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Study of Harbour Infilling using Sand Tracer Experiments

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ABSTRACT

The harbour of Fortaleza (Ceará - Brazil) is facing infilling processes by sand and fine-grained sediments. The influx of sand into the harbour resulted in the generation and growth of an internal beach (Praia Mansa), located on the sheltered side of the main jetty (Titan). Two tracer studies were performed in the harbour vicinity in order to understand sand transport patterns around the jetty and inside the harbour. For this purpose 1,410 kg (experiment FORT I), and 420 kg (experiment FORT II) of dyed sand were released from a boat at depths between 3.5-5 and 6-11 m below mean sea level, respectively. For FORT I a series of 23 surveys were carried out over a period of two months, including the collection of about 1,000 samples. Detailed maps of sand transport and dispersion were obtained for each survey. During the FORT II experiment only 45 samples were collected at different surveying days, giving an idea of the broad sediment dispersion patterns.

The general tracer dispersion and transport pattern observed at FORT II proved that the sediment arriving to the main jetty arrives by littoral drift from the Futuro beach, after bypassing the Titanzinho groin. The analysis of FORT I maps showed that the sand moved along the external part of the Titan jetty at rates about 30 m/day. Subsequently, due to wave refraction and diffraction around the jetty tip, the tracer started to be transported towards the internal part of the harbour. The computed average displacement rate of the tracer head was about 5 m/day. The last survey, 58 days after the tracer release, shows the existence of dyed sand inside the harbour, at the nearshore portion of Praia Mansa beach. This confirms that Praia Mansa is still slowly but continuously accreting, by addition of sediment transported around the jetty. The results also demonstrate the durability and the effectiveness of dyed sands for the study of sediment transport and harbour infilling.

ADDITIONALINDEXWORDS: *Fortaleza, Brazil, Longshore transport, Jetty, Dyed sand*

INTRODUCTION

There is a large variety of methods to determine or estimate the infilling of harbours and its causes. Historical methods include the comparison of bathymetric data, while recent analyses are normally based on computer modelling. However, only few methods allow a direct and comprehensive understanding of sand transport processes that produce harbour infilling. The use of natural or artificial tracers is one of such methods, having a great potential for both qualitative and quantitative assessments. Despite the large experience on tracer studies confined to the shoreface, for short time periods and with small amounts of tracers, there are only a few studies on large experiments including underwater sampling. As a result, the use of tracers for defining harbour infilling still poses some problems, since it normally implies the use of underwater sampling for extensive monitoring periods. In the particular case of fluorescent tracers, a large tracer quantity is also required to ensure a significant recovery at the end of the experiment. The use of a large amount of tracer will induce the existence of a continuous injection point or area, which in turn makes the sediment transport quantification difficult.

This paper aims to contribute to a better understanding on the processes leading to the infilling of the Fortaleza harbour (Ceará, Brazil), using large-scale fluorescent tracer experiments. It also discusses problems and advantages of using this kind of tracer experiments.

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Figure 1. Study area location. The inner box shows the area where the experiments were performed and the relative positions of Praia Mansa beach, the main jetty (Titan) and the updrift groin (Titanzinho). The grid coordinates are metric and the grid is north-south and east-west orientated.

Study area

Fortaleza harbour (Figure 1) is located at the eastern extreme of Fortaleza, capital of the state of Ceará, in northeastern Brazil. The Ceará coast is mesotidal, with semi-diurnal tides, reaching maximum tidal ranges of about 3.3 m during spring tides. The Fortaleza region is greatly influenced by winds, with almost constant directions from E-SE, and average velocities between 1.6 m/s and 6.1 m/s (PETCON, 2000). According to INPH (1996), waves at Fortaleza are characterized by an almost constant direction (93% of the waves approach from azimuths 75º to 105º), moderate wave energy (62% of the significant wave heights are between 0.9 and 1.3 meters), and short periods (91% of the mean periods range from 4 to 7 seconds). The potential net annual drift estimated for the Futuro beach (east to the Fortaleza harbour, Figure 1) is between 600,000 m^3/year (VALENTINI, 1997) and 876,000 m^3/year (INPH, 1992), with the lowest value being obtained by applying the CERC formulation and the higher one by indirect estimation of the accumulated sediments.

