permanent outlet should be located between the 1st and 5th groynes of Cova Gala (Coelho et al., 2021b).

Feasibility studies recommend the following:

1. Construct a pipeline to discharge the water-sand mixture to the location of the permanent outlet, in the Cova Gala groyne field, whose 1st groyne is located 1 km to the south of the S breakwater and the 5th groyne is approximately at 3.1 km;
2. Establish temporary discharge points along the pipeline, between the S breakwater and the permanent discharge, to allow temporary discharges at the top of the beach profile, until a stable profile is established;
3. After the establishment of a stable coastline, generated by the initial operations, build a permanent discharge to discharge directly into the active beach profile.

The location of the system discharges on the southern beaches of the river mouth is not related to the sand collection solution on the upstream beach. However, it is assumed that the annual volume of the ASBP is comparable to the net LST for all systems.

ISSUES WITH LARGE CAPACITY FIXED SYSTEMS

Accumulation of debris

The accumulation of debris in the sand trench of a fixed system is a frequently asked question. Clausner, J. (WES-USACE) visited the GCS 3 years after entry into service and was critical of the system saying it would fail due to debris accumulation (Figure 10).

Although the initial system did not have specific provisions for removing debris, operators quickly implemented improvements and developed procedures for doing so, and the system has been running successfully for over 35 years. Modern systems now have mechanisms and procedures to handle debris.

A fixed ASBP will capture everything that is transported along the coast, such as wood debris, rocks and pebbles, various types of human waste, geotextiles, seaweed, and more. This debris is mostly unseen and difficult to quantify. As part of design, a study to estimate debris characteristics is necessary, based on data from dredger operators and surface observations.

Figure 10. TRESBP in Australia. Vibrating harrowing screen, stones and pebbles extracted from the mixture, wood fragments next to the extraction cones and large trunks in the sand trench.

Past Experience

A relevant number of ASBP systems did not reach their initial objectives. This happened for several reasons, namely:

1. Incorrect or inadequate understanding of coastal processes at the installation site.
2. Inappropriate design (e.g. Ngqura Port in Algoa Bay, South Africa);
3. Systems altered by coastal interventions in adjacent areas.
4. Inadequate materials and/or poor maintenance.
5. Development by organizations without the necessary experience across the range of disciplines required in their teams; and
6. Inadequate bypass capacity.

Several ASBP systems failed their principal objective as they were not sized to handle the entire LST balance, which limits or prevents their ability to produce changes in adjacent coastal stretches. A review of ASBP around the world shows this clearly (Boswood & Murray, 1997).

With regard to fixed ASBP, it is considered that the failures that occurred in other bypass systems are not limiting factors for new systems, as long as the lessons learned from previous systems are applied to prevent certain failures from occurring again.

A modern fixed ASBP system must be designed for a long service life (over 30 years) in a severe marine environment, with the use of materials resistant to the corrosive/abrasive sand/seawater slurry. For example, pipelines carrying sand/seawater slurry may be polyurethane lined steel.

Why aren't there more systems?

Most of the inlets where sand bypass is required are ports under the control of the port authorities, which carry out the essential dredging to maintain maritime accesses and are not involved in coastal management outside their area of jurisdiction. They also assume that the inlet conditions are inevitably dynamic, disregarding the possibility of a fixed installation, whose scope and investment clearly exceeds their jurisdiction.

Port authorities have the idea that conventional dredging is necessarily more flexible, faster and cheaper. Dredging is seen as a cost-effective periodic operation financed as a maintenance expense, compared to an ASBP that requires high initial investment and special approvals. It is actually simpler to just dredge.

Port authorities' revenues are based on port fees, and alternative sources of funding are needed if other benefits are to be obtained. Such sources can come, for example, from national entities, responsible for the management of the coast, and/or from local entities that benefit from the ASBP located in their municipalities. These benefits include more stable quality beaches and improved surfing conditions.

The involvement of the national government, regional authorities and/or other interested parties is essential when intending to implement of ASBP, since, due to their broader vision, they can consider and weigh all the benefits and risks, including benefits arising from better conditions in coastal management, climate change adaptation, navigation safety, tourism, surfing, etc.

FEASIBILITY STUDY CONCLUSION

The feasibility studies developed for the Portuguese Environment Agency confirmed the technical feasibility of the several ASBP solutions as discussed above and showed that the fixed system option was the most economically viable for Figueira da Foz (Coelho et al., 2021a).

The table below presents summary of ASBP solutions at the Figueira da Foz estuary. Costs take into account the total 30-year life cycle of the bypass solution, including construction, operation, maintenance, and dismantling, as applicable (Carvalho et al., 2021d). The benefits of the SABP solutions were estimated by multiplying the non-lost territory areas per coastal stretch by the monetary value assigned to each stretch that makes up the study area.

Of the various alternatives to the current solution, Solution 1 has the lowest unit cost per cubic meter of sand bypassed, with an updated unit cost of € 1.64/m^3, followed by Solutions 2 and 3 with similar updated unit costs of about € 2.0/m^3.

Solutions of type 4 have updated unit costs of around € 3.00/m^3, the highest among the various solutions. However, unlike Solutions 1-3, Solution 4 does not require a significant initial investment in permanent or semi-permanent infrastructure.

In Solutions 1-4, costs in the first years of operation are higher due to the larger volumes of sand bypass required to achieve beach N recession.

The results indicate that if the current policy of carrying out artificial nourishment to the south of the Figueira da Foz inlet is maintained, using dredged material from maintenance dredging carried out as part of the maritime activity of the Port of Figueira, the economic loss over 30 years will reach € 64 million. However, the cost-benefit analysis of the evaluated ASBP solutions shows that it is economically viable to intervene in this coastal sector (Coelho et al.,2021c and 2021d).

