JICA

THE ADDITIONAL STUDY ON COASTAL PROTECTION AND PORT IMPROVEMENT IN THE COOK ISLANDS

FINAL REPORT

SEPTEMBER 1994

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JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE OFFICE OF THE PRIME MINISTER
THE COOK ISLANDS

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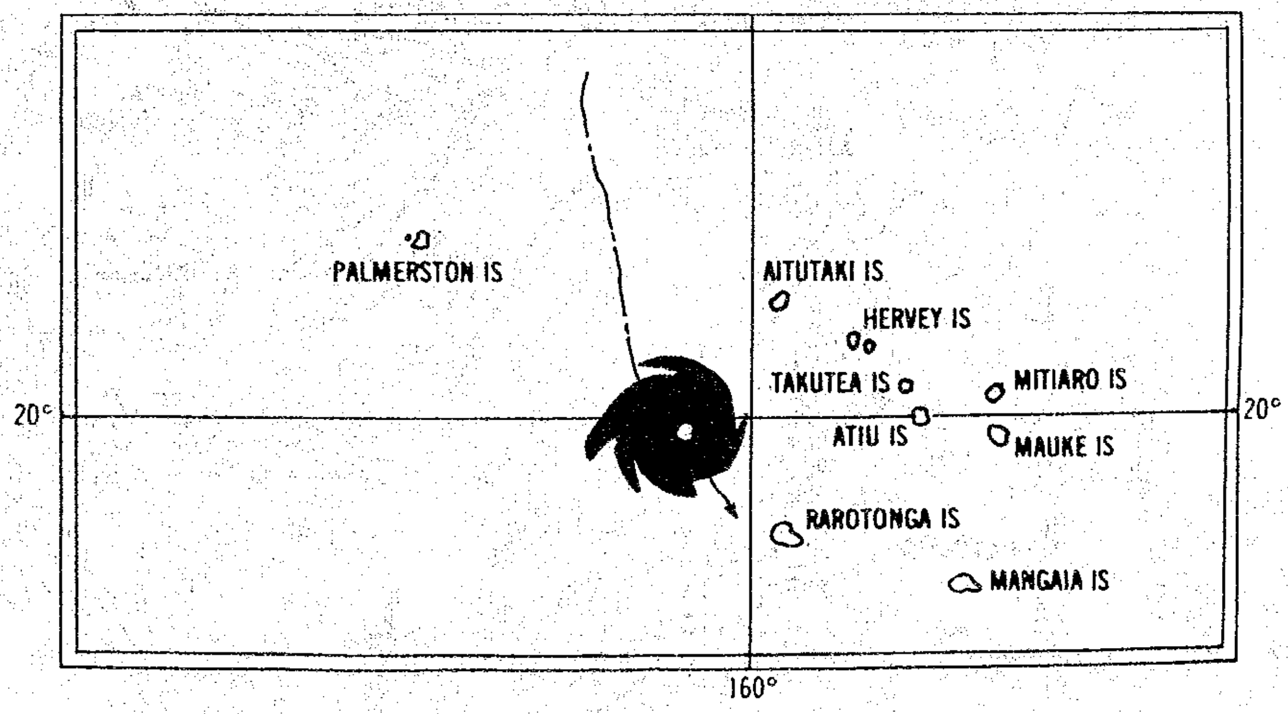

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PACIFIC CONSULTANTS INTERNATIONAL

THE OVERSEAS COASTAL AREA DEVELOPMENT INSTITUTE OF JAPAN

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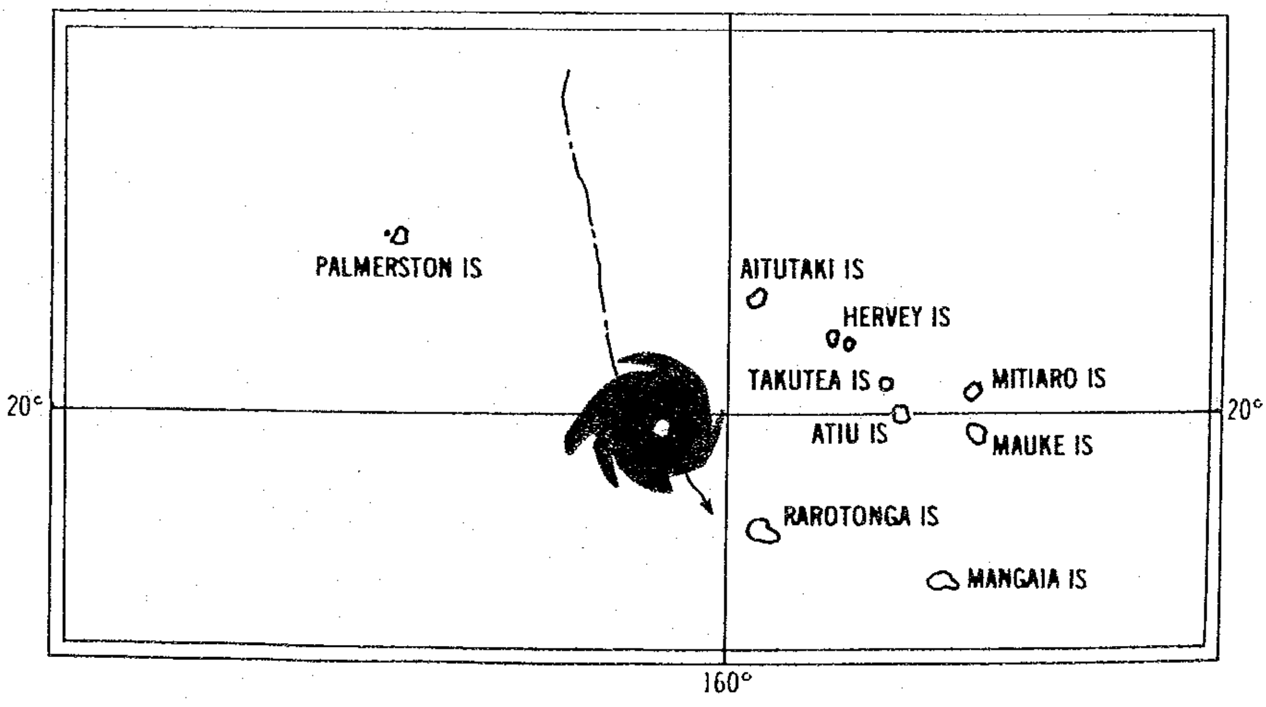

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(as of October 1993)

PREFACE

In response to a request from the Government of the Cook Islands, the Government of Japan decided to conduct an additional study on Coastal Protection and Port Improvement and entrusted the study to the Japan International Cooperation Agency (JICA).

JICA sent to the Cook Islands a study team headed by Mr. Nobuo Endo, and composed of members from Pacific Consultants International Co. Ltd., and the Overseas Coastal Development Institute of Japan from October 1993 to December 1993.

The team held discussions with the officials concerned of the Government of the Cook Islands, and conducted a field survey at the study area. After the team returned to Japan, further studies were made and the present report was prepared.

I wish to express my sincere appreciation to the officials concerned of the Government of the Cook Islands for their close cooperation extended to the team.

September 1994

Kimio Fujita

Kimio Fujita
President
Japan International Cooperation Agency

LETTER OF TRANSMITTAL

September 1994

Mr. Kimio Fujita
President
Japan International Cooperation Agency

Dear Mr. Fujita,

It is my pleasure to submit herewith the Final Report for the Additional Study on Coastal Protection and Port Improvement in the Cook Islands.

