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Control of Littoral Drift in Caldera Port, Costa Rica

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ABSTRACT

Caldera Port was constructed in 1981 on the coast of Costa Rica, Central America, facing to the Pacific Ocean. Ever since the beginning of operations, however, there had been a serious problem of sand transportation around the tip of breakwater, into the inner basin due to the northward longshore sand transport under the action of steady and obliquely incident waves. To prevent this situation, the existing breakwater is extended 272 meters based on results of numerical simulation done using the one-line theory. Furthermore, two additional countermeasures are also considered. One is the construction of a jetty located on the upper-side beach to reduce the rate of longshore sand transport. Another is to remove sand from the beach outside of the breakwater. This paper narrates the historical vents that occurred while implementing these these countermeasures.

Key Words: Wing-Breakwater, Longshore Sand Transport, Shoaling of Basin, Jetty
Costa Rica

1. INTRODUCTION

Costa Rica extends roughly from the latitude of 11 ° N to 8 ° N. It is a narrow country, located roughly between the longitude of 83 ° W and 86 ° W, comprising part of the Central American isthmus. Costa Rica is bordered on the north by Nicaragua, on the south by Panama, on the west by the Pacific Ocean and on the east by the Atlantic Ocean. Its minimum width from the Pacific Ocean to the Atlantic Ocean is 119 km. In 1981, Caldera Port was constructed on the Pacific coast to be a major gateway for the international trade of Costa Rica, as well as the port nearest to the national capital, San Jose. The port began to lead the national economy and industry and support the livelihood of the Costa Rican people through commodity supply. Just after opening the port, however, one of the three berths of the port, which is the deepest and most important, became gradually shallower due to the sand sedimentation in the harbor. Since then, various technical efforts have been done for maintaining the port, through the field survey, repeated dredging of basin, extension of the breakwater, construction of a jetty and so on.

Here, the history of desperate endeavors and its result are reported.

2. NATURAL CONDITIONS AROUND CALDERA PORT

As shown in Figure 1, Caldera Port is located at the latitude of 10.4 ° N and the longitude of 84.7 ° W, and it is situated at the eastern shore of the Gulf of Nicoya, the mouth of which is open to the Pacific Ocean in the south to southwest direction. The natural conditions around the port are as follows, of which some parts are the summary of the report by JICA (Japan International Cooperation Agency) of 1986.

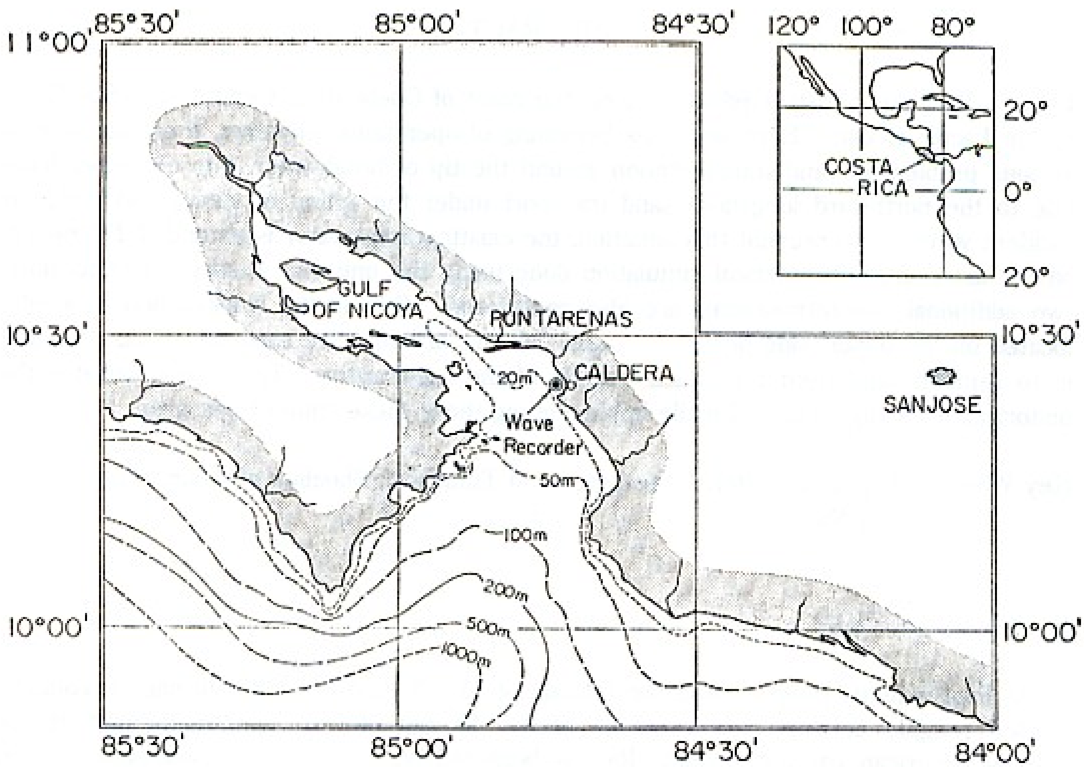

Figure 1 Location map of Caldera Port, Costa Rica (Goda, 1983) .

2.1 Wave Conditions

Waves were intermittently measured at a spot approximately 1.8 km offshore from Caldera Port, at a water depth of 15.5 meters below the datum line, during 7.3 years from June 1978 to November 1985. A total duration of wave observation was 3.3 years. According to the wave data obtained, the probability of significant wave heights between 0.5m to 1.5m is 88.3%, and that of significant wave periods longer than 10.5s is 61.6%. Using the data of the 29 waves of significant wave height greater than 1.8 meters, probable wave heights were estimated by adopting a Weibull distribution with an exponent of 1.25. The results are listed in Table 1. The significant wave period of each probable wave is estimated from the relationship between the significant wave height and the period of extremely large waves as shown in Figure 2.

Table 1 Probable wave heights.

Recurrence Period (years)	Significant Wave Height $H_{1/3}$ (m)	Significant Wave Period $T_{1/3}$ (s)
5	3.692	17.97
10	3.980	18.26
20	4.259	18.50
30	4.419	18.62
50	4.617	18.78

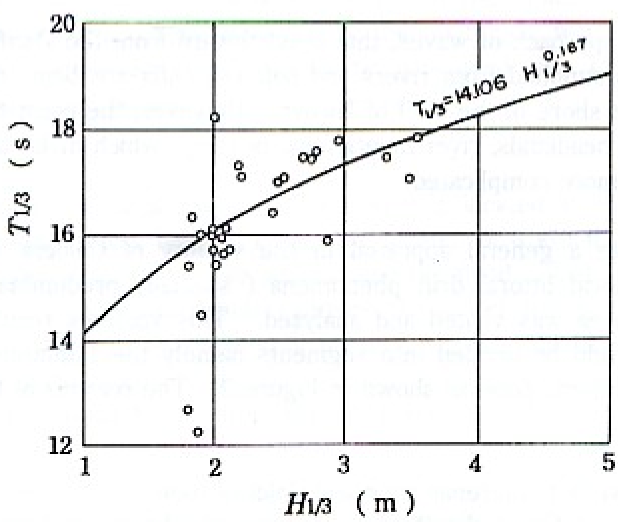

Figure 2 Relationship between significant wave height and period of large waves.

