# CHAPTER 78

## RIO GRANDE BAR - THE CASE HISTORY OF A LAGOON OUTLET INTO A TIDELESS SEA

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Abstract

Rio Grande harbour is situated inside the outlet of Lagoa dos Patos (9 910 km2) and Lagoa Mirim (3 770 km2). Most of the rivers in the State of Rio Grande do Sul, that are not tributaries of river Uruguay, flow into the two lagoons and the latter discharge through Canal do Norte into a tideless sea. Flood flows can exceed 20 000 cumecs. The outlet is on a sandy coast with littoral drift in both shoreline directions.

The time history of the outlet can be divided into three periods. Before breakwater construction, the bar was extremely unstable in lay-out, position and controlling depth. The latter ranged from 2.5 to 7 m. From 1911 to 1916 two 4 km long rubble mound breakwaters were built. They deepened the entrance channel to 8 - 10 m but a new bar came about further offshore entailing objectionable navigation conditions in the approach channel. No previous dredging was carried out as the breakwater construction proceeded out to sea, and as result a total of 14 million cubic metres was scoured out between the two breakwaters and discharged offshore to build up the new bar. Some improvement by dredging was not achieved until 1962.

The improvement of the approach channel lay-out as well as deepening the entrance to 14 m below datum are under consideration. Field and model investigations have been designed for this purpose.

I) The Coastal Environment and Hydraulic Conditions, Rio Grande harbour is situated inside the outlet of Patos Lagoon (9 910 km2) and Mirim Lagoon (3 770 km2). The key map of Fig.1 shows the area discussed in this paper. It lies near the southern border of Brazil, Rio Grande being the main port in the State of Rio Grande do Sul.

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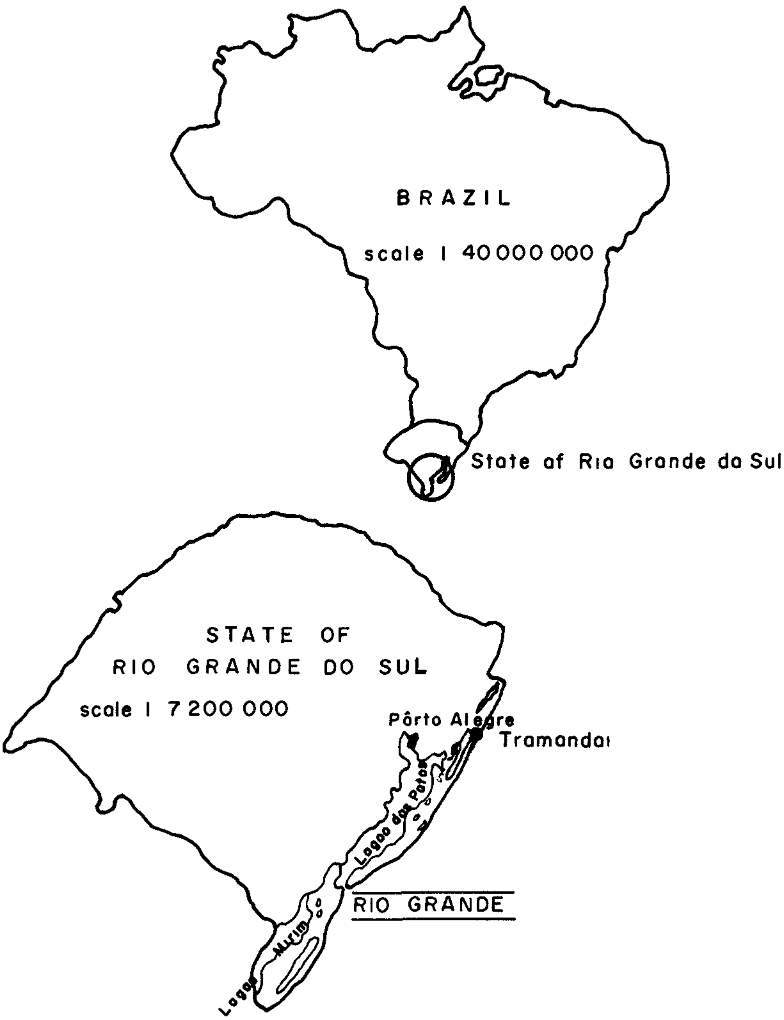


Fig 1

GEOGRAPHICAL LOCATION OF
RIO GRANDE HARBOUR

The coast of this State is a long barrier beach dividing several lagoons from the sea. Patos and Mirim lagoons are the two most important bodies of water. They are connected by a 70 km long channel, Canal São Gonçalo, and they discharge into the sea through a common outlet (Canal do Norte) on whose western bank the port of Rio Grande has been built. Most of the rivers in the State of Rio Grande do Sul, that are not tributaries of River Uruguay, flow into these two lagoons. As a result, the upland flow in Canal do Norte drains a basin with an area of 162 000 km2, and peak flows can exceed 20 000 cumecs. Canal do Norte is quite stable in position, width, depth and length. Its width varies from 1.5 km at the mouth to about 3 km at the northern end, a major portion of its shipping channel being over 15 m deep.

The lagoon outlet is on a sandy coast with littoral drift in both shoreline directions. The coast is fairly straight, flat, and uniform in profile, the offshore slope from the -1 to the -15 m contour being about 1%. The beach material is fine sand, a representative mean diameter being about 0.20 mm. The shoreline runs on a SW to NE alignment but the axis of Canal do Norte nearly coincides with a meridian, which accounts for its name the Portuguese for Northerly Channel.