The report is the result of the additional study, to supplement the previous study conducted in 1992, carried out by Pacific Consultants International (PCI) and the Overseas Coastal Area Development Institute of Japan (OCDI) as per the contract with the Japan International Cooperation Agency (JICA). The study team conducted a field survey between October and December 1993.

Based on the findings of the survey and on data and information collected and analyzed in Japan, the master plan formulated by the previous study team was reviewed and up-dated concentrating mainly on hurricane sea protection on the northern coast of Rarotonga Island including a feasibility study.

The study shows that the implementation of the coastal protection works as proposed in the master plan does not seem to be feasible, however, selective protection works would be recommended in order to protect national and private assets.

On behalf of the study team, let me express my heartfelt thanks for the generous cooperation, assistance and warm hospitality extended to the study team during their stay in the Cook Islands.

Our thanks are also due to the Japan International Cooperation Agency, the Ministry of Foreign Affairs, Ministry of Construction, Ministry of Transport and Japanese Embassy in New Zealand for their valuable advice and support during the field survey and preparation of this report.

Yours faithfully,

Nobuo Endo
Leader
Japanese Study Team for
the Additional Study on Coastal Protection
and Port Improvement in the Cook Islands
(General Manager,
Pacific Consultants International)

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1. EXECUTIVE SUMMARY

1.1 Background

The northern coast of Rarotonga Island is a hurricane-fated area. Recently cyclones hit the area and brought about disastrous damages; Sally in 1987, Sini and Peni in 1990 and Val in 1991.

Nevertheless, the area will remain the commercial and political center of The Cook Islands. Many private assets and public facilities are concentrated there. Among others, Avatiu Port handling all the in-and-out-bound cargoes of the country and Rarotonga Airport accommodating B-747 between Los Angels and Auckland are vital. The importance of the area is increasing as the island economy will depend more on the tourism industry in future.

The Government of The Cook Islands is desirous, therefore, to protect the northern coast of Rarotonga Island from "a hurricane which probably occurs once in 100 years".

JICA had previously conducted several studies on the coastal protection and port development of Rarotonga Island. This time, however, JICA study focused on the estimation of the sea state probably caused by a hurricane sea state of 100-year return period on the northern coast of Rarotonga and the preliminary design for the coastal protection works against such a sea state.

1.2 Conclusions

<u>Hurricane Sea State for a 100-Year Return Period</u>

It is at the beginning of the additional study, that the Cook Islands Government requested in its policy paper that design waves with a return period in the order of 100 years should be used for engineering design purposes. As this is the policy of the government, the additional study was conducted for the 100-year-return-period-waves. In the previous study, the design waves were those which are hindcast during Cyclone "Sally" which were estimated to be about 30-year-return-period-waves.

The design wave and water level are estimated in the following steps:

- A100-year significant wave height on the northern coast of Rarotonga is estimated after Kirk (1992), extraction of which was provided by a local coastal consultant, and the corresponding wave period is forecast by means of Wilson's Method.

- The wave direction is assumed to be the north which is most dangerous to the project site.

- The water level for a hurricane sea state of a 100-year return period is expressed as an addition of the maximum spring tide level, the sea water level rise by the reduction of atmospheric pressure, the wind set-up generated by the wind during a 100-year recurrence interval hurricane, the wave set-up given by a theoretical model study, and the surf beat calculated by an empirical equation.

- The computer model with two parameters is developed to estimate the wave height and wave set-up on a coastal lagoon and the wave run-up on a beach slope or a sloping revetment. The most likely value of these parameters in the model is determined by simulating the wave height and wave run-up height to the observed facts during Cyclone Sally.

The calculation results indicate that the sea state of a 100-year return period will bring a serious damage to the northern coast. The sea state is summarized in Table 1-1.

Coastal Protection Works Required for Protecting the Coast from the Hurricane Sea State for a 100-Year Return Period

Based on the above results, the works to protect the northern coast from the hurricane sea state of a 100-year return period are worked out. The criterion for permissible wave over-topping volume is set forth to be 0.05 $m^3/m/sec$. In Japanese Standard Design Criteria of coastal protection works, the wave over-topping of this value does not result in damages onto unpaved shore protection dike.

According to the technical knowledge at present, the combination of artificial wave dissipating concrete blocks, rocks and concrete sea wall seems to be only solution as to provide the protection against such sea state.

From an engineering point of view, it is extremely difficult to protect the coast from the hurricane sea state of a 100-year return period by fulfilling all the objectives of the policy of the Cook Islands Government; particularly with respect to preservation of the scenic value of the natural shorelines.

The summary of the likely coastal protection works is tabulated in Table 1-2.

Economic Feasibility of the Coastal Protection Works for Protecting the Coast from the Hurricane Sea State for a 100-Year Period

A very rough cost estimate shows that the protection works of the northern coast of Rarotonga Island against the 100-year sea state will cost the Cook Islands Government about NZ$209,000,000. A very preliminary economic analysis indicates that the economic internal rate of return of the coastal protection works will be very low, i.e. about 1.11 % and the coastal protection of its full scale is not viable from the economical point of view.

1.3 Recommendations

Selective Protection Works

As the full scale development of the coastal protection works seems not economically viable, selective protection is recommended; particularly Avatiu Port, the airport runway and the fuel tanks must be properly protected since these facilities are vital for the Cook Islands' economy.

Relocation of Important Assets on the Northern Coast

As the coastal protection works are very expensive, it is recommendable for the Cook Islands Government to consider the relocation of important assets like fuel depots to inland.

For other private assets it is recommended for the government to financially assist the people in relocating or protecting them from the hurricane sea state.

Newly Innovated Coastal Protection Units

With regards to the newly innovated concrete units, which the Cook Islands Government considers to apply to the coastal protection of the northern coast of Rarotonga Island, it is recommended that a scale model testing be carried out at first by means of a water tank and then, when the scale model testing shows successful results, a prototype model testing be carried out at the actual site in order to collect engineering data and establish the construction specifications therefor.

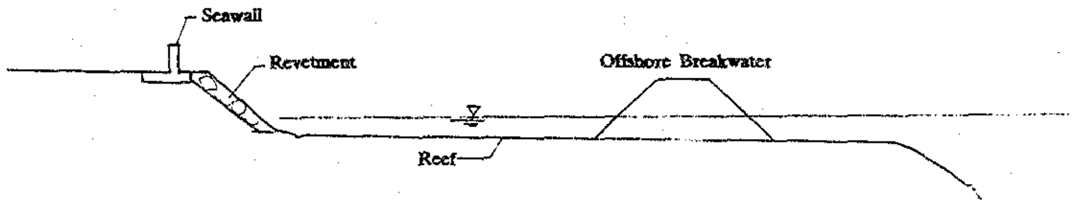
Table 1-1 Sea State of a 100-Year Return Period Hurricane