As prevailing wave periods are relatively long, the waves are swells which are coming from the Pacific Ocean through the mouth of the Gulf of Nicoya. Predominant direction of incident waves is considered to be from the SEE to the SW. In the case of extremely large waves, the significant wave period of 18s or so belongs to a quite long periodicity. By analyzing the wave data obtained in Caldera Port in May 1981 and inspecting the weather charts of the Pacific Ocean, Goda(1983) found that strong winds were blowing over the Southwest Pacific Basin which was 7000 to 9000 km far from Costa Rica, about 5 to 7 days before the coming of extremely large waves to Caldera Port. After some considerations, he concluded that the swells with such a long period were generated by strong winds in a large fetch area near the New Zealand and travelled over a long distance.

2.2 Tidal Conditions

A harmonic analysis was performed using the data obtained by means of a simple water pressure type tide gauge at Caldera Port on 15 days in October 1985. According to the result, a half day $M2$ periodic component is prevailing, while a single day component is of lesser importance. The representative tide levels were calculated with constants of the foue principal tidal harmonics. The large tidal range is 2.59 meters, the mean range is 2.05 meters, and the small range is 1.51 meters, respectively.

The results of field measurements on tidal currents in the offshore area of Caldera Port show that the northward currents during the flood and the southward currents during the ebb are prevailing, respectively. The maximum current velocities are approximately 20 cm/s in the both directions.

2.3 Conditions of Littoral Drift

Due to one way approach of waves, that is northward from the Pacific Ocean as explained above, the sands supplied from rivers and soft sea cliffs are being transported northward along the eastern shore of the Gulf of Nicoya. However, the coast line is not straight but consists of some headlands, river mouths and beaches, which make the condition of littoral drift in this area more complicated.

In order to make a general appraisal in the vicinity of Caldera Port that would help understand the local littoral drift phenomena (specially predominant directions of sand transport) the area was visited and analyzed. This analyses resulted in the conviction that the area should be divided into segments namely the Puntarenas Zone, the Caldera Zone and the Southern Zone as shown in Figure 3. The reasons of these subdivisions are as follows:

1) Boundary between Puntarenas zone and Caldera zone

(a) The foreshore slopes in the Puntarenas zone are about 3 to 5 degrees, while those on Caldera beach between Carballo Cliff and Caldera Port are about 10 degrees or more.

(b) A color of sand on the beach in the Puntarenas zone is light brown. On the other hand, on the backshore higher than the high tide level in the Caldera zone, a large amount of black sand which is heavy and magnetic is accumulated everywhere.

(c) The formation of long sand spit in the Puntarenas zone definitely indicates the

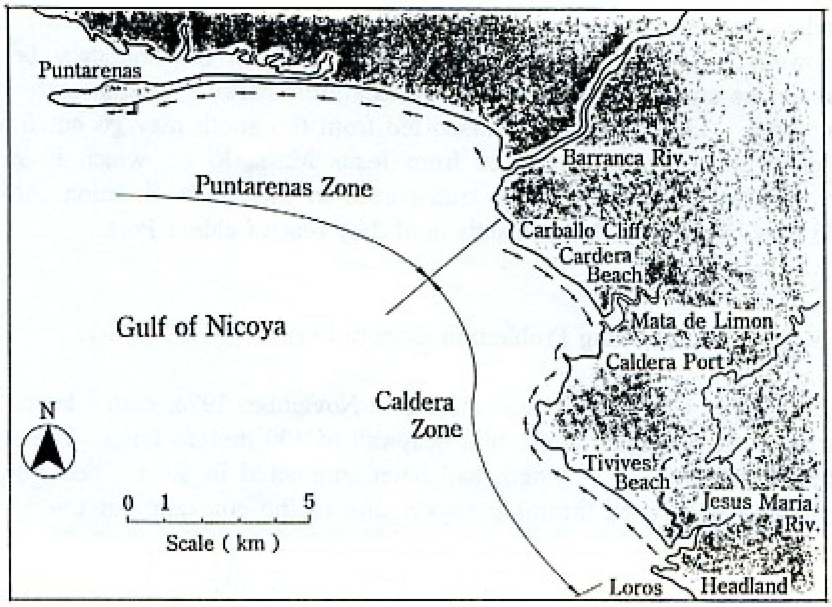

Figure 3 Littoral segments.

westward sand transport which is shown by arrows in Figure 3. On Caldera beach of about 3 km long, the mean diameter of sand is 1.0 mm near Carballo Cliff, which gradually decreases in the southeast direction to be 0.1 mm near the mouth of estuary, Mata de Limon. This change of mean diameter suggests the southeast-ward sand transport as shown by arrows in Figure 3. Then, it can be concluded that Carballo Cliff is the boundary between these two zones.

2) On long sand spit

Since the bed slope of Barranca river, whose mouth is located at the east-end of the Puntarenas zone, is very steep, being 1/160 in the stretch of 6 km from the mouth, it is supposed that the water discharge is fair amount and the flood is fast in the rainy season. Although it is very hard to quantitatively estimate the actual volume of sand discharged from this river due to a lack of information at present, we can infer that a large quantities of sediment must be discharged. Then, the sand spit of 7.5 km long is considered to have been formed with the sand discharged from Barranca river.

3) On the Carballo Cliff

The height of Carballo Cliff is about 60 meters. It consists of sands and rocks with weak interlocking. Thus, the base of the cliff can be easily eroded by the action of waves. As a matter of fact, a railway was constructed around the base of cliff in 1910. Seven years after, however, the route had to be shifted to the hinterland due to the rapid erosion. At present, the trace of railway has completely disappeared. This cliff is the source of sand to Caldera Beach.

4) Boundary between Caldera zone and southern zone

The boundary between these two zones, or the south-end of the Caldera zone, is not so clear. However, we think that Loros Headland may be the boundary between them, because it angles out into the sea and there exists the rocky shoal that extends about 300 meters offshore. Then, the sand transported from the south may go out from this point into the deep sea. Sands originated from Jesus Maria River, which is located in the south-end of the Caldera zone, are transported in the north direction through Tivives Beach and pass by small scale headlands until they reach Caldera Port.

3. Initial Stage of the Shoaling Problem in Caldera Port

The construction of Caldera Port was started in November 1974, with a landfill confined by two external jetties and one sheet pile quaywall of 490 meters long. The rubble mound breakwater of 250 meters in length had been completed in 1981 (see Figure 4). As there exists the northward littoral transport due to the constancy of the wave incidence

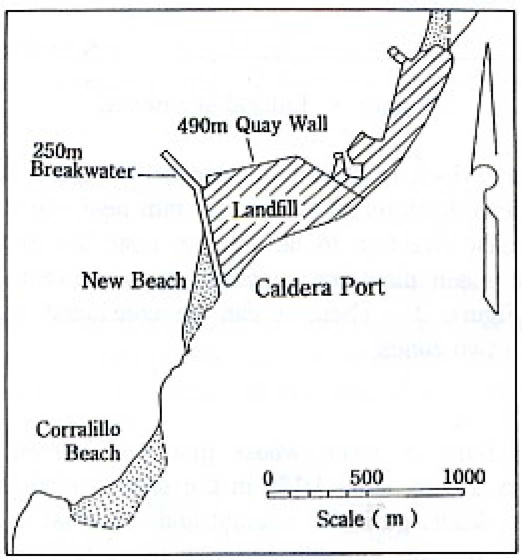

Figure 4 Caldera Port in 1981.

angle, ever since its initial construction in 1974 there has been a process of sedimentation going on at the west sea side of Caldera Port, where New Beach has been formed as seen in Photo 1. New Beach has kept growing and in 1981 the excess sand began to be transported around the tip of breakwater into the port (see Figure 5).