The coastal zone of Ceará is mainly constituted by exposed sandy beaches backed by large dune fields or by cliffs cut into soft sandstones. Rocky outcrops or headlands sometimes interrupt the exposed and long sandy beaches. The most prominent rocky headland is the "Ponta de Mucuripe", separating two coastal stretches with different orientations. The existent Fortaleza harbour was built immediately to the west of this point, profiting from the natural sheltering effect of the headland. The present location of Fortaleza harbour is the fourth in its history and all previous locations were abandoned because of silting up of the port area. The new harbour at Ponta de Mucuripe, which includes a 1,400 m long main breakwater, was built between 1939 and 1945 (MAIA *et al*., 1998). According to (MAIA *et al*., 1998) three problems were noticed during the harbour construction: (i) the breakwater was rapidly infilled with sand, (ii) the breakwater did not shelter the area from the eastern waves and (iii) beaches downdrift of the port began to erode. The new port interrupted the natural sediment transport around the headland and as a consequence induced serious erosion at the beaches of Fortaleza. To promote sediment by-pass around the harbour,

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minimizing the infilling, the Titan breakwater was extended to a length of 1,910 m. An additional 550 m long groin (Titanzinho) was also built eastwards of the port (Figure 1). This groin was afterwards extended to a total length of 1,000 m in 1974. At that time several groins were also built at the Fortaleza waterfront. A synthesis of the Fortaleza coastal structures history can be found at SALIM (1998). At the same time that the coastline of Fortaleza was eroded, the harbour continued to silt up, both with fine sediments and sand. The sand transport into the harbour was responsible for the formation of Praia Mansa, a 1,000 m long sandy beach placed on the inner part of the Titan breakwater, the most sheltered area of the harbour (PETCON, 2000). This beach is presently backed by dense vegetation, established over the accumulated sand. At the end of the 1990's, the dredging effort needed to maintain the port fully operational was in the order of 500,000 m^3/year (SILVA *et al*., 2000).

METHODS

Two tracer experiments were performed at Fortaleza to obtain more information about the sand transport partially responsible for the infilling of the harbour and subsequent formation of Praia Mansa beach.

The main goal of the first experiment (FORT I) was to understand and quantify the transport of sand from the external part of the Titan breakwater to the interior of the port. After a study of the sedimentological characteristics of the area, more than 2,000 kg of sand were collected from the beach face of Praia Mansa, and 1,500 kg dyed with orange fluorescent ink. These sediments were fine sands, corresponding to the type of sand found in the entire area surrounding the Titan breakwater. Medium to coarse sand only occurs seaward of the breakwater at places deeper than 7 m below mean sea level. A total of 1,410 kg were released from a boat along a 170 m line parallel to the Titan jetty on the morning of the 7th of April 1999. This operation was performed during high tide, allowing the tracer to be released as close as possible of the jetty. The traced sands settled down on the sea bottom at depths between 3.5 and 5 m below mean sea level.

A first tracer survey (Day 0) was carried out on the afternoon of the releasing day (7th of April) to evaluate the initial sand dispersion induced by the injection method. A slight dispersion was observed, with the tracer occupying a relatively small area with an alongshore length of about 200 m. A series of daily surveys were carried out during the first two weeks being followed by surveys at intervals of 3 to 5 days, until the 4th of June 1999 (Day 58), 58 days after the tracer release. A total of 23 surveys were performed, including the collection of 989 sediment samples. The samples were collected with a grab sampler along a previously defined grid. The grid profiles were normal to the jetty up to the 10 m depth contour. The sediment samples were washed, dried, weighted and observed under a UV lamp to determine the amount of dyed grains. The number of counted grains was divided by the sample weight in order to obtain a tracer concentration in grains per weight unit. For the purposes of this study, 13 surveys were selected, with intervals between consecutive surveys ranging from 3 to 9 days.