According to |1| the main characteristics of the deep-water wave climate are the same from Punta del Este (in Uruguay) to Tramandai, some 320 km north of Rio Grande, where wave characteristics were recorded at a 20 m depth for more than a year, in 1962-63, in connection with the design of an offshore oil terminal. The main characteristic of this wave climate is that swell comes mostly from SE whereas the dominant and prevailing winds blow from NE. As a result, there is a marked correlation between wave periods and directions as shown is Fig. 2. The waves with the greatest energy (Fig. 3) and least steepness - therefore with the greatest transport capacity - come from SE which causes the northwestward littoral drift to be dominant over the southwestward drift. The latter is induced by the waves, mostly locally generated sea, from the NE quadrant.

The only indication available as to the intensities of this two-way littoral drift is that the average dominant littoral drift would be 1.5 times as great as the secondary drift. The average total annual volume of the dominant littoral drift would amount to some 100 000 m3 per year. These figures were arrived at from the results of a mobile-bed model investigation into the control of Tramandai inlet which was carried out in 1964 at the Hydraulics Research Institute of the Federal University of Rio Grande do Sul |2|. A time scale for bed movement was worked out by comparing model and prototype durations of the northward inlet migration when Tramandai inlet was uncontrolled, and the transport capacity of the waves reproduced in the model was measured by trapping sand at the downdrift end of the model. The total volume of littoral drift in a model year was then scaled up. The amount of 100 000 m3/year for the dominant drift seems rather lower than values reported for similar conditions in other parts of the world and may be due to the model improperly simulating suspended transport in the surf zone. On the other hand, it should be noted that the angle of attack of the dominant waves is usually small about $10^{\circ}$ at a 20 m depth. Whatever the accuracy

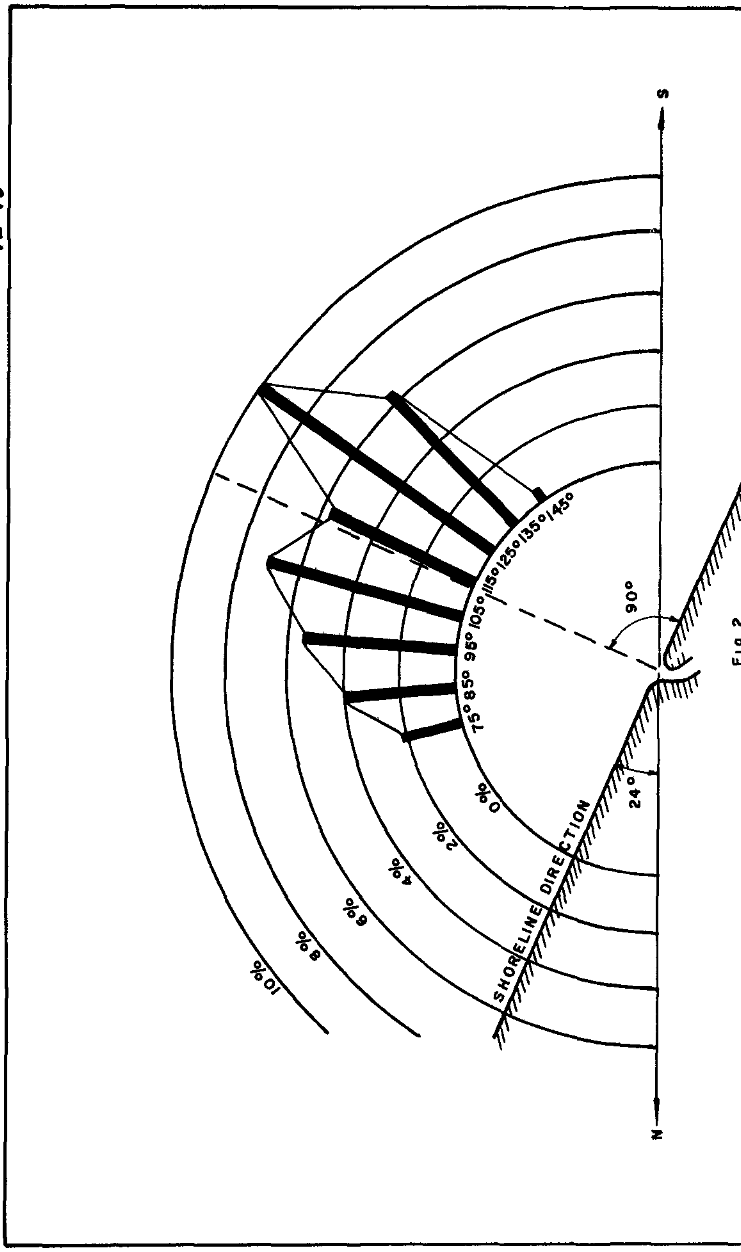


Fig 2
CORRELATION BETWEEN ANGLES OF ATTACK ( AT THE 20m DEPTH ) AND SIGNIFICANT PERIODS EQUAL TO OR GREATER THAN 10s OFF TRAMANDAI