In order to increase the sand holding capacity of New Beach and so diminish the sand transport into the inner harbor, the Ministry of Public Works and Transports (MOPT) initiated construction of a wing-breakwater oriented 45 degrees off the main breakwater (see Figure 6). This expansion of the main breakwater was so designed as to use

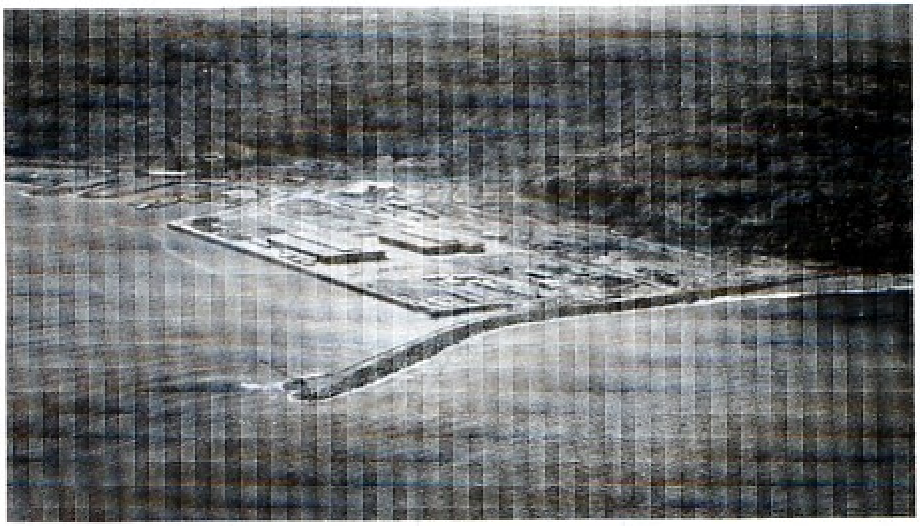

Photo 1 Caldera Port in 1981.

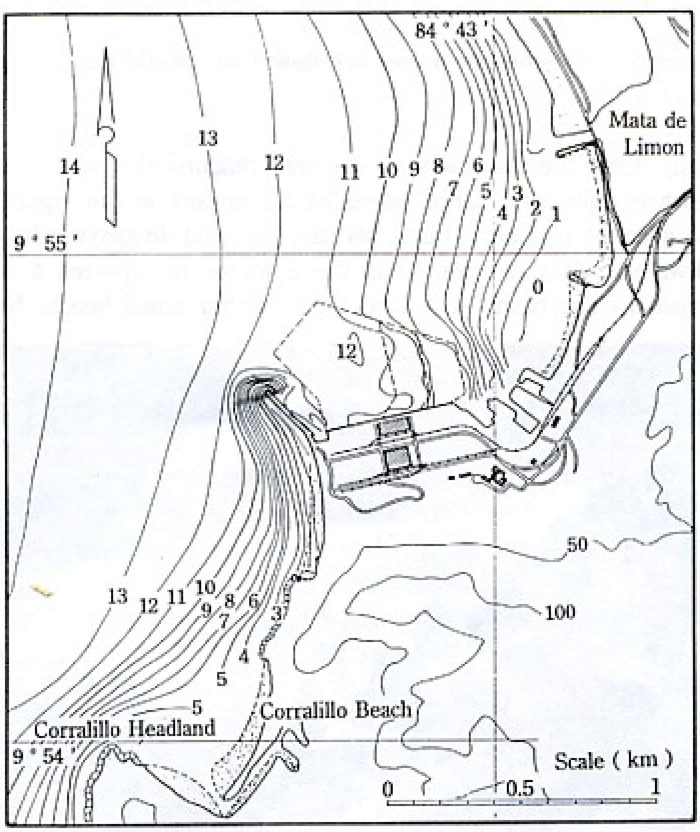

Figure 5 Topography in September 1981.

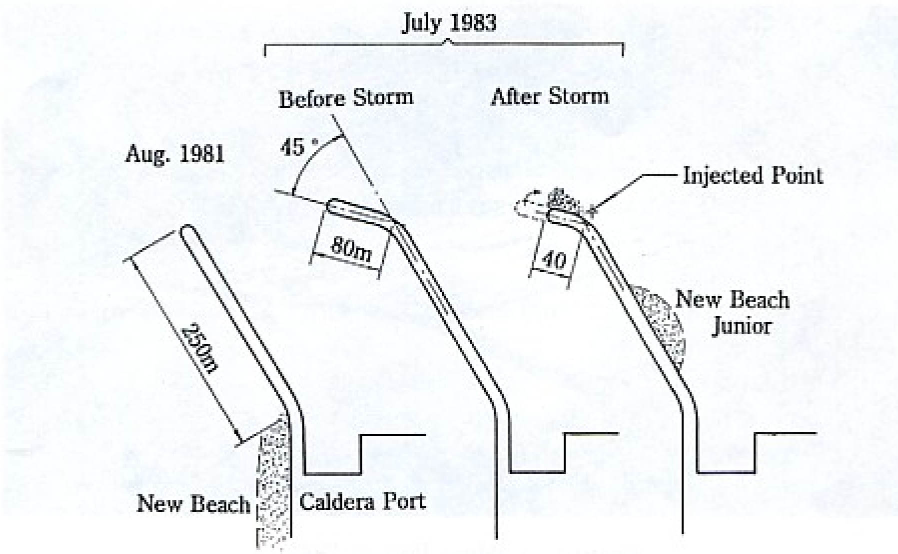

Figure 6 Wing-breakwater before and after large waves.

breaking wave energy to generate a counter flow that should delay growth at the north side of New Beach.

Beginning on July 1983 the breakwater extension reached the 80 meters long. On the 17th and the 18th of July 1983, large waves of 3.5 meters in the significant wave height and 17.5 to 18.5 seconds in a period attacked the port and destroyed the last 40 meters of the wing-breakwater. At the same time, these waves transported a large quantities of sand into the main harbor basin, which built up another small beach, New Beach Junior,

Photo 2 New Beach Junior on the 21st July 1983.

behind the breakwater as shown in Figure 6 and in Photo 2. In order to make fluorescent sand tracer, we took the sand from New Beach Junior, of which diameter is about 0.2 mm. During an attenuation of this storm, on the 26th July, when the breaking waves still diffracted and propagated along the inner side of the breakwater, we injected fluorescent sand tracers of 200 kg at the point near the base of wing-breakwater, which is indicated by an asterisk in Figure 6. On the next day, the sands were sampled from the surface of New Beach Junior. Figure 7 shows a distribution of fluorescent sand tracer, which well agreed with the topography of New Beach Junior. Then, it is inferred that the sand transported from New Beach around the tip of breakwater into the port was carried in suspension farther along the inner side of breakwater to New Beach Junior where the turbulence of diffracted waves well diminished. From here on a subsequent slow process of sand dispersion toward the first berth surely occurred. That is because the scale of New Beach Junior gradually decreased by the action of diffracted waves and disappeared by the beginning of August.