Offshore Wave: Wave Height $H_{1/3}$ = 12.0 m
Wave Period $T_{1/3}$ = 13.5 sec

Location	at Airport Runway Section 5-4	at Parliament Bldg. Section 4-3	at TPP Fuel Depot Section 3-6	at Westpac Bank Section 2-2	at Banana Court Section 2-1	at Beachcomber Section 1-9	at Health Department Section 1-2
Ground Elevation	+3.90 m MSL (parapet wall top)	+3.41m MSL (road center)	+3.63 m MSL (shoulder)	+4.34 m MSL (road center)	+3.10 m MSL (road center)	+4.08 m MSL (road center)	+5.84 m MSL (road side)
Water surface elevation due to:							
Tide	+0.40 m MSL	+0.40 m MSL	+0.40 m MSL	+0.40 m MSL	+0.40 m MSL	+0.40 m MSL	+0.40 m MSL
Atmo. Pressure	85 cm	85 cm	85 cm	85 cm	85 cm	85 cm	85 cm
Wind	23 cm	51 cm	23 cm	32 cm	22 cm	26 cm	24 cm
Wave	146 cm	143 cm	148 cm	148 cm	144 cm	147 cm	148 cm
Total	+2.94 m MSL	+3.19 m MSL	+2.96 m MSL	+3.05 m MSL	+2.91 m MSL	+2.98 m MSL	+2.97 m MSL
Surf Beat Height	0.90 m	0.90 m	0.90 m	0.90 m	0.90 m	0.90 m	0.90 m
Wave Height ($H_{1/3}$)	3.90 m	1.32 m	2.75 m	2.26 m	2.85 m	2.78 m	2.90 m
Wave Over-topping	0.116 m^3/m/sec	0.157 m^3/m/sec	0.185 m^3/m/sec	0.178 m^3/m/sec	0.323 m^3/m/sec	0.150 m^3/m/sec	0.064 m^3/m/sec

Note: "Section 5-4", etc. shown in the table are referred to the survey lines along which the bathymetric and topographic surveys were conducted.
This note shall be applied to all the relevant tables.

Table 1-2 Coastal Protection Works Preliminary Design against a 100-Year Return Period Hurricane



Offshore Wave: Wave Height $H_{1/3} = 12.0$ m
Wave Period $T_{1/3} = 13.5$ sec

Design Criterion: Wave over-topping volume must be less than 0.05 m^3/m/sec.

Location	at Airport Runway Section 5-4	at Parliament Bldg. Section 4-3	at TPP Fuel Depot Section 3-6	at Westpac Bank Section 2-2	at Banana Court Section 2-1	at Beachcomber Section 1-9	at Health Department Section 1-2
Ground Elevation	+3.90 m MSL (parapet wall top)	+3.41m MSL (road center)	+3.63 m MSL (shoulder)	+4.34 m MSL (road center)	+3.10 m MSL (road center)	+4.08 m MSL (road center)	+5.84 m MSL (road side)
Breakwater Approx. Length: Top Elevation:	20 ton Tetrapods 600 m +4.25 m MSL	None	25 ton Tetrapods 1,400 m +4.50 m MSL	25 ton Tetrapods 800 m +4.00 m MSL		25 ton Tetrapods 500 m +4.25 m MSL	None
Revetment Approx. Length: Top Elevation:	0.5 ton Tetrapods 500 m +3.90 MSL	0.5-1.0 ton Rock 1,800 m ---	0.5-1.0 ton Rock 1,400 m ---	0.50-1.0 ton Rock 800 m ---		0.5-1.0 ton Rock 500 m ---	0.5-1.0 ton Rock 600 m ---
Sea Wall Approx. Length: Top Elevation:	Existing Parapet --- +3.90 m MSL	RC 1,800 m +4.10 m MSL	RC 1,400 m +4.20 m MSL	RC 800 m +4.40 m MSL		RC 500 m +4.50 m MSL	RC 600 m +6.00 m MSL
Remarks				Temporary coastal protection works should be incorporated.	A small yacht basin with -3.0 m MSL and wave energy dissipating concrete blocks (vertical type).	Temporary coastal protection works should be incorporated.	

2. INTRODUCTION

2. INTRODUCTION

2.1 Background of the Additional Study

During the new year days in 1987, Cyclone Sally crossed Rarotonga Island and brought considerable damages to properties of the island. The damages were mainly due to the high waves and strong winds.

Before the cyclone hit the island, the Government of the Cook Islands had started construction of the breakwaters at Avarua Port and completed them in the same year.

From January 10 through 17, 1987, JICA conducted urgent investigation of the cyclone disaster. JICA also made additional investigation from February 26 through March 19 of the same year.

After experiencing cyclones Peni and Sini in 1990, the Government of the Cook Islands started construction of temporary coastal protection works mainly on the northern part of Rarotonga Island. Simultaneously, the Government requested JICA to work out a master plan and short-term development plan of coastal protection and port improvement for the island.

In response to the request, JICA conducted a master plan study covering the entire island and a short-term development plan of the northern part of the island. The short-term development plan for the coastal protection covers the coasts between Avatiu Port and Avarua Port, near the airport, near the fuel tanks of the airport and near the Health Department Premises. Avarua and Avatiu Ports were studied for the port improvement.

The final report of the above mentioned study was submitted to the Government of the Cook Islands in August 1992.

In 1993 the Government of the Cook Islands expressed its request to make a further study coping mainly with the need to provide a greater degree of protection against hurricane force seas to the essential infrastructure and commercial and national assets located on the Northern Coastline.

JICA dispatched a team to the Cook Islands in June 1993 to investigate the situation of the study area including the removal of the breakwaters. After the investigation and the discussions with the officials of the Government of the Cook Islands, the team confirmed the requests. Consequently, JICA decided to conduct the additional study.

2.2 Objectives of the Additional Study

The objectives of the Additional Study are as follows:

(1) Review and up-date the master plan of the coastal protection and port improvement of Rarotonga Island concentrating mainly on hurricane sea protection of the northern coast.

(2) Review and up-date the short-term development plan of the coastal protection and port improvement plan at the northern part of Rarotonga Island in accordance with the Cook Islands Government "Coastal Protection Policy."

In reviewing and up-dating the previous study, particular emphases were placed on the following:

(1) To incorporate more information and opinions of the Government of the Cook Islands in the study results through discussions and technical elaboration.

(2) To complete most of the activities on site, except the computer simulation of the waves and preparation of the final report of the Additional Study, in close cooperation with the Government of the Cook Islands.

(3) To compare the estimated waves on the lagoon with results of wave observation to be conducted during the study period in order to find more reasonable design waves to be used for the coastal protection and port improvement.

(4) To harmonize the coastal protection works with natural environment of Rarotonga Island in order to preserve amenity for the tourism.

2.3 Scope of the Additional Study

The Additional Study covers the following:

(1) Collection and analysis of additional data and information

(2) Review of JICA's previous reports of "The Study on Coastal Protection and Port Improvement in the Cook Islands"

(3) Site reconnaissance (including the coast area where the breakwaters of Avarua Port have been removed)

(4) Wave observation

(5) Computer simulation of waves

(6) Review of analytical methods for determining natural conditions and design criteria

(7) Analysis of natural conditions (wave height and direction, calmness of the port, wave run-up, etc.)

(8) Review and up-dating of the conclusions of the previous master plan and feasibility study

3. REVIEW OF MASTER PLANNING

3. REVIEW OF MASTER PLANNING

3.1 Site Reconnaissance

The JICA Study Team carried out the site reconnaissance from October 2 through October 19, 1993. The findings are summarized as follows (See Figure 3-1 for location of beaches and facilities.):

(1) Northern Coast

The northern coast lies almost perpendicular to the North. The lagoon (Reef flat is correct in geological terms. However, "lagoon" will be used meaning "reef flat" since this usage is popular in Cook Islands.) is generally narrow and shallow. At the center of the northern coast, there are two passages where two ports of the island were built; Avarua Port and Avatiu Port. Avarua is the commercial and political center of the island. Many governmental and private assets and historical buildings and cultural facilities concentrate on this area. On the West, the airport runway is running almost parallel to the coast and its runway is extended onto the lagoon.