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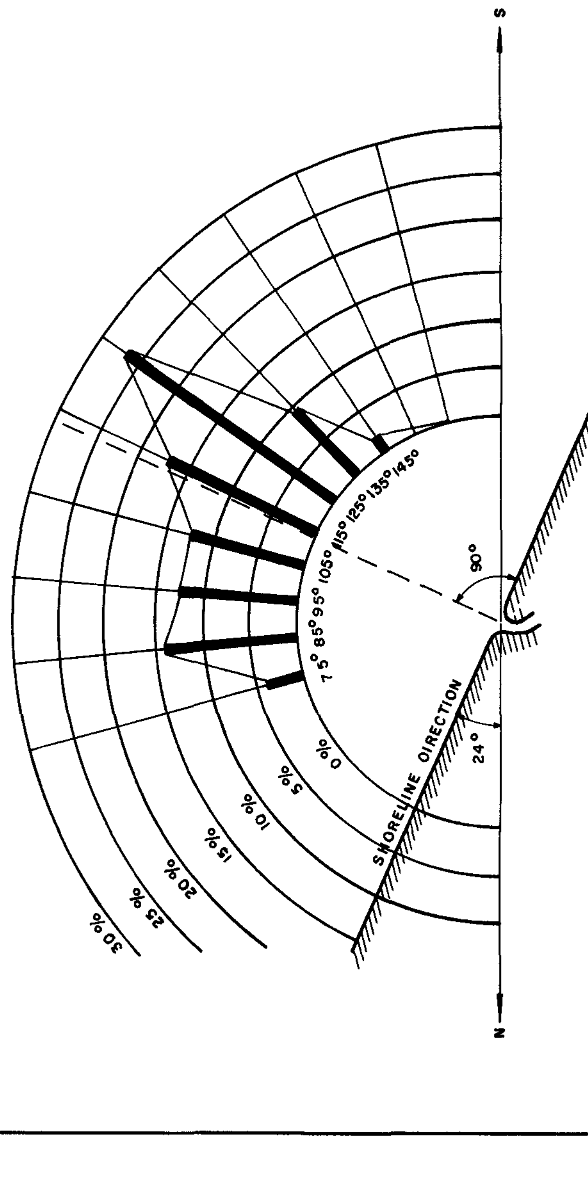


Fig 3

CORRELATION BETWEEN ANGLES OF ATTACK (AT THE 20m DEPTH) AND WAVE ENERGY ($\Sigma H_s^2 T_s$) OFF TRAMANDAI of the above estimate for littoral drift on the coast of Rio Grande do Sul may be, what is actually known is that the most frequent significant wave height is 1.5 m at the 20 m depth, and the most frequent significant wave period is 9 s. Wave heights of 4 m at the 20 m depth occur at least once in a year.

The most striking feature of Rio Grande harbour entrance is that fresh-water flow largely dominates over tidal flow in determining its hydraulic and morphological characteristics. This is the reason why the present paper refers to Canal do Norte as a "lagoon outlet" instead of adapting the usual expression "coastal inlet". While six sizable rivers flow into Patos Lagoon and five into Mirim Lagoon the sea off the harbour entrance is practically tideless. The area of Patos Lagoon alone is about three times as large as that of the Ijsselmeer, the dammed Zuiderzee, in the Netherlands. On the other hand, the mean monthly tidal range is usually below half a metre. The overall result is that waterlevels as well as velocities, directions and durations of flow through Canal do Norte are mainly determined by a complex interaction between wind effects at sea and in the lagoon system, and fresh-water flow in the latter. Instead of periodical reversals of ebb and flood in Canal do Norte, the flow may be out to sea for several days on end in the rainy season if no strong winds blow from the south whereas strong winds from the south can bring about flow from the sea into the lagoons for several days in the dry season.

Increase in upland flow or northerly to northeasterly winds tend to cause ebb flow in Canal do Norte. Decrease in upland flow or winds from the south (SE to W) tend to cause flood flow. The greatest ebb discharges obviously take place when upland floods occur together with winds from N to NE. The greatest flood discharges are brought about by wind action from the south in the dry season.

The values of the upland discharges as well as the pattern of seasonal changes of rainfall and wind characteristics are such as to make ebb flows in Canal do Norte largely dominant over floods both in discharge values and durations throughout the year. Rainfall reaches a maximum in late winter, August and September, the southern Hemisphere winter and spring being the seasons with greater rainfall Summer, December to March, is the dry season. Although northeasterly winds prevail over the year, they are more frequent from September to March. Winds from the southern quadrant are more frequent during the winter, from June to September. As a result, the greater upland discharges in winter counteract the flood-producing effect of the southerly winds. In the summer the effects of the northeasterly winds offset the decrease in upland flow to some extent.

One of the French engineers who built the breakwaters at the entrance in 1908-1916, M. B. Malaval |3|, made an analysis of discharge values and durations of ebb and flood in Canal do Norte for six years(1908, 1911, 1912, 1913, 1914, 1915). The water surface profile was determined by two water level recorders 8 250 m apart, one near the port and the other near the entrance. Discharges were calculated with the aid of the Chezy formula, the assumptions on the value of the Chezy coefficient being controlled by some velocity measurements. The average results of Malaval's analysis for the six years under consideration were as follows:

1) 2 604 hours of flood per year, or 108 days in a year, with a mean discharge of 6 767 m3/s, a mean velocity of 0.8 m/s, and an annual volume of 63 x $10^9$/m3,
2) 4 925 hours of ebb per year, or 205 days in a year, with a mean discharge of 8 650 m3/s, a mean velocity of 1.0 m/s, and an annual volume of 149 x $10^9$ m3,
3) 1 239 hours of slack water, or 52 days in a year, for which no flow was assumed.