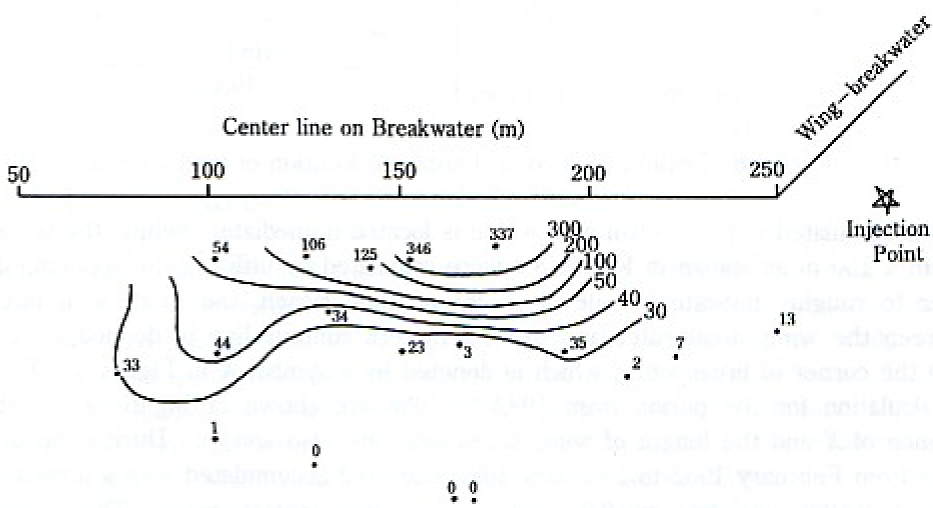

Figure 7 Distribution of fluorescent sand tracer (one day after injection).

It was urgently necessary to extend the wing-breakwater as far as possible to prevent the further shoaling in the basin. Then, MOPT continued construction of the wing-breakwater at a constant but slow pace due to the limited budgets. A slow speed of construction brought a favorable condition: the small deposits on the extension of the center line of the wing-breakwater (2 to 5 meters below mean sea level) reduced significantly the cross sectional areas to be built, when compared to the original breakwater construction depths (which were in the range of 10 to 12 meters). In spite of decreased rock volumes to be placed, construction difficulties increased due to the closeness to the wave breaking zone. Common storm waves easily scoured the breakwater foundations, which made the breakwater unstable.

In order to roughly understand the volume of sand entered into the basin, the volumes of

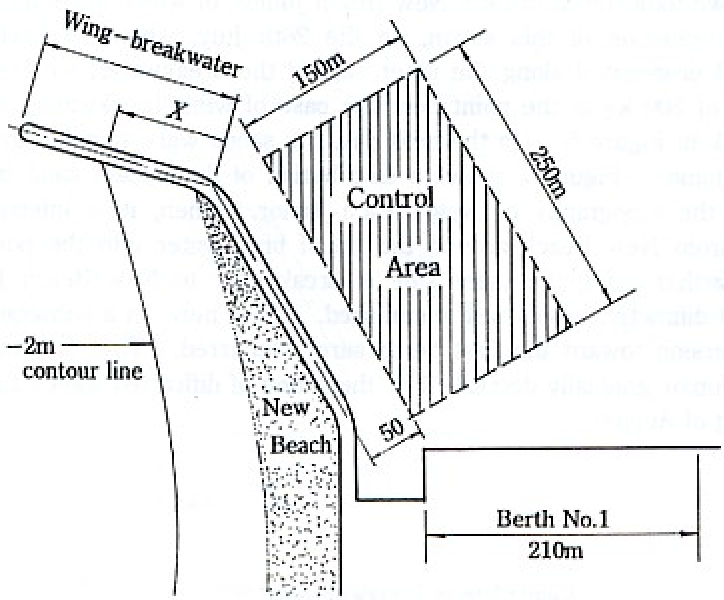

Figure 8 Definition of control area and location of intersection.

sand accumulated in the control area which is located immediately behind the breakwater (250 m x 150 m as shown in Figure 8) were calculated by utilizing the sounding data. In order to roughly indicate the development of New Beach, the location of intersection between the wing-breakwater and the −2 meters contour line is defined as a distance from the corner of breakwater, which is denoted by a symbol *X* in Figure 8. The results of calculation for the period from 1982 to 1986 are shown in Figure 9, in which the distance of *X* and the length of wing-breakwater are also shown. During the first three years from February 1982 to February 1985, the sand accumulated with a almost constant rate of 26,000 m^3/yr, or 0.7 m/m^2/yr in the control area. The extension of wing-breakwater was not very effective in preventing the sand from entering into the basin. This is due to the slow construction of the wing-breakwater, which was nearly same as the speed of advancement of −2 meters contour, as shown with a dotted line in Figure 9. In other words, the speed of New Beach developing was nearly same as that of extension of wing-breakwater.

On 13th September 1985, large waves of 2.77 meters in a significant wave height and 17.6 seconds in a period attacked this port, by which the last part of the wing-breakwater was destroyed and at the same time the sands were transported into the basin. This situation induced a loss of adequate depth for docking at the berth No.1. Then, in order to keep designed operational depths at the inner basin of the harbor, an urgent dredging was done until January 1986. A dredging volume was 30,000 m^3 in total. The second full dredging was executed during the months from March to April in 1987 for a total dredged volume of 303,000 m^3, of which 80,350 m^3 were taken from the control area.

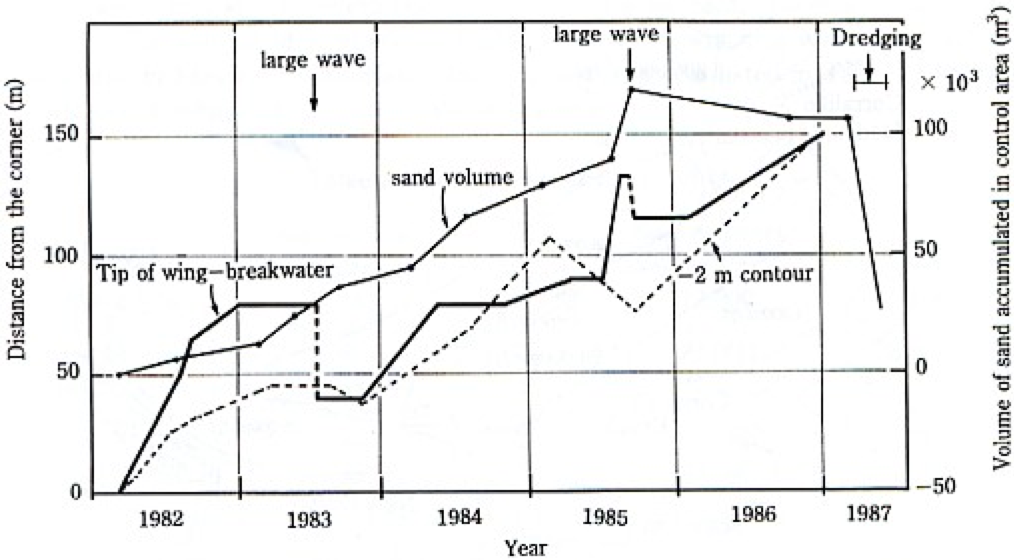

Figure 9 Volume of sand accumulated in the control area, length of wing-breakwater and location of −2 meters contour line.