The northern coast is the hurricane-fated area. Hurricanes are likely to reach to the island from the north-west to north-north-west of the island. As the winds strongly blow down to the south on the east-side of the hurricane eye, by being augmented by the hurricane move itself, the waves will reach to the northern coast of Rarotonga Island gaining more energy if they take a track slightly west of the island. Worse in this case, the sea water will rise due to both the low atmospheric pressure of hurricanes and wave set-up being blocked by the northern coast.

(a) Beach at the End of Airport Runway

The lagoon is rather narrow, about 120 m at the narrowest. The lagoon is slightly deeper when compared with the other lagoon of the northern coast. Large, but not many, coral boulders are studded in the lagoon. The coast is composed of coral pebbles, cobbles and small boulders. (See Photos 3-1, 3-2.)

The observation suggests that the offshore waves generated by hurricane winds will reach to the coast with such energy that can carry large coral boulders. Therefore, hurricane waves will attack the coast road which runs around the runway extended on the reclaimed embankment.

(b) Beach at Parliament Building

The beach is made of sandy gentle slope. There are houses broken and abandoned near the beach. Obviously, they were smashed by high waves. (See Photos 3-3, 3-4.)

The lagoon is relatively wide near the parliament building, about 500 m, and narrow at both ends, about 120 m on the West and 160 m on the East. The lagoon forms a bay. Thus, this coast reflects the invading waves to the center of the concave-shaped lagoon and, consequently, raises the water level. This phenomenon caused flooding of sea water across the beach over to the hinterland, where the runway has been constructed since then.

(c) Coast near Fuel Tanks

The coast is made of coral boulders. The lagoon is rather narrow (approximately 80 m to 150 m) and shallow. The slope of the coral boulder coast is about 1:2 to 1:5. (See Photos 3-5, 3-6.)

The catholic cemetery exists between the road and the coast. Coral boulders, which were thrown up by waves, covered several times the cemetery in 1970's.

There are three fuel depots on the coast between Avatiu Port and the airport terminal. Among them, two depots (Triad Pacific Petroleum Bulk Fuel Terminal and JUHI Fuel Terminal) are located on the coast and they were damaged by Cyclone "Sally". Mobil depot is located across the coast road to the land side. This depot was also damaged by the cyclone but not as heavily as the other two.

Fuel pipelines are running between the coast and the road. They had been previously embedded near to the coast and exposed as the waves of Cyclone "Sally" washed away the covering on them. They have been shifted, therefore, land-ward after the incidents.

(d) Avatiu Port

The port was built at the passage. The end of the port basin leads to the low hinterland. The rise of the water level generated by Cyclone "Sally" caused flooding at the end of the port basin and the hinterland. Boats were hauled on the coast.

When Cyclone "Sally" attacked the northern coast, the east breakwater had almost been completed. The breakwater was not heavily damaged and is completed at present. Meanwhile, the west breakwater was under construction. Large amour rocks were displaced by waves of Cyclone "Sally." Since then, smaller amour rocks and core materials have been scattered leeward of the planned alignment of the west breakwater. (See Photo 3-7.)

The port accommodates ocean liners up to 3,000 DWT, and leisure boats. The use by both the commercial ships and leisure boats have the port congested. As accidents took place, the Cook Islands Government intends to accommodate leisure boats at Avarua by constructing there a small yacht basin. (See Photo 3-8.)

(e) Avarua - Avatiu Coast

The rocks previously composing the breakwaters of Avarua Port were removed and temporarily placed on the slope of the coast road between Avarua and Avatiu. The slope is about 1 to 3. The rocks are of volcanic origin (basalt) and their surface partly became brown owing to corrosion of ferrous minerals they contain. The size of the rocks ranges from about 1 ton to 6 ton in weight. At several places, rubber sheets are placed between the rocks and the embankment to prevent erosion beneath the rocks. (See Photos 3-9, 3-10.)

In front of the coast, shallow lagoon is spreading between Avatiu and Avarua. The width of the lagoon is approximately from 100 m to 210 m. The lagoon bed is mainly composed of coral boulders. At the reef edge (algal rim in geological terms), beach rock is formed. The lagoon bed is almost flat at the elevation of -0.20 m MSL. Many coral boulders from approximately 500 kg to 6 ton are studded in the lagoon which the strong waves thrown up onto the lagoon and less strong waves gradually carried them forward to the coast. (See Photos 3-11, 1-12.)

Waves are breaking offshore the reef edge and they advance onto the lagoon forming a shape of bore. The littoral currents are induced as the waves advance and they finally return offshore through the passage of Avarua and over the reef near Avatiu Port entrance.

The 4-lane road divided by parking lots and green area runs along the coast. The elevation of the road is very low at both ends at Avarua (about + 1.87 m MSL) and Avatiu (about + 2.56 m MSL) and high in between (about + 4.80 m MSL at the highest point). The road bank is composed of coral boulders. (See Photos 3-13, 3-14.)

(f) Avarua Port

The east breakwater has been completely removed. The end of the west breakwater has been removed by about 70 m. Thus, Avarua Port is protected by natural reef and passage; the former blocks the invading waves, while the latter deflects them aside. No damages of Avarua Port have been reported after the breakwater removal.

Under the calm sea conditions, the port is sheltered from the invading waves. However, the water area at the west side of the passage, the potential site for a small yacht basin, is rather rough owing to the waves reaching across the lagoon. For sheltering the small yacht basin, a breakwater aligned in parallel to the reef edge seems necessary. (See Photo 3-15.)

The existing quay wall is made of steel-sheet-piles with the backfill of coral boulders. The steel-sheet-piles have been corroded. They have been lost at the splash zone. Concrete pavement has caved in at several places. The retaining wall, however, still stands, probably owing to large internal friction angle of the fill of coral boulders. As Avarua Port is included in the new town development, the existing quay wall and the concrete apron are to be repaired. (See Photo 3-16.)

(g) Avarua Port to Pue

The coast has relatively narrow and shallow lagoon. The coast is mainly composed of coral pebbles and fragments. The natural slope is gentle about 1:5. A few large coral boulders are studded in the lagoon. Hurricane waves were supposedly large and strong enough so that large coral rocks were thrown onto the shore. (See Photos 3-17, 3-18.)

The coast road runs on the top of the heap made of coral boulders. There are many houses built between the coast and the road, which are very difficult to protect from the hurricane waves.

About 300 m from Avarua Port, the coast is protected with amour rocks which were removed from the breakwaters of Avarua Port. (See Photo 3-19.)

The Health Department buildings are built closer to the coast. The existing low seawall is almost covered with coral boulders, which suggests that high waves ran up over the seawall and intruded the department buildings. (See Photo 3-20.)

(2) Eastern Coast

The eastern coast of the island is divided into three categorized coasts; the coral-boulder coast with narrow and shallow lagoon on the North, sandy beach with wide and deep lagoon on the South and the sand-coral-boulders-mixed beach in between.

The prevailing winds blow from the east. However, strongest winds caused by hurricanes will not last long from the east since hurricanes will not remain at the north of the island but move to the south. The coast is not hurricane-fated.

Muri Beach is the most famous tourist spot in the island, where wide and deep lagoon is stretching out calm and blue embroiled by reef and sand beach, adorned by four small islands.

(a) Matavera Coast

The lagoon is very narrow about 40 m to 70 m. The coast is made of coral boulders which diameter ranges from 5 cm to 20 cm. No coastal erosion is observed. The slope is steep about 1:2. The coast faces the north-east, in which direction winds are most prevailing. (See Photo 3-21.)