Malaval's analysis did not take salinity effects into account.

Malaval also drew a list of ebb and flood periods with durations from 18 to 24 consecutive hours. He found an ebb period lasting for 19 consecutive days in July 1915 and a flood period lasting for 9 days in December 1915. On the average in a year he found for the ebb

2 periods lasting for 10 to 19 consecutive days
5 " " " 5 " 10 " "
18 " " " 2 " 4 " "
21 " " " 1 whole day

and for the flood

1 period lasting for 5 to 9 consecutive days
6 periods lasting for 2 to 4 consecutive days
21 " " " 1 whole day

Analysis of flood and ebb durations in Canal do Norte more refined than Malaval's were not carried out to this day.

The two lagoons act both as large storage basins for the upland flow and sediment traps for the bed load brought down by the rivers. As a result, the sand in and around the harbour entrance is brought in by wave action on the continental shelf. The bed material is sand at the entrance and in the outer stretch of Canal do Norte. The inner stretch and the harbour basin have a muddy bed. Coastal currents are wind induced and can only cause sand transport in conjunction with waves.

## II) The Uncontrolled Outlet and the Effects of Breakwater Construction.

The main object of this paper is the time history of the bar that came into being off the entrance to the lagoon outlet as a result of the interaction between the transport capacity of the waves and the flushing action of the upland flow. This time history can be divided into three periods

1) The situation of uncontrolled outlet, before breakwater construction in 1908-1916,
2) the changes which breakwater construction brought about,
3) the present situation that prevails since the bar, the shoreline and the outer stretch of Canal do Norte adapted themselves to the new conditions.

The time history of the bar is fairly well known as from

1883, annual surveys being available from that year to 1956 |4|. Surveys have been less frequent since 1956. Prior to 1883 the information available is poor.

Before breakwater construction the bar was extremely unstable in controlling depth, distance to the shoreline and pattern of the channels, Between 1883 - when the first comprehensive, reliable survey was carried out - and 1914 - when the influence of the breakwaters then under construction was brought to bear for the first time - the controlling depth varied in an erractic manner from a minimum of 2,5 m (1883) to a maximum of 7 m (1894). However, the most frequent values ranged from 4 to 5 m.

Figs. 4, 5 and 6 show the time history of the bar as taken from |4|. In Fig. 4 the annual values of the controlling depth are plotted from 1883 to 1956. Fig. 5 correlates the controlling depth to distances to a reference alignement joining two triangulation vertices on the shore. Fig. 6 is a plot of the variation in time of the least depths over the bar outside the shipping channel.

The distances from the reference alignement to the contour standing for the controlling depth ranged from a minimum of 2.8 km (in 1885, 1898 and 1899) to a maximum of 5.0 km (in 1892). The average distance of the controlling depth to the reference alignement was therefore 3.9 km (actual positions in 1886 and 1894). Very different values of controlling depth could be associated to a given value of dietance to the reference alignement. For instance, the 4.0 km distance wae associated to a controlling depth of 2.5 m (1883), 5.0 m (1902) and 6.0 m (1893). The 3.9 km distance was associated with values of 4.0 m (1886) and 7.0 m (1894). The minimum 2.8 km distance was aseociated with 3.0 m (1885) and 6.0 m (1898 and 1899). The maximum 5.0 km distance, which occurred only once (1892), was associated with 5.0 m.

Lack of reliable data for rainfall or upland diecharges at the time under consideration in all the river basine involved preeludes any attempt at correlating bar characteristics with upland flow values.

The lay-out of the main channel accross the bar used to swing from SW to S and SE, although a SW alignement was most frequent. The instability of natural-channel pattern can also be eeen in the different breakwater lay-outs proposed by different engineers at different times. Each proposed design was baeed on the most recent available survey.

While the bar underwent the changes discuesed above the outlet itself, Canal do Norte, remained remarkably stable in position, width and depth. It is interesting to point out that the other lagoon outlet (Tramandai) and the mouths of small rivers(Chui, Mampituba and Ararangua) on the same stretch of the Brazilian coast migrate northwards, in the direction of the dominant littoral drift. It appears that the stability of Canal do Norte was due to its much greater upland flow which flushed to considerable distances out to sea the sand brought in by the waves from the sides and in frontal action. At the other lagoon outlet and river mouths mentioned above the bar builds up much nearer the shoreline, and the interaction between littoral drift and the transport capacity of the upland flow in this tideless sea cause inlet migration.

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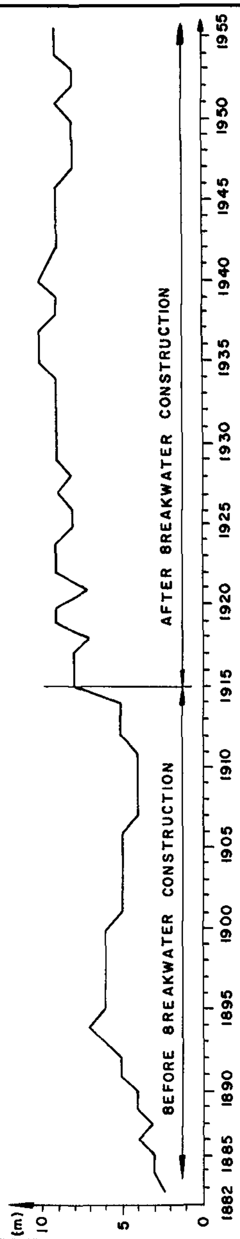