4. RESULT OF FUNDAMENTAL SURVEY IN 1985

In response to the request of the Government of the Republic of Costa Rica, the Government of Japan decided to conduct a study on the maintenance project of Caldera Port and entrusted the study to JICA. A most important objective of the study was the establishment of adequate strategies to respond to the sedimentation problem. JICA send to Costa Rica a study team during a period from September to November, 1985. The study team conducted a field survey, an analysis of existing data, and numerical simulations on the littoral drift, of which result was reported in JICA Report (1986). Here, we quote important items from JICA Report, which are strongly related to the littoral drift in Caldera Port.

The budget of sand transport in the south side area of Caldera Port is estimated based on the results of soundings which have been executed repeatedly by MOPT since 1981. Figure 10 shows roughly estimated budget of sand transport in areas less than −10 meters deep. The annual northward drift sand volume offshore Corralillo Headland is estimated as 200,000 m^3/yr. Within this volume, the sand volume transported in the zone between the −5 meters and −10 meters contour lines is estimated as 88,000 m^3/yr. A sand volume of 14,000 m^3/yr accumulates at Corralillo Beach, and 98,000 m^3/yr is supplied to New Beach. Part of the sand supplied to New Beach, which is estimated as about 26,000 m^3/yr, accumulated there. The rest passes by the wing tip, goes toward the north side of the foot of the breakwater and accumulates near its foot.

According to Figure 9, it seems on the whole that the sand deposited in the control area at

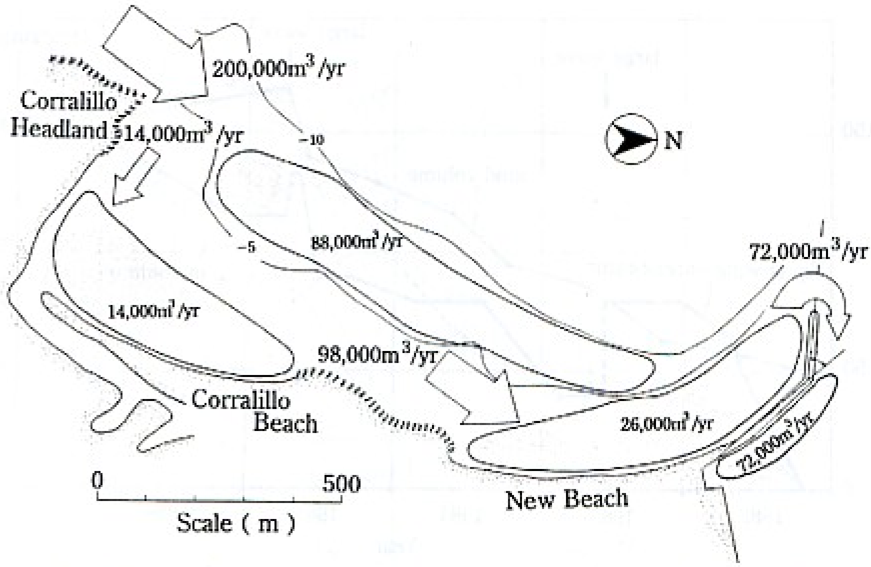

Figure 10 Budget of sand transport at the southern beach of Caldera Port.

a constant rate, being independent of the extension of wing-breakwater. However, it is noticed that rate of sand deposition changed a little from period to period. The volume of sand going into the basin in a short period depends on the relative relation between the sand volume stored in the out side area of port and the location of wing tip. Figure 11 shows the extension progress and the location of −2 meters contour line which is utilized as an indicator for the sand volume stored in the outside area, for the years from 1980 to 1985. From this figure, the distance, *D*, from the wing tip to the intersection of the

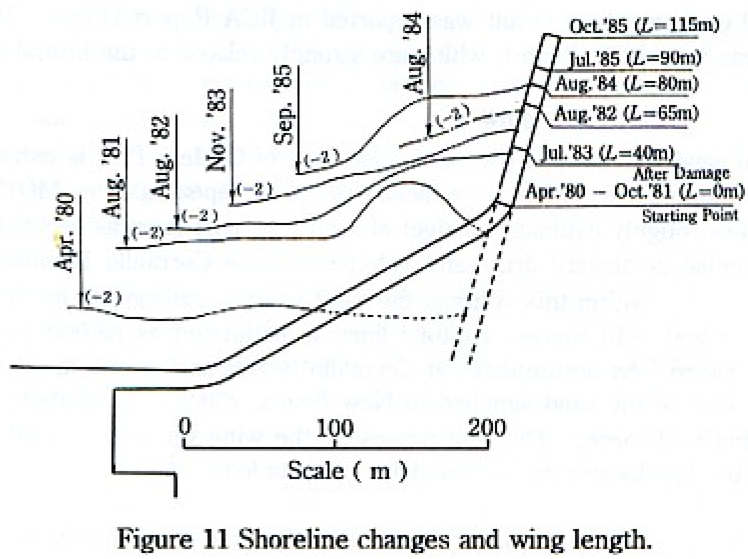

Figure 11 Shoreline changes and wing length.

wing-breakwater and −2 meters contour lines is read for each, of which result is listed in Table 2. The volume of sand accumulated in the basin, which is wider than the area of control area in Figure 7, is calculated for each term and also listed in Table 2, where Q_s is the equivalent volume of sand accumulated in a year.

Table 2 Relation between D and Q_s.

Period	Length of Wing-breakwater (m)	D (m)	Sand Sediment Volume (m^3)	Q_s (m^3/ year)
1980. 4−1981.10	0	45 *2 (Average)	12,000	8,000
1981.10−1982. 7	65	25	21,000	28,000
1982. 7−1983. 8	65 *1 (During damage)	15	40,250	37,000
1983. 8−1984. 8	80	20	24,125	24,000
1984. 8−1985. 9	90	10	94,500 *3	87,000

*1 The length of wing during damage in July 1983 is assumed as 65 meters.
*2 D in 1984.4−1981.10 is assumed as an average value.
*3 This value includes the dredged sand volume.

Figure 12 shows the relation between D and Q_s, which shows that Q_s is depending on D. When D is more than 60 meters, the value of Q_s is zero. If D becomes shorter, then Q_s becomes greater. Finally, Q_s approaches asymptotically to 112,000 m^3/yr, that is the sum of the littoral drift volume at Corralillo Beach and New Beach (see Figure 10). Therefore, under the situation of continuous accumulation of sand in the upper beach, the distance D gradually becomes shorter with time, which brings the undesirable condition; namely that the sand volume of more than 100,000 m^3/yr enters into the basin and deposits there in future. In any case, it is clear that countermeasures must be taken against the sand accumulation in Caldera Port, that is, extension of wing-breakwater or

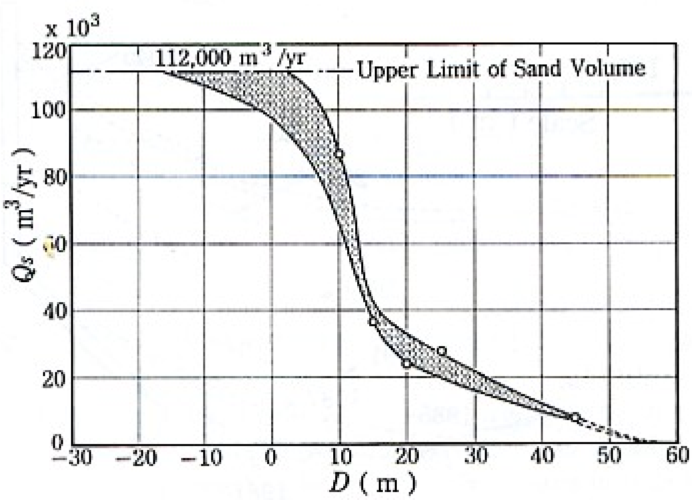

Figure 12 Relation between D and Q_s.

continuous dredging in the basin, or their combination.