For the definition of the mass centre and the tracer transport rate, a computation grid composed by more than 100 cells with different sizes was defined (Figure 2). Each cell is described by its area and central point in x, y coordinates, were x represents the alongshore distance to the injection area and y the cross-shore distance to the jetty. It was possible to define the tracer concentration and its relative importance in the total tracer transport for each cell at each survey. The mass centre was determined using the Spatial Integration Method (vide CIAVOLA *et al*., 1997). Furthermore, the position of 25, 10, 5, 1 and 0.1 Percentiles in relation to the injection point, was determined for each survey. Percentile X represents the X% of tracer that has experienced greatest transport, being therefore the X% of sediment most distant from the injection point.

A second experiment (FORT II) was performed in October and November 1999 to complement the results obtained with FORT I. The main goal of FORT II was to verify if there was sediment transport from the Futuro beach to the Titanzinho groin (Figure 1) and around the groin to the Titan jetty. The release of circa 420 kg of sediment was made by boat on the 30th of October 1999, along a line 145 m long, placed near the Titanzinho groin at a depth between 6 and 11 m above mean sea level. The sample surveys were carried out for the duration of two weeks, and included the collection of a total of 45 samples. An extensive sampling grid was not established due to the extreme wave conditions in this area (i.e., reflected waves, wave shoaling, and wave breaking), which imposed particular difficulties to the navigation near the jetty. The tracer concentration at each sample was determined by using the same approach as with the first experiment. Despite the different surveying days, the collected samples were analysed as a whole, representing a single analysis moment. This allowed the acquisition of a broad picture of the sediment transport pattern. However, a quantitative analysis of the sediment displacement could not be made.

RESULTS

FORT I (First Experiment)

Using the obtained tracer concentration values per sample and per surveying day, concentration maps were made, allowing a spatial analysis of the tracer distribution. Figure 2 shows the map for the releasing day (Day 0, Figure 2a) and for the final surveyed day (Day 58, Figure 2b). Slight tracer dispersion can be observed at the Day 0 survey. It was

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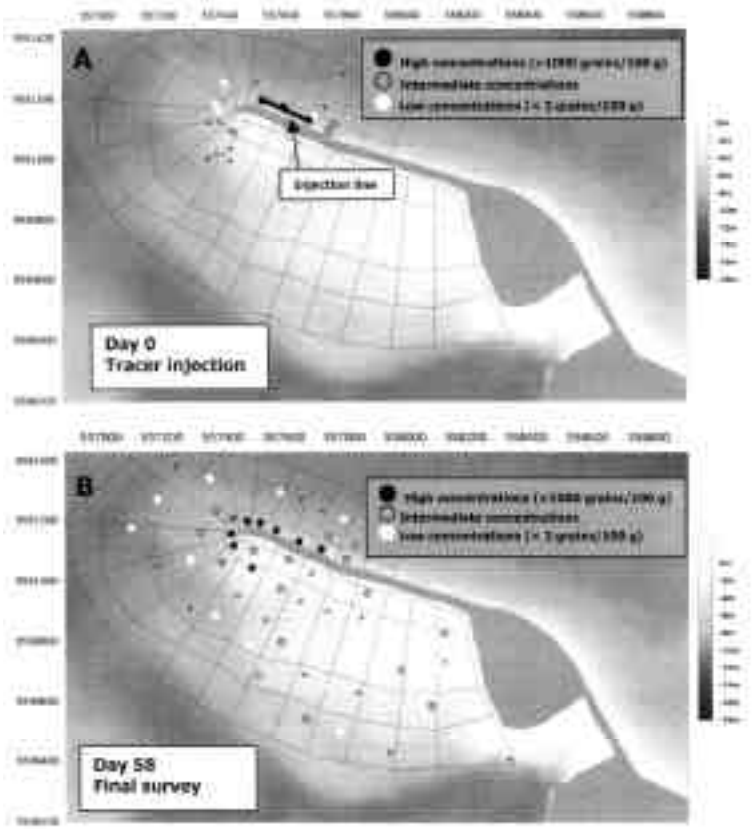