Fig 4

CONTROLLING DEPTHS OVER RIO GRANDE
BAR FROM 1883 TO 1956

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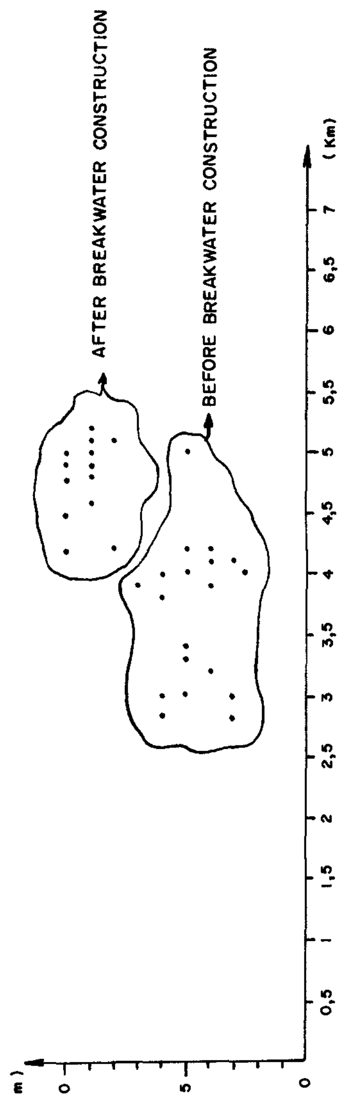


FIG 5

CORRELATION BETWEEN
CONTROLLING DEPTHS AND
DISTANCES TO SHORELINE

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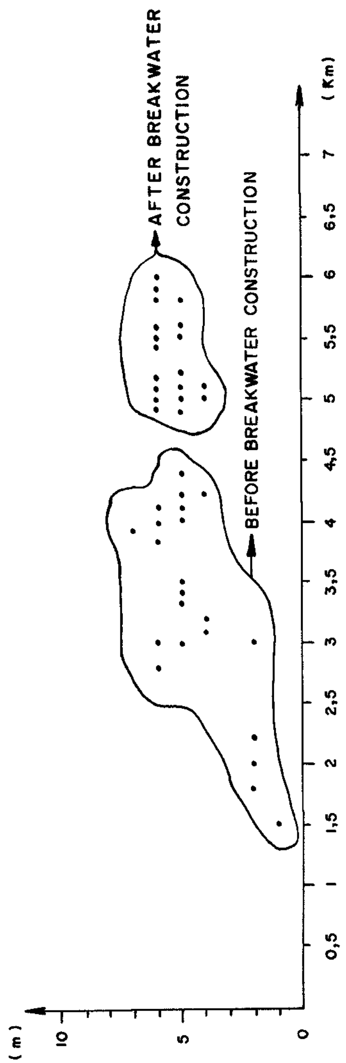


FIG 6

LEAST DEPTHS OVER THE BAR OUTSIDE THE SHIPPING CHANNEL

On the other hand, the great instability of Rio Grande bar eeems to be largely accounted for by the fact that upland flow, and not tidal flow, ıe the natural agent whose flushıng action tends to preserve depths over the bar. Upland flow discharges are much lese repeatable from year to year than would be tidal flow dischargee in a place with a regular tide.

As far ae it can be ascertained from the available surveye the shorelines on both sıdes of the lagoon outlet were fairly stable ae long as it remained uncontrolled.

The earliest propoeal for breakwater construction at Rio Grande wae put forward by a Britıeh engineer, sir John Hawkshaw, who was commiseioned by the Brazilian Imperial Government ın 1872 to report on methode to provıde for a eafe ehipping channel accroes the bar. However, in hıs report |5| Hawkehaw pointed out that the size and cost of the requıred breakwaters would be such as to make the construction of a ehoreline harbour at Torres,near the northern boundary of the State of Rio Grande do Sul, more advisable.

In 1883 the Brazilian Imperial Government entrusted a Brazilian engineer, H. Bicalho, with the taek of carrying out the field surveys and design work to improve Rio Grande entrance. Bicalho |6| propoeed the conetruction of two 4 km long breakwaters and requeeted the Government to seek the advice of a European or American engineer with a great experience in harbour entrance training to pase judgement on his propoeal. The Government choice fell on the Dutch engineer, P.Caland, who had been in charge of the works for Rotterdam harbour entrance. Caland |7| approved of Bicalho'e proposal with some minor changee in lay-out.

Hawkshaw, Bicalho and Caland were the first men to graep the behaviour of Rio Grande bar and lay down rules for its improvement although the lack of the eea and swell concept in their time misled them ae to the direction of the dominant lıttoral drift on the coast of Rio Grande do Sul becauee of the prevailing and dominant winds from NE.

Caland was prophetical ın his recommendation that, when the breakwatere would be built, previous dredging should be carried out as the construction work proceeded out to sea in order to forestall ecour caused by the increaeed traneport capacity of the upland flow between the breakwatere, of which the formation of a new bar further offehore would be the inevitable result.