If the wing is extended enough in length, the maintenance dredging will not be necessary. The construction cost of breakwater, however, is very high. On the other hand, no extension of wing costs nothing, but the cost of maintenance dredging becomes high. Then, an optimum extension length must be so determined as to minimize the total cost of construction and dredging. For this purpose, the one-line theory was applied. First of all, it was confirmed that the actual shoreline changes and the calculated ones on New Beach and Corralillo Beach were quite similar for the period from September 1981 to September 1985, in which the sand budget shown in Figure 10 was taken into consideration. In this calculation, the shoreline was defined as the contour line of D.L.+1.4 meters. Next, by utilizing the same theory, the further estimations of shoreline change and volume of sand deposited in the basin of Caldera Port were carried out for several cases of varying extension length of the wing-breakwater.

The usual one-line theory can hardly predict the volume of sand which is transported around the wing tip into the basin. Here, however, a smart method of utilizing Figure 12 made it possible to predict it as follow. At first, the location of shoreline on New Beach was calculated by the usual one-line theory. Next, the location of −2 meters contour line was estimated by assuming from the result of data analysis that it is always 68 meters offshore from the shoreline, D.L.+1.4 meters, near the wing−breakwater. When the distance *D* becomes less than 60 meters, the sand volume which enters into the basin is evaluated from Figure 12. The resultant shoreline is calculated by taking the annual sand volume (Q_s) into consideration. As the distance, *D*, becomes shorter and Q_s increases with time, this treatment is repeated in every calculation step. Figure 13 shows the result of prediction for the case of 350 meters in total wing length as a typical example. As seen

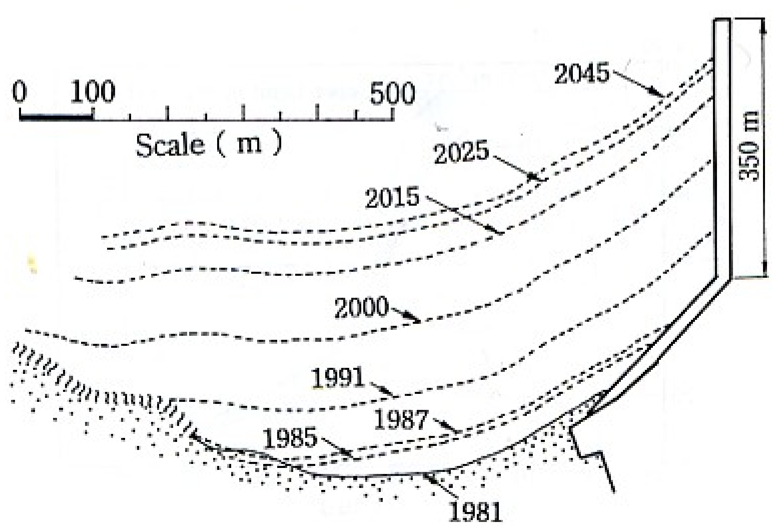

Figure 13 Predicted future shoreline (Wing length = 350 m).

in this figure, the annual shoreline advance rate in the early stage is 7m/yr. It becomes less in the latter because the water depth gradually becomes deeper and also the sand volume going around the wing tip into the basin becomes larger with the advancing of shoreline.

Now, costs are estimated assuming the most reasonable procedures for the wing construction and the dredging for each extension length. In the estimation of dredging cost, not only the dredging of sand coming around the wing tip, but also a primary dredging of sand deposited before 1985 and the usual maintenance dredging every five years are included. The maintenance dredging in the entire basin is necessary because very fine material, being about less than 0.1 mm in diameter, is being accumulated at the rate of 12 to 16 cm/yr. The transport of this fine material is mostly due to tidal currents. Figure 14 shows the wing construction costs, the dredging costs and the total costs of each wing length over the lifetime of 30 years, including the case where the wing-breakwater is not extended at all. From this figure, it is decided that the most economical countermeasure against sand deposition in the basin is to extend the wing-breakwater by a length of 350 meters in total. It is also confirmed in the simulation that the wing extension does not significantly influence on the counter movement of sand from the north side beach, Caldera Beach, into the basin.

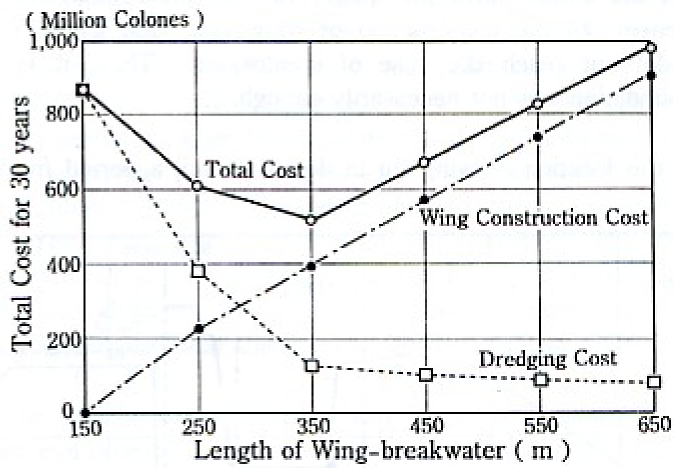

Figure 14 Cost comparison of each wing length.

5. EXTENSION OF WING–BREAKWATER AND OTHER COUNTERMEASURES

According to JICA Report in 1986, two works were urgently required for Caldera Port. One was a primary dredging in order to extract sand which had already deposited. Another was an extension of the wing-breakwater up to be 350 meters in total length. During the first months of 1987, a maintenance dredging program was completed satisfactorily. At this time, the wing of 150 meters in length had been already constructed (see Figure 9), but the distance D was nearly zero. Then, the extension of wing-breakwater for 200 meters more had to be done as soon as possible. However, as financial prospects for a maintenance for Caldera Port turned meager due to the political and economical difficulties, MOPT eas forced to tackle the construction job for the 200 meters of additional length for the wing on its own, with the reduced resources of the ordinary budget and with old equipments in bad condition.