Figure 2. Distribution maps for the tracer injection day (Day 0; Figure 2A) and final surveyed day (Day 58; Figure 2B) on FORT I experiment. The computation grid used for the definition of the tracer transport velocity is also shown. X represent samples where tracers were not found.

assumed that this dispersion mainly resulted from the injection method, since the dyed sand was released from the deck of a boat to the water surface and only afterwards settled down on the sea bottom. Therefore, the centre of mass computed for Day 0 was assumed as the initial centre of mass (injection point) for the entire experiment. All tracer velocity computations were made in relation to this point. The tracer centre of mass displacement in relation to the centre of mass position on Day 0 and along time is expressed in Figure 3. A rapid displacement of the centre of mass occurred during the first 8 days after the tracer injection, along the external part of the Titan jetty and towards NW. The total displacement value for this period was about 248 m (31 m/day) and the centre of mass becomes positioned at the head of the jetty. After Day 8 the position of the centre of mass showed some oscillations, with a tendency to stabilise at about 250 m distance from the injection point. However, it was observed that a significant part of the sediment began drifting into the harbour just 4 days after the tracer release, with concentrations increasing during the following course of the experiment. The centre of mass position does not properly express this transport. In fact, the head of the tracer was positioned inside the harbour already on Day 4, and at all other surveys until the end of the experiment.

The displacement through time of Percentiles 25, 10, 5, 1 and 0.1 was analysed to find an alternative method to represent the tracer head movement. A linear regression was made and a trend line obtained for the displacement of each analysed percentile through time. It was observed that the best fit was achieved for Percentile 5. It was also verified that the positions of Percentiles 25 and 10 were too dependent on the mass centre, while Percentiles 1 and 0.1 showed a stronger scatter. Despite some oscillations, Percentile 5 shows a coherent trend for the entire survey, and seems to be an adequate parameter to describe effective tracer advection inside the harbour (Figure 4). Therefore, Percentile 5 can be considered as a proxy to define the displacement of the tracer head. The computed displacement velocity of the tracer head inside the harbour obtained by analysis of Percentile 5 was in average 4.94 m/day, directed to SE. In fact, the tracer head made a complete U turn around the jetty, showing a net transport directed towards Praia Mansa beach.

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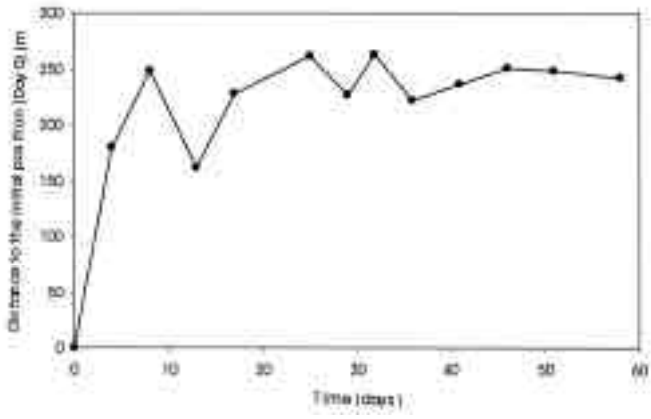


Figure 3. Centre of mass displacement trough time in relation to its initial position on Day 0.

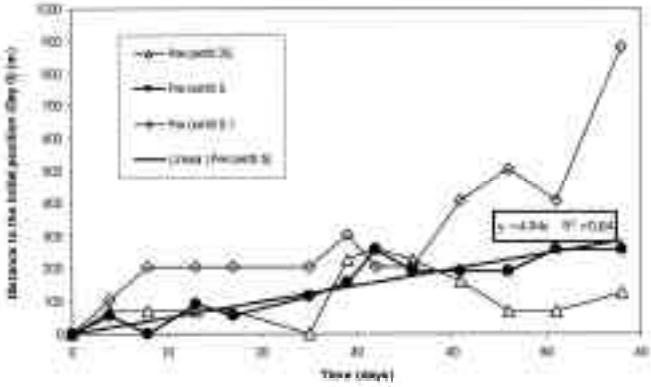


Figure 4. Displacement of Percentiles 0.1, 5 and 25 trough time in relation to their initial position on Day 0. The linear fit to Percentile 5 is also shown.