Table 1. Figueira da Foz. Summary of cost estimates of ASBP solutions 0 to 4.

ASBP / Total Life Cycle Costs	Solution 0 - Mobile System: Reference Situation	Solution 1 - Fixed System: Gold Coast Type-AU	Solution 2 - Mixed System: Adelaide Type-AU	Solution 3 - Mixed System: Capbreton Type-FR	Solution 4 - Mobile System: Intensive Dredging
I. CONSTRUCTION (year 0)	0	18,077,000 €	17,691,000 €	16,552,000 €	0
II. OPERATION (years 1-30)	30,000,000 €	43,002,000 €	61,210,000 €	59,550,000 €	127,500,000 €
III. MAINTENANCE OPERATIONS (years 1-30)	0	10,304,000 €	10,084,000 €	9,458,000 €	0
IV. DISMANTLING (year 30)	0	859,000 €	840,000 €	788,000 €	0
TOTAL COST constant prices (30 YEARS)	**30,000,000 €**	**72,242,000 €**	**89,824,000 €**	**86,348,000 €**	**127,500,000 €**
TOTAL COST updated rate 2% (30 YEARS)	**22,396,000 €**	**58,861,000 €**	**72,051,000 €**	**69,203,000 €**	**97,680,000 €**
TOTAL SAND BYPASS VOLUME (30 YEARS)	9,000,000 m3	35,820,000 m3	35,750,000 m3	35,750,000 m3	33,500,000 m3
UNIT COST constant prices	**3.33 €/m3**	**2.02 €/m3**	**2.51 €/m3**	**2.42 €/m3**	**3.81 €/m3**
UNIT COST tax rate 2%	**2.49 €/m3**	**1.64 €/m3**	**2.02 €/m3**	**1.94 €/m3**	**2.92 €/m3**

The solutions costs are offset by the benefits and the break-even year is between the 7th and 10th year of the project. It is also observed that the evolution of the NPV (net present value) and BCR (benefit-cost ratio) indicators depend on how the areas of non-lost territory are distributed along the coast, and therefore, the evolution obtained for the economic indicators, for the same solution, may vary depending on the coastal management followed in sediment deposition.

Increasing the discount rate results in the ASBP lead to a worse economic performance due to changes in the NPV value after 30 years. However, the impact is relatively small in terms of the break-even year. Sensitivity analysis of maintenance costs shows that increasing costs naturally leads to poorer performance. However, for ASBP solutions to become economically unfeasible maintenance costs must exceed 50% to 85% of the total value of benefits of the solution over the 30-year project period.

The feasibility studies concluded that ASBP solutions are economically viable within a 30-year time horizon, given the defined assumptions. It should be noted that local, cultural, and social factors must be taken into account in decision-making and that, often regardless of associated costs, maintaining the territory should be a priority.

CONCLUSIONS

The "Feasibility Study of Artificial Sand Bypassing of Aveiro and Figueira da Foz inlets". Task T5 - Definition and Comparison of Technical Solutions" was developed by consortium Universidade de Aveiro (UA) and R5 Marine Solutions (R5), with support of consultants OCEANING and MALCPERL, for the Portuguese Environment Agency from December 2019 to May of 2021.

The study addressed technical feasibility of various ASBP solutions at Figueira da Foz beach, namely a platform with jet pumps (type GSC and TRESBP-AU), tractor drawn sand scrapers on the beach (type Adelaide-AU), mobile cranes supporting jet pumps (Capbreton-FR), or dredgers operating intensively in the active beach profile where most of the LST occurs.

Two types of sediment discharge are proposed on the beaches of the coastal area located to the S of the mouth of the Mondego river, which may be common for different types of sand extraction systems: permanent discharges, located where a large volume of sand is intended to be discharged into the sea over a long period, and temporary outlets, located only where a small amount of sand is discharged directly for beach nourishment, for use in only a limited number of days, or prior to development of a stable beach and construction of the permanent discharges.

These types of discharges, which can be used alternately throughout the annual cycle of sediment transport, allow flexible management of coastal sediments, directing them to the coastal zone by deposition in the active profile, where they will be moved under action of natural agents (diffuse action) or to locally feed the beach profile (local action).

All studied solutions offer a main advantage of generalized coastal protection downstream of the port, resulting in favorable outcomes compared to the reference situation. The expected results in all solutions are comparable, since all of them have similar flexibility with regard to deposition of dredged materials in the immersed and emerged beach profiles.

In any of the solutions, dredging of the navigation channel will not be eliminated, but it will potentially be reduced over the years, given the decrease in influx of upstream sediments. Eventually, dredging can be reduced to a multi-year cycle. The safety of the port navigation channel will be improved, as solutions allow for more stable depths of the submerged bars at the river mouth.

Regarding the ASBP objective, collecting sand from the sea in front of Figueira da Foz beach using dredges has operational constraints. Dredgers cannot effectively dredge the active LST profile when too close to the coastline.

In fixed and mixed systems, and optionally in a mobile system, the transport of the sand slurry is carried out by a fixed hydraulic circuit, whose route extends from the sand collection beach to the south, crossing under the navigation channel, and extends for a few kilometers, up to the existing groyne field in a coastal zone which is vulnerable to erosion.

In conclusion, implementing any of the studied solutions that achieve an ASBP volume equal to or greater than the average LST volume based on sand collection from the beach will enable the control of the size of the N beach (Praia da Figueira da Foz) and adjacent beaches to the south (Cabedelo, Cova-Gala, and Costa de Lavos), as well as mitigate coastal erosion in these areas.

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