Figure 15 shows the location of the wing tip during a period from 1987 to 1992. The location of −2 meters counter line is also shown as well as the volume of sand deposited in the control area. As seen in this figure, the extension rate was almost constant, but it was very slow. Only 275 meters reach of wing had been constructed by 1992, which is 75 meters shorter than the target length. Furthermore, the location of wing tip retreated often, which was due to accidents with rubble stones that were scattered to the inside by actions of large waves because the weight of armor stone was too light to overcome the large waves. According to JICA Report (1986), the design weight of armor stone is 17 tons and, particularly for the head of wing, the stones used should be no less than 25 tons in weight. In actuality however the weight of the stones used for construction was 6 to 8 tons. There were large stones more than 20 tons in a quarry and a construction crane on the breakwater had enough capacity for lifting them. However, a loading capacity of trucks which transported the stones from the quarry to the construction site were 8 tons in maximum. Moreover, as the construction of wing was done from its crown, the arm length of crane did not reach the base of breakwater. Then, it is inferred that an execution of its foundation was not necessarily enough.

Figure 16 shows the location of wing tip in detail, during a period from May to August

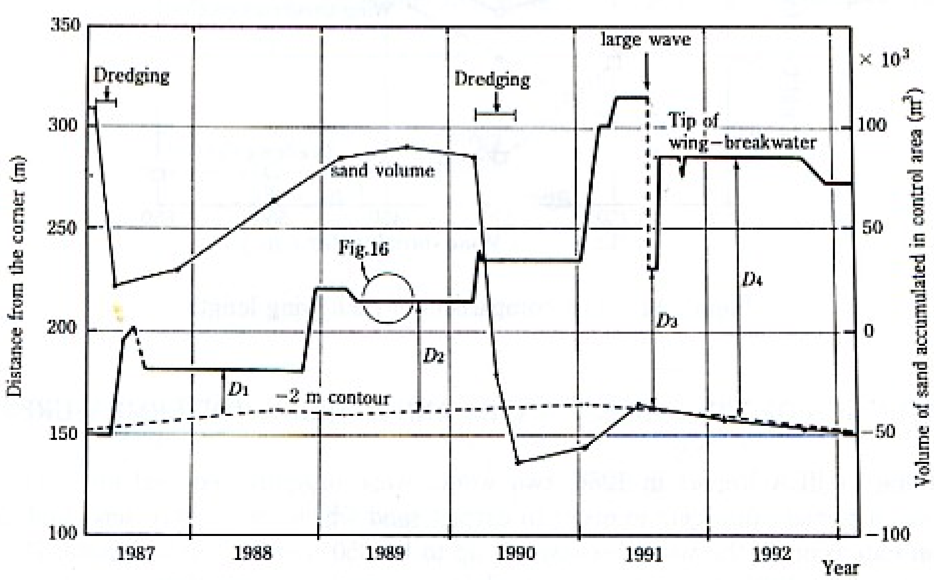

Figure 15 Changes of wing tip location (from 1987 to 1992).

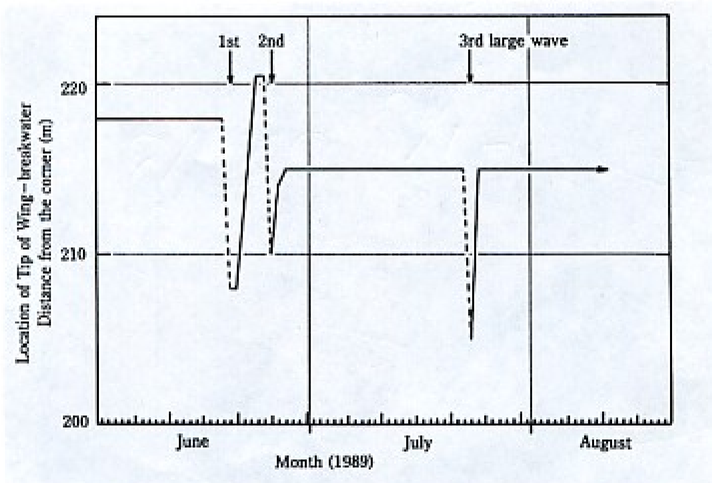

Figure 16 Changes of wing tip location (from May to August 1987).

1987. On the upper side, the days when large waves came are indicated by arrows. At first the large waves came on the day of 18th June, Sunday, by which the rubble stones in the crown of breakwater above L.W.L. and within 10 meters from the wing tip were scattered into the lee side area. As the lower part of wing was still remained, the destroyed part was quickly restored to the former condition and extended a little more by putting other stones on the top. However, the second waves came on the day of 25th June, Sunday, and destroyed again the 12 meters from the wing tip. On the next day, the part of destroyed reach was restored again. Moreover, another large waves came on the day of 23rd July, Sunday, which destroyed the further 10 meters from the wing tip. Also in this case, the restoration work was done on the next day. The fight against the large waves was similar to an ant fighting an elephant. Beside, it is only known that the large waves were long period waves. There is no further information on these waves, because no wave gauge was installed near Caldera Port and every large waves came on Sunday.

The wave on the days of 27th, Saturday, and 28th, Sunday, July were extremely large. According to an eyewitness, a large overtopping occurred over the wing in the reach of about 100 meters from the wing tip. The rubble stones located 85 meters from the wing tip and above L.W.L. were scattered into the lee side area. Also in this disaster, a reach of 56 meters was restored with other stones in a short period. The total length of wing is 272 meters at present (see Photo 3).

As seen in Figure 15 again, the distance from the wing tip to the −2 meters contour line, D_1, was about 20 meters in 1987 and 1988. Under this situation, the sand of bout 64,000 m^3 in volume had been deposited in the control area by the beginning of 1989. The large waves came three times during months from June to July 1989, which transported sand into the port around the tip and made New Beach Junior again just behind the breakwater. However, the distance, D_2, was about 50 meters due to the extension works

Photo 3 Wing–breakwater in 1993.

of wing in 1989. In this conditions, the sand deposition in the control area did not take place. Apart from this preferable situation, as the extension speed of the wing was slow, the sand already accumulated in the basin until 1989. Then, a third full dredging program was carried out in the whole area of basin during the period from March to June in 1990. On this occasion an over–dredging job was accomplished to create a sand trap in the control area with a maximum depth of 16.8 meters. The net dredged volume was about 300,000 m^3, of which 150,000 m^3 were taken from the control area.

In the first half of 1991, the wing was extended 80 meters more from 235 meters to 315 meters in length at a high pace. In July 1991, however, almost full length of newly extended reach was destroyed by very large waves. Although the distance from the wing tip to −2 meters contour line, D_3 in Figure 15, was still about 60 meters, some volume of sand deposited in the control area since the waves were too large. Immediate reconstruction extended the wing to 286 meters, which made the distance, D_4, longer to be 125 meters. After that, in the second half of 1991 and in 1992 there was some erosion in the control area.

Furthermore, the location of −2 meters contour line near the wing retreated onshore as seen in Figure 15. This retreat of the beach is considered to be due to a local counter flow in the southward direction generated by the waves reflected by the the wing. This situation is welcome for reducing the volume of sand transported around the wing tip into the basin. However, we must keep in mind the undesirable possibility that a local scouring at the toe of wing–breakwater may occur in the neighborhood of the tip, which will require us to reinforce the toe of wing for its safety.