The coast road runs on the top of the heap made of coral boulders. This indicates that hurricane waves ran up to the top of the heap at the coast road. The houses built between the coast and the road will be in danger of wave run-up. No protection works would effectively protect these houses from hurricane waves. (See Photo 3-22.)

(b) Ngatangiia Coast

The lagoon is relatively narrow and shallow. The coast is covered with sands and coral fragments and boulders, i.e. transition from the coral boulder beach to sandy beach. The beach slope is tender and seems stable even though the coast faces the prevailing winds. (See Photo 3-23.)

(c) Muri Beach

Generally the west coast is exposed to high waves generated by the strong and prevailing winds at Rarotonga Island. However, a wide lagoon exists at Muri. The 4-islands are considered to have attributed to forming of this wide lagoon even the coast is exposed to the strong waves. (See Photo 3-24.)

The beach sands are fine, which may be due to the wide lagoon. In the wide lagoon, coarse sand particles will fall on the sea bed and be carried to the passage by littoral currents during the storm. While, fine sand particles will reach to the beach by normal wave actions.

Beach erosion was reported in the previous JICA report. The erosion might be due to the dredging of the sands from the passage, which has been prohibited. Nowadays, the beach seems in a stable condition as the two photos taken at the same point in 1987 and this time show no significant changes. (See Photos 3-25, 3-26.)

(3) Southern Coast

The southern coast is very unlikely to be attacked by hurricane waves since the winds do not strongly blow from the sea.

The southern coast has wide, about 550 m to 740 m, and deep lagoon. The beach is sandy but not so wide as it is on the western beach. Few boulders are found on the beach. Beach rock is exposed at several areas. At the river mouth, small black cobbles, which origin is basalt base rock of the island, are scattered. (See Photos 3-27, 3-28.)

It is told that the sand was richer before and it covered the beach rock. The reason why the beach sand loses may be attributed to not a single reason of high waves but compounded effect of several reasons from ecological changes to long-term global weather changes, i.e. previous quarrying of beach sand, death of corals in late 1960's to early 1970's.

(4) Western Coast

The western coast has relatively wide and deep lagoon, too. However, the lagoon becomes gradually narrower up to the north. The narrower the lagoon becomes, the wider the beach extends on the coast. This may be due to a certain width of the lagoon where the energy of hurricane waves can be transmitted to the beach, pushing up sand particles onto the shore. This conjecture can be justified by increase of existence of coral boulders as the lagoon becomes narrower.

(a) Beach near the Rarotongan Resort Hotel

The beach is located at the south-west corner of Rarotonga Island. The lagoon is wide, about 500 m, to protect the coast from the direct attack by hurricane waves.

To the North, the coast road is running close to the beach where the embankment for the road was constructed on the natural beach. The embankment is being eroded. (See Photo 3-29.)

At the south-west corner of the island, the hotel resort is built. The beach had long suffered from erosion. Several measures were taken to protect the beach, e.g., groins, seawall. After all had failed, an invention was made by a coastal engineer. He invented Coastal Protection Units as shown on the photograph. The basic idea of this invention is to dissipate the wave energy, allow sand particles pass the units and settle behind them. This was made possible by dissipating the wave energy upward so that the water behind the units can be stabilized. (See Photos 3-3-, 3-31.)

(b) Arorangi Beach

Almost all the west coast of the island is sand beach occasionally with beach rock exposed. The lagoon is wide, about 200 m to 400m, but narrow enough to move up the sand particles from the lagoon.

The waves maintain the beach very stable, gentle and sandy. Many bungalows are located in the shade of trees where coral boulders are sparsely scattered. Exception to this natural landscape is artificial reclamation for Edgewater Resort which is likely to be eroded by the waves and littoral currents. (See Photos 3-32, 3-33.)

(c) Black Rock Coast

The cape of Black Rock is formed of basalt which is the base rock of Rarotonga Island. This is the only point where the base rock is exposed on the coast. Except this point, the coast around Black Rock is made of sand and beach rock. The lagoon is deep and wide. (See Photos 3-34, 3-35.)

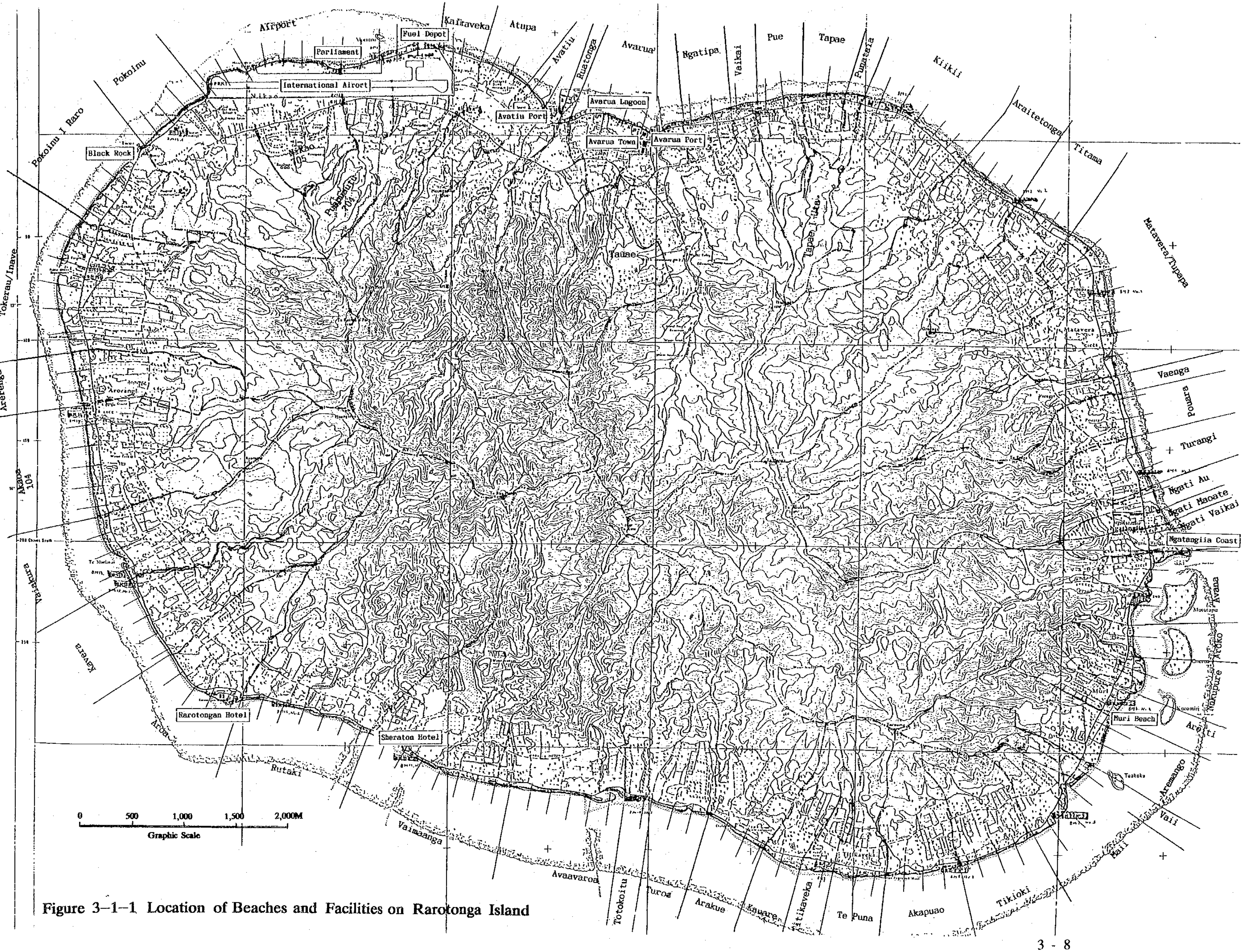


Figure 3–1–1 Location of Beaches and Facilities on Rarotonga Island

Photo 3-1 Lagoon near the western end of the runway.