The transported dyed sands were generally confined to areas shallower than the 7/8 m bellow mean sea level on the seaward side of the jetty and 6 m below mean sea level on the internal part. This gives an indication on the depth of closure (active profile) for the longshore sediment transport at the study area.

FORT II (Second Experiment)

During the second experiment a single dispersion map was obtained (Figure 5), showing a clear sediment transport from the injection point towards the Titanzinho groin head. This transport was observed to occur mainly near the 6 to 10 m depth contour. However, it was not possible to confirm if there was transport at shallower areas since it was impracticable to collect samples at those positions. The groin transposition is also clearly visible, with a marked tracer dispersion immediately downdrift of the groin. It is also observed that tracers are sometimes transported to areas deeper than 12m below mean sea level, namely in the vicinity of the groin head. Even if transport rates cannot be defined, it can be pointed that some of the recovered tracers were found at more than 600m from the injection area, only a few days after the tracer injection.

DISCUSSION

The joint analysis of the tracer experiments performed at Fortaleza give detailed information of the sand transport patterns occurring outside and inside the harbour. In fact, the results of FORT I and FORT II clearly show that sediment coming from Praia do Futuro beach, a few kilometres updrift from the harbour, is transported into the port, despite the existence of a long groin (Titanzinho) and a long harbour breakwater (Titan).

The existence of an apparently unsaturated groin, as is the case of Titanzinho, could indicate that this groin would still be in a process of infilling. However, results from experiment FORT II show that the sediment involved in the littoral drift at Praia do Futuro is transported along and around the groin, at depths that can reach 16m below mean sea level. This transport is related to rip (contour) currents generated in the area surrounding the groin. These currents are in part associated to the littoral drift, which is deflected towards offshore by the groin effect, but also to the return current generated by the constant water mass build up against the groin, induced by waves and wind at this particular area. The strong currents are also responsible for the bathymetric contours in this area, inducing a maximum depth near the groin head of about 18m below mean sea level.

Downdrift of the Titanzinho groin the transported sands experienced a relatively strong dispersion, being transported, by the combination of currents and shoaling waves, towards the Titan jetty and to a small beach between the two coastal structures.

According to FORT I results, the sand had a strong transport along the Titan jetty seaward area, at average rates of about 31 m/day. The sediment was transported along a relatively steep and narrow strip, rarely exceeding a distance of 200 m from the jetty, at depths from almost 0 m to 8 m bellow mean sea level. When the transported sediment reached the head of the Titan breakwater, it experienced a deceleration, which is probably responsible for the existent sediment accumulation at this point, and for the formation of sand banks at the tip of the breakwater. This process was previously identified by MAIA *et al.* (1998), after analysing the bathymetric changes occurred during the construction of the Titan jetty. A significant portion of the sands accumulated at the tip of the breakwater