As the extension speed of wing was slow and the existing length was still shorter than the designed length, two more countermeasures have been considered. One is the

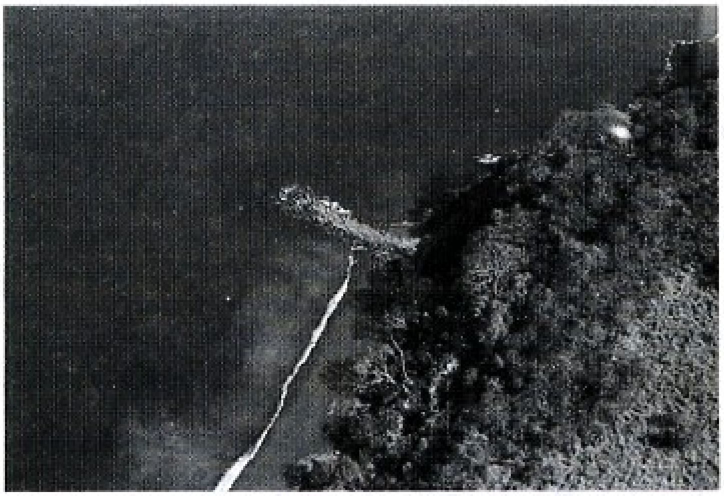

Photo 4 Small jetty located between New Beach and Corralillo Beach.

construction of new jetty at the upper side of the littoral drift. Another is direct sand extraction from New Beach.

It is also effective to construct a new jetty at the upper side of the littoral drift. The most effective location for this construction is at Corralillo Headland (see Figure 10). However, there is no approach road for the jetty construction there. Temporary works such as the construction of an approach road would be very expensive. Construction of the new jetty from the sea using a construction ship would also be very expensive. Moreover, as you can easily infer from the coastline configuration shown in Figure 3, the wave energy concentrates to Corralillo Headland. The design cross section of the jetty should be as same as that of the wing or more. Then, as the second best location, the new jetty of 90 meters long was constructed on a rocky reef located between New Beach and Corralillo Beach in 1990 (see Photo 4). The jetty could be designed with smaller size rock than that used for the wing by virtue of diffracted small waves. An effect of this jetty has emerged as an advancement of the shoreline on Corralillo Beach (in the foreground in Photo 4). However, its efficiency is not enough, because some of the drift sand is supplied from the offshore of Corralillo Headland to New Beach directly as shown in Figure 10.

Removing the sand at the seashore of New Beach is also an effective way to prevent sedimentation in the harbour. As a complementary step, sand removing by a private industry has been done at New Beach with the objective of reducing its growth. In spite of the small grain size of these sands (d_{50} = 0.2 mm), which makes them of a little use for developers and builders, mean extracted volumes of 3,400 m^3 /month have been noted since 1992. A system of sand extraction is very simple and requires no special machinery. The sand is scraped up to the higher level by bulldozing at the low tide. Because the

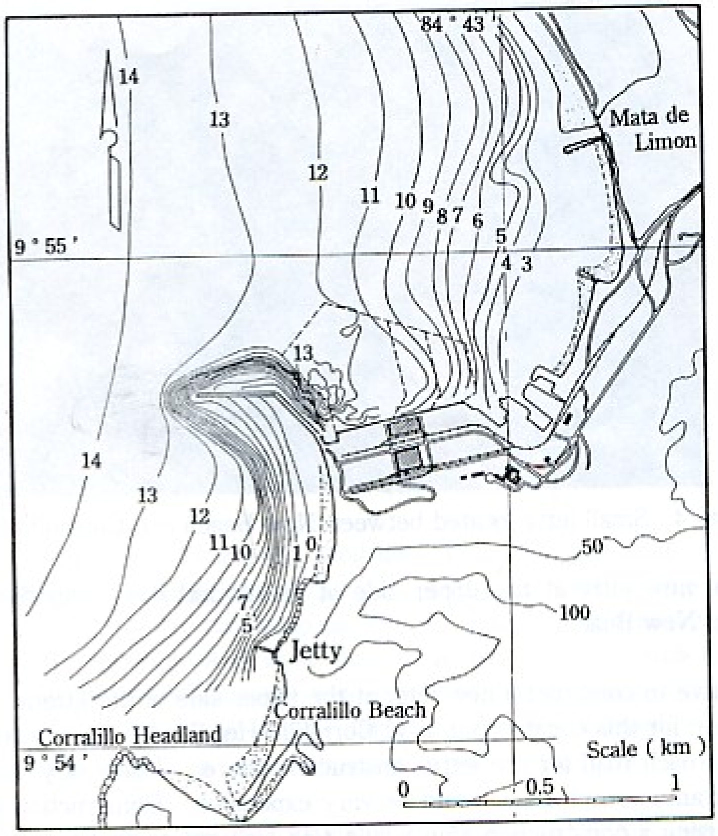

Figure 17 Topography in February 1993.

sand accumulates again during the successive high tide, the process can be continuously done by this simple system.

Figure 17 is a contour map of topography in February 1993. A depositional topography is noticed in a north side area of wing-breakwater, where the rubble stones scattered from the wing were settled due to the repeated disasters and no dredging was conducted in the past. The sand trap topography in the control area, which was formed by over dredging in 1993, is almost unchanged. The sand deposition is not recognized on the basin in front of berth. In short, since February 1992 no shoaling has been detected in the basin, which means that the combination of three kinds of countermeasure is helpful to prevent the further entering of sand into the basin of Caldera Port.

6. SUMMARY AND CONCLUSIONS

Since its completion in 1981, Caldera Port has been exposed to a serious matter of sand sedimentation in the basin, which is due to the northward littoral drift of about 200,000 m^3/yr by the predominant waves in obliquly incident. To prevent this situation, the extension of wing-breakwater started. According to the result of numerical predictions by the one-line theory, the optimum length of wing-breakwater was 350 meters. However, due to lack of funding, the extension works of wing were done at a slow pace with old equipments in bad condition. The wing was repeatedly destroyed by the large long waves of about 18 seconds in period. At present, the wing has been reconstructed up to be 272 meters in length, which is considered to be not long enough for the near future. Then, other two countermeasures have also been considered to reduce the volume of sand transported into the basin. One is the construction of jetty at the up-side of littoral drift, another is to take sand from New Beach. The latest results of topographic monitoring show that the combination of these three kinds of countermeasure is helpful in preventing further sedimentation in the port.

The valuable experiences piled through the fight against the littoral drift problem in Caldera Port are of fundamental importance. These can be enumerated as follows:

(1) The phenomena of littoral drift are very complicated, so there is very much left to study. The result of sand movement, however, is exceedingly simple, that is to say, either there is resulting erosion or deposition. Then, in order to sufficiently grasp the result of sand movement, it is basically important to monitor the change of topography by conducting repeated sounding survey. In the case of Caldera Port, sounding surveys has been carried out with a high frequency since 1981. Especially the data accumulated by 1985 were very helpful for improving the accuracy of numerical simulation.
(2) An effect of countermeasures for the littoral drift doesn't always appear soon. Then, there is a possibility of making an incorrect decision and taking the haphazard way of doing them. In order to avoid this kind of mistake, it is of importance to examine thoroughly the effect of countermeasures on the topography in advance by a scientific method such as the one-line theory. It is also kept in mind that quantitative predictions of topographical changes are still difficult at present due to the multiplicity and high level of complexity of the various processes involved. To make up for this deficiency, the effect of countermeasures must be followed and checked in the field at regular intervals, during and after their the execution.

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