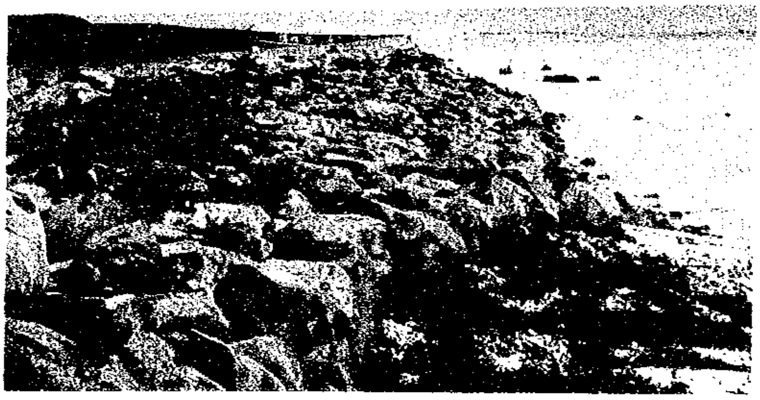


Photo 3-2 Coral fragment beach at the western end of the runway and the temporary revetment with amour rocks.

Photo 3-3 Sand beach near the parliament building.

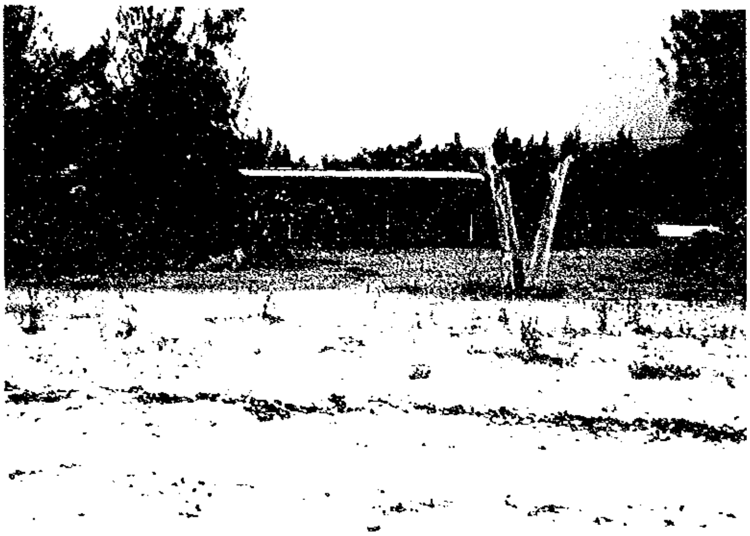


Photo 3-4 An abandoned house smashed by hurricane waves.

Photo 3-5 Shore protection for the fuel depots.

Photo 3-6 Coral boulder shore near the cemetery.

Photo 3-7 The west breakwater of Avatiu Port, abandoned incomplete.

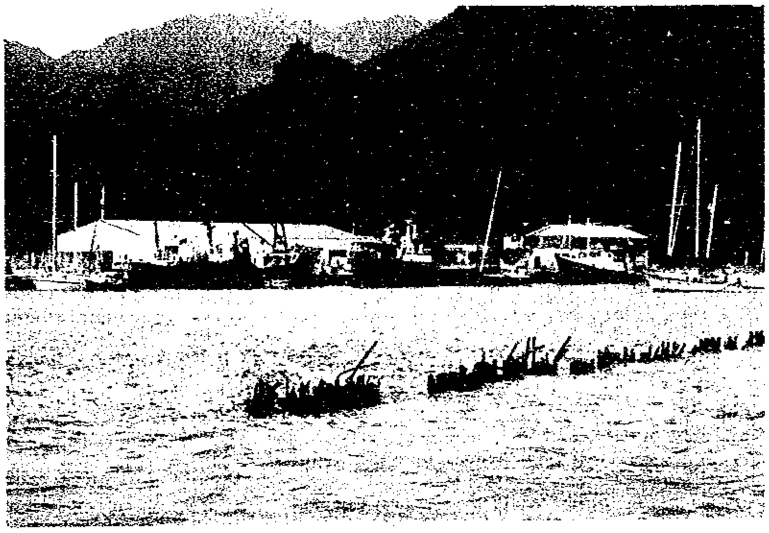


Photo 3-8 The port basin of Avatiu Port with several leisure boats and commercial ships.

Photo 3-9 The temporary coastal protection work between Avarua and Avatiu by use of armor rocks removed from the breakwaters of Avarua Port.

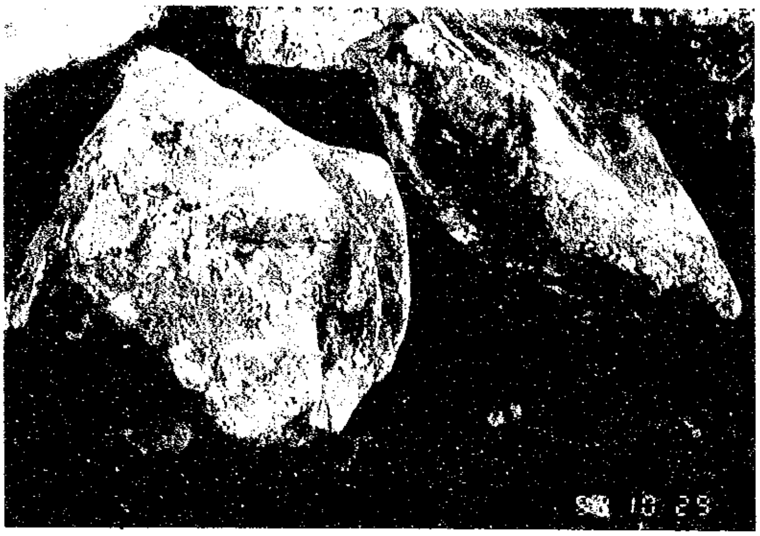


Photo 3-10 Details of the temporary coastal protection.
Armor rocks with rubber sheet for sand-loss prevention.

Photo 3-11 Overall view of the lagoon between Avarua and Avatiu.

Photo 3-12 Coral boulders studded on the lagoon between Avarua and Avatiu.

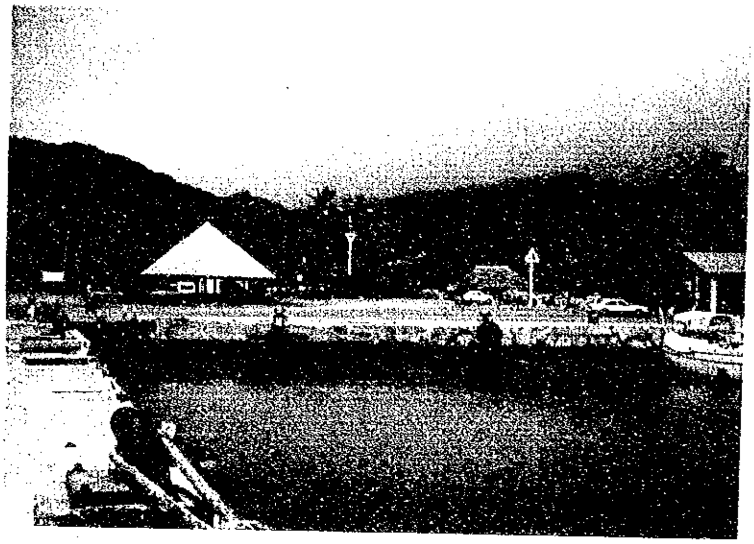


Photo 3-13 The coastal road at Avatiu referred to the sea surface.