Breakwater construction wae not started until 1908 when a French company wae awarded a concession to build the breakwaters and dock facilıtıee. Work in the breakwaters themeelves wae carried out from 1911 to late 1915, and major effects on the bar came about in 1914 which was a year with great rainfall and long, strong ebb flows in Canal do Norte. The Rio Grande breakwaters were the biggeet hydraulic-engineering etructures built in Brazil until some fifteen years ago, and at the time they ranked among the largest coaetal works in the world. From 1922 to 1928, already under Brazilian administration, the outer 288 m of the eastern breakwater, which had been left in 1916 as a submerged dyke, were brought to the same top level (+ 3.00 m) ae the remainder of the etructure.

M. B. Malaval, one of the French engineers in charge of the conetruction work, left a detailed account |3| of its progrese and effects on the bed configuration. Malaval's paper followed up of deepening process from 1913 to 1919 in great detail.

Fig. 4, 5 and 6 bring out the effects of the breakwaters on the bar. Fig. 5 shows that the deepening of the former bar was quite sudden: from 1914 to 1915 the plot jumps from 5 to 8 m. Ever since that occasion

1) the least controlling depth has always been above 7 m and this minimum only occurred in two years (1918 and 1921) in the time interval from 1915 to 1956, the most frequent value being 9 m (which occurred in 23 years), a value of 8 m occurring in 11 years, and the maximum between 9 and 10 m occurring in 4 years (1935, 1936, 1937 and 1940),

2) the range of the controlling-depth variation has decreased from 2.5 - 7.0 m before breakwater construction to 8-10 m as from 1922.

Fig. 5 proves that, in addition to increasing the controlling depth, breakwater construction increased its distance to the shoreline.

However, it can be seen from Fig. 6 that, although the breakwaters did increase the depths at the harbour entrance, the scheme was not entirely successful. The former bar was destroyed but a new bar built up further offshore. This fact entailed objectionable conditions for navigation at the entrance because the ships had to follow tight S - curves between the breakwater tips and the new bar. The radius of curvature did not exceed 500 m.

The obvious reason for this unhappy outcome was the fact that Caland's recommendation for previous dredging as breakwater construction proceeded out to sea went unheeded. No previous dredging was carried out, and as much as 14 million cubic metres of sand was scoured out between the breakwaters from January 1913 to January 1919 of which 10 million in 1914 alone. Such a huge volume was discharged offshore, and since it far exceeded the transport capacity of waves and currents offshore, a new bar came into being. The bed levels were irreversibly raised off the breakwater tips, and the interaction between the transport capacity of waves and upland flow has gone on ever since over the submarine mound thus created. Previous dredging has proved successful in forestalling the formation of a new bar at other harbour entrances |8|.

The first approach channel to deepen was the one leading to the seaward end of the eastern breakwater. This channel was the main route to negotiate the entrance until 1962. The eastern channel was the first to deepen because construction of the eastern breakwater went ahead of that of the western breakwater. Another unfortunate feature of the construction work was the fact that advance of both breakwaters was not kept at the same distance to the shoreline. This seems to have been mainly due to difficulties in access to the western breakwater as a result of the 1914 upland floods which caused damage in a railway bridge. The western channel did not deepen completely until 1917 but in 1919 it was nearly 10 m deep. Adaptation of the bar and channels to the new conditions went on until 1922 when the new configuration became stable in its main features. Fig.7 reproduces the 1922 survey and shows the shipping lanes to negotiate the entrance.

Breakwater construction at Rio Grande harbour entrance had two other noteworthy effects. A deep scour hole developed around the eastern breakwater tip which eventually reached depths above 20 m. At the same time a shoal came about in the middle of the entrance which considerably reduced the available width between the breakwaters for shipping. The shoal developed in step with the scour hole, and it is believed to be formed by material from the latter. Velocity measurements carried out with floats in the late twenties sketched out the flow pattern and showed that, whereas ebb flows use the full width between the breakwaters, flood flows separate from the seaward end of the western breakwater and hug the eastern one. This flow concentration along the seaward end of the eastern breakwater is believed to be the main cause of the scour hole However, both the scour hole and the middle shoal eventually reached equilibrium. To this day the shipping lane in the shelter of the breakwaters runs between the middle shoal and the western breakwater

The other outstanding effect was beach accretion on both sides of the breakwaters although accretion on the western side was much greater than on the eastern side. Accretion on the western side was very fast shortly after breakwater construction. It amounted to a 200 m shoreline advance over a great length and went as far as Cassino beach some 6 km west of the western breakwater. Later on, the accretion slowed down and the shoreline on both sides seems to have reached a new equilibrium. Fig. 8 shows the shoreline position on both sides of the breakwaters in 1911, 1919, 1922, 1950 and 1956. Lack of adequate data on beach profiles and boundaries in plan and elevation precludes a cubature of this accretion

The outer portion of Canal do Norte was also considerably deepened by breakwater construction.

## III) The Situation after Breakwater Construction.

The main outlines of the bed configuration that came about as a result of breakwater construction are fairly stable since the early twenties. The main features are the outer bar, the two 8 to 10 m deep approach channels between the bar and the breakwater tips compelling the ships to follow tight curves around the latter, the scour hole around the eastern breakwater seaward end, the middle shoal and the deep, wide Canal do Norte.

As already seen the controlling depth in the two outer approach channels fluctuates between 8 and 10 m. The depth over the top of the outer bar fluctuates between 5 and 6 m. However, in terms of volume the outer bar is far from stable, annual fluctuations of over 1 million cubic metres in a year having been detected There is evidence to the effect that the volume of the bar is very sensitive to yearly changes of the natural forces at play. On the other hand, no correlation can be found between the volume of the bar and the controlling depth in either of the two approach channels.