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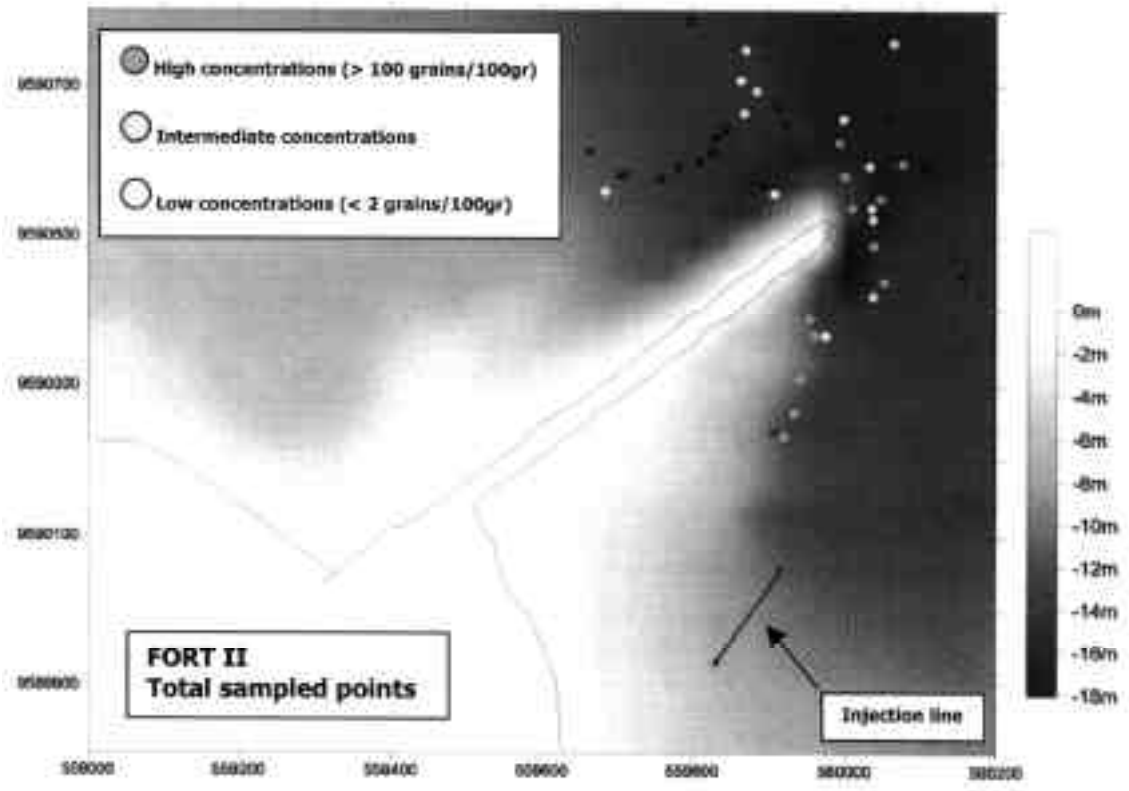


Figure 5. Distribution map of the tracer concentration including all obtained samples at FORT II experiment. X represent samples where tracers were not found.

are afterwards transported inside the harbour by the action of refracted and diffracted waves, which have been observed and characterized by PITOMBEIRA (1976), and modelled by SILVA *et al*. (2000). The sand transport velocity inside the harbour is represented by the displacement velocity of the tracer head, but not by the centre of mass velocity since this one remained at the tip of the breakwater, inducing the existence of a second and constant injection point. The transport velocity (about 5 m/day) inside the harbour was one order of magnitude smaller of the external one. However, the involved area is bigger since includes all the internal extension of the jetty until maximum widths of 600m to the interior of the harbour. The sand transport inside the harbour was responsible for the formation and development of Praia Mansa beach and is still responsible for its growth. This was clearly proved by the results of the last surveys, where tracers were identified near the beach face of Praia Mansa.

No transport to outside the studied area was observed during the analysed surveys of FORT I experiment. This leads to the conclusion that sediments involved in the longshore transport near the Titan jetty are either deposited at the tip of the jetty or transported into the harbour, depositing at internal banks, channels or Praia Mansa beach. This result clearly explains the sand starvation on Fortaleza beaches since the establishment of the harbour.

CONCLUSIONS

The tracer analyses provided good results on the identification and clarification of the transport mechanisms that lead to the infilling of the Fortaleza harbour by sands. It also allowed some quantification of these processes, namely regarding tracer advection velocity computations. Therefore, the method used seems to be useful in the identification of transport patterns and processes inducing large-scale harbour infilling by sands. The existence of a large amount of sediment not completely remobilised during the first days of the experiment, and subsequently accumulated at the tip of the main breakwater, inducing the existence of two continuous injection areas, make any transport rate computation difficult. The use of the percentiles can help on the determination of tracer head

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velocity, minimising the impact of continuous injection. The development of a method for mixing depth determination is still necessary for future experiments, in order to allow the quantification of sediment transport volumes.

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