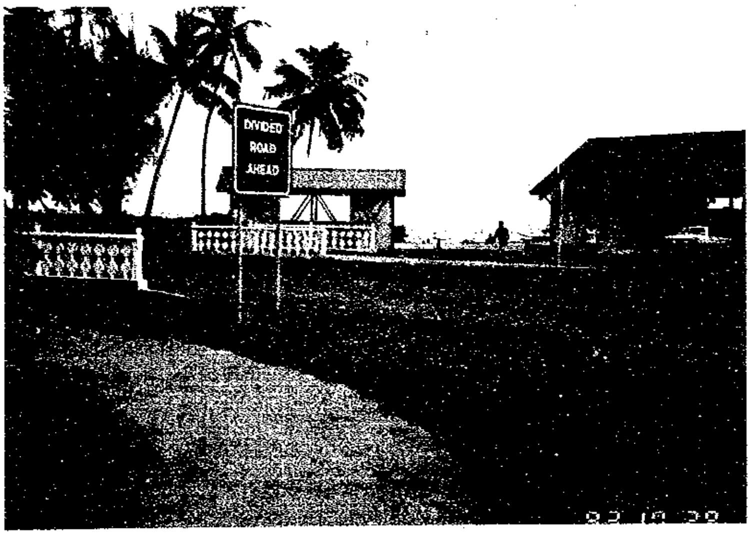


Photo 3-14 The coastal road at Avarua referred to the sea surface.

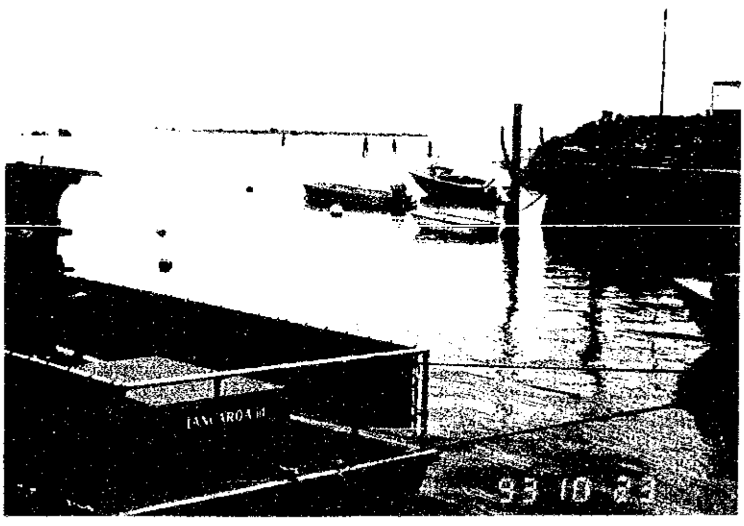


Photo 3-15 The potential water area for a small yacht basin in Avarua Port.

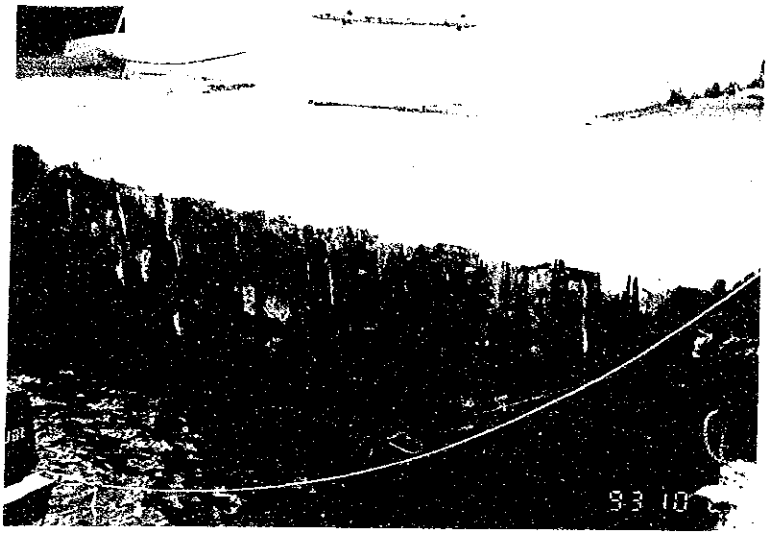


Photo 3-16 The corroded quay wall of Avarua Port, including the fill of coral boulders.

Photo 3-17 Coral fragment and boulder beach at Pue.

Photo 3-18 A coral boulder in the coconut tree area near the Health Department premises.

Photo 3-19 The temporary coastal protection by use of armor rocks removed from the Avarua breakwaters.

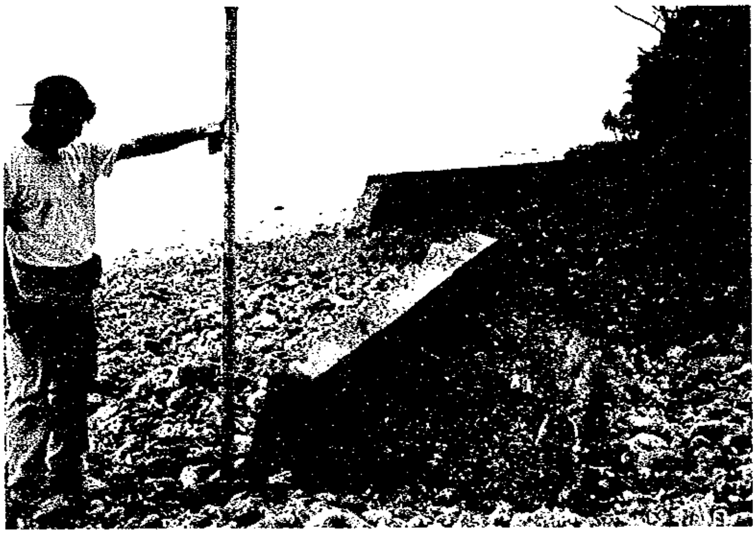


Photo 3-20 The seawall at Health Department premises.

Photo 3-21 Coral boulders on the coast at Matavera.

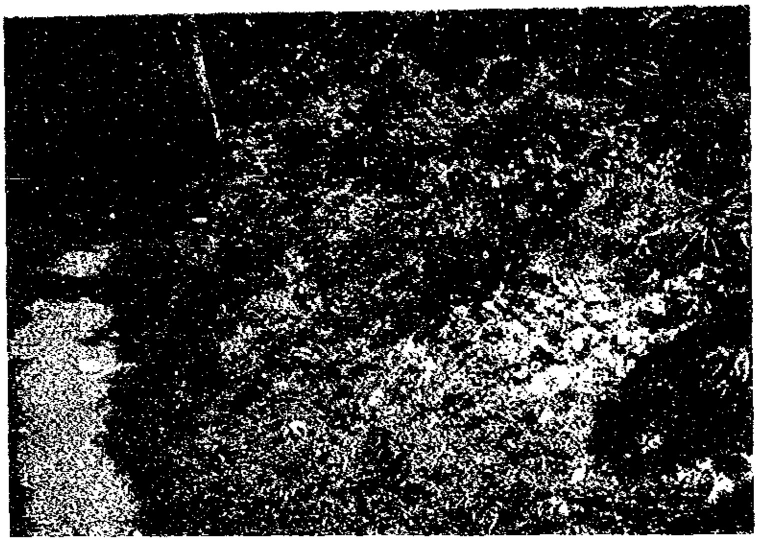


Photo 3-22 Accumulation of coral boulders exposed on the bank of a stream at Matavera.