The annual changes in volume of the bar have ranged from

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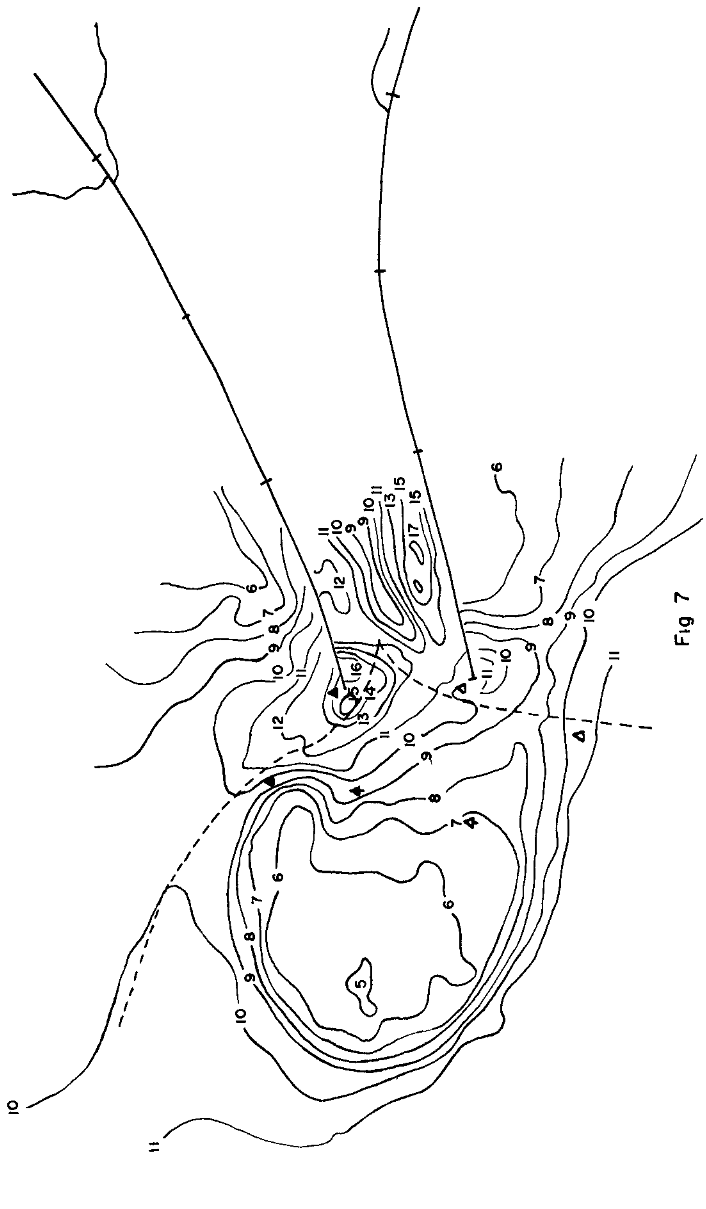


Fig 7
BED CONFIGURATION
IN 1922
Scale 1 20000

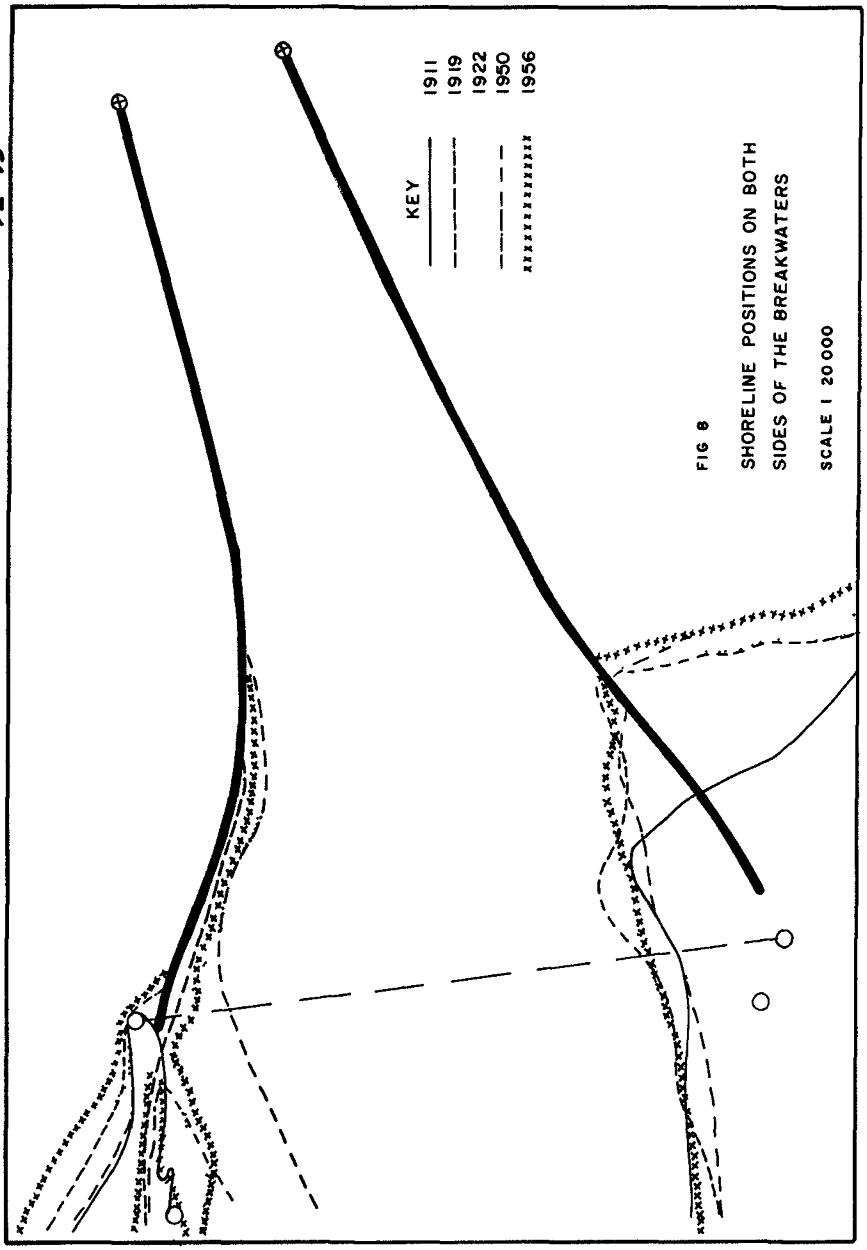


FIG 8
SHORELINE POSITIONS ON BOTH SIDES OF THE BREAKWATERS
SCALE 1 20000

2.000 m3 (1952-53) and 1 264 000 m3 (1929-1930) for accretion, and from 58 000 m3 (1931-32) to 1 238 000 m3 (1926-27) for erosion.

An important event that took place after breakwater construction was the great upland flow in April-May 1941, the greatest on record. The table below lists estimated mean monthly discharges in Canal do Norte for several months in 1941 |9|.

| Month | Mean discharges ($m^3/s$) |
|---|---|
| January | 3 100 |
| February | 7 800 |
| March | 1 600 |
| April | 21 600 |
| May | 22 700 |
| June | 6 000 |
| July | 6 800 |

Surveys of Canal do Norte and the outer bar were made before and after the peak flows. Therefore, the effects of the high upland flow in April and May on the bed configuration could be readily assessed. The outer bar was displaced offshore, the - 6 m contour having moved nearly 500 m out to sea, the middle shoal was topped off, and the scour hole around the seaward end of the eastern breakwater filled up to some extent, the 18 m depth being reduced to 12 m. However, the effects of this powerful flushing action vanished in a few months.

Endless discussions were held in Brazil during the twenties and the thirties about remedial measures to improve shipping conditions at Rio Grande entrance but no action was taken. Several proposals were put forward with a view to extending the breakwaters or changing their top levels. Many modern coastal engineering concepts were not available at the time, and knowledge of the wave characteristice at the site was poor. As a result, in the light of modern ideas several of those proposals now seem ill-founded. One particular proposal |10| was bound to have disastrous effects, had it been implemented, because it was still implicitly based on the wrong assumption that, if the prevailing and dominant winds blow from NE, the dominant sand transport must be towards SW.It consisted of keeping the western breakwater as it is and extending the eastern breakwater in a curved shape.

No improvement was achieved until 1961-62 when a 12 m deep eastern approach channel was dredged in the outer bar in order to eliminate the S - shaped curves in the entrance route and provide for a greater radius of curvature which was increased to 1 400 m. No maintenance dredging was done but the total deposit in the dredged channel from January 1963 to October 1967 did not exceed 120 000 m3. In the most recent available survey (1965) the 12 m dredged depth had been reduced to 10.5 m The maximum draught presently allowed by the harbour authority is 8.8 m (29 ft). Maintenance dredging in this channel is under way at the time of writing.

The Federal and State harbour authorities now contemplate improving Rio Grande harbour entrance and deepening it to 14 m. The Coastal Division of the Hydraulics Research Institute of the Federal University of Rio Grande do Sul (IPH da UFRGS) has acted as consulting engineer to the State dock and harbour authority by giving advice as to the problems to be solved and by making recommendations. In the light of the progress in dredging technology extension of the two 4 km long breakwaters is not deemed an economical solution. A new approach channel must be set up and maintained by dredging. The radius of curvature of the eastern approach channel is to be increased to 2.500 m, and the width at the bottom to 250 m. IPH da UFRGS has proposed to carry out a fixed-bed model investigation using radio-controlled model ships to determine the most suitable lay-out of the approach channel to be dredged outside the breakwaters. However, the State dock and harbour authority has preferred not to increase the 2.500 m value so as to keep the amount of capital dredging to a minimum.

In addition to dealing with the outer-bar problems the improvement of Rio Grande harbour entrance has to cope with the middle shoal between the breakwaters. A 14 m deep shipping channel with a 250 m width at the bottom cannot be accomodated between the middle shoal and the western breakwater. A mobile-bed model investigation is to be carried out into the means to eliminate the middle shoal or reduce the amount of maintenance dredging in a channel that cuts into it.

Dredged spoils in Canal do Norte are to be pumped ashore or dumped in dyked-in disposal areas. A radioactive tracer experiment is to be carried out to check on the suitability of the dumping grounds of the material presently dredged in the harbour basin.

Deepening the approach channel to Rio Grande is inseparable from building new dock facilities on the west bank of Canal do Norte. Depths along the quays of the present port to not exceed 10 m and cannot be increased because of structural reasons.

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