Photo 3-23 Coral fragment beach at Ngatangiia Coast.

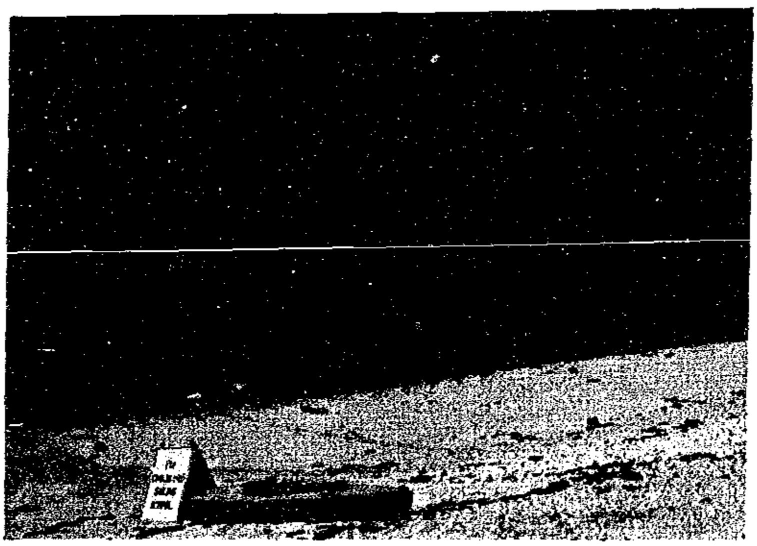


Photo 3-24 Lagoon, beach and islands at Muri Beach, including sand beach.

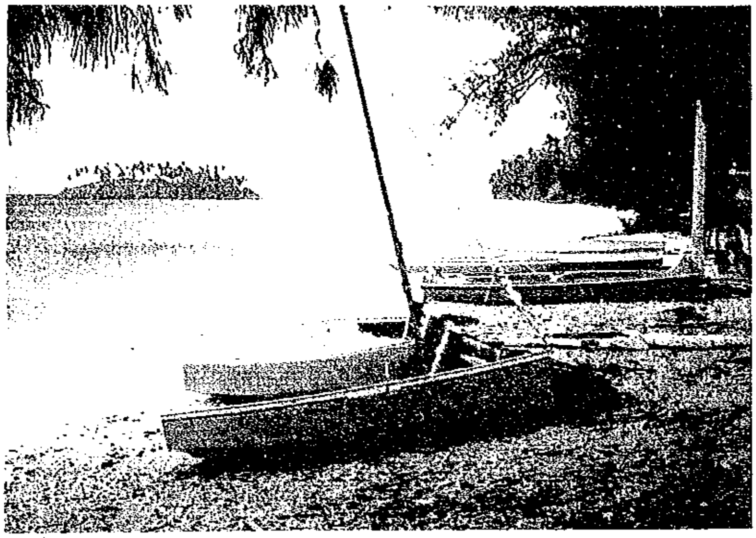


Photo 3-25 Sand beach at Muri. The JICA photo taken in 1987.

Photo 3-26 Sand beach at Muri. The same spot where the JICA photo was taken.

Photo 3-27 Beach at Titikaveka with beach rock exposed.

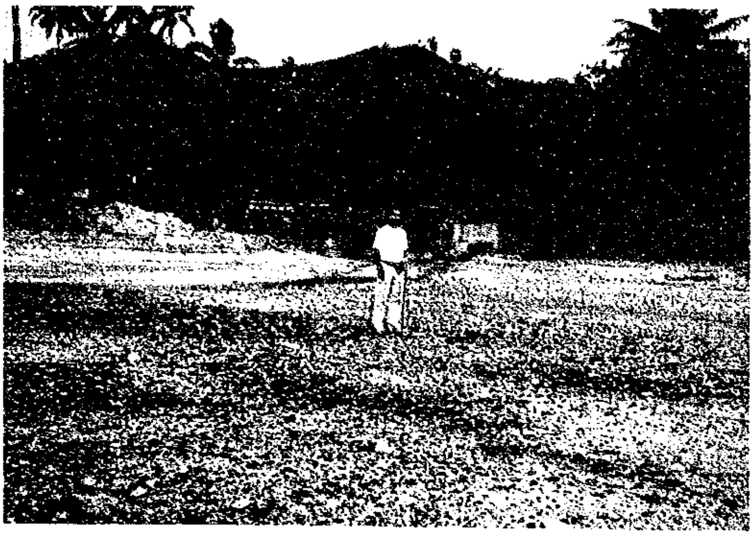


Photo 3-28 The river mouth with basalt cobbles at Titikaveka.

Photo 3-29 Collapse of the road embankment north of the Rarotongan Resort Hotel.

Photo 3-30 Coastal Protection Units (CPU) from the front.

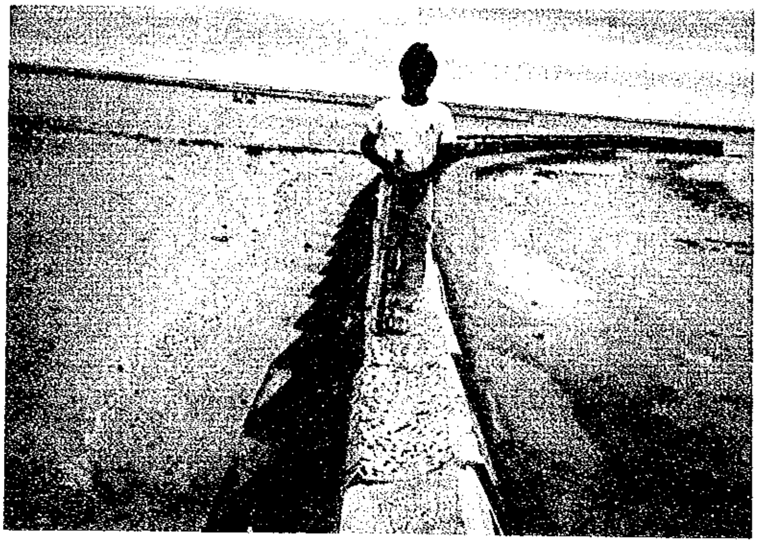


Photo 3-31 Coastal Protection Units (CPU) from the top.

Photo 3-32 Natural sandy beach at Arorangi.

Photo 3-33 The coastal protection in front of Edgewater Resort.

Photo 3-34 Black Rock.

Photo 3-35 Beach with beach rock, taken from the Black Rock.

3.2 Coastal Protection

(1) Government Policy on Coastal Planning

The Cabinet of the Government of the Cook Islands passed the Policy Paper (Policy Paper, Coastal Protection - Northern Coast, Rarotonga - Cook Islands and Coastal Protection against Hurricane Sea States, Northern Coast - Rarotonga, Cook Islands) regarding the coastal protection on the northern coast of Rarotonga Island. The objectives of the policy are described in the Policy Paper as follows:

A. It should provide effective protection for all vital infrastructure and domestic, commercial, and national assets on the designated area of the North Coast from hurricane-force seas, "from whatever direction they may arrive";

B. For engineering design purposes, design waves with return periods in the order of 100 years should be used. (I.E. an event with a 1% risk of occurrence in a given year)

C. The system should assist the efforts to preserve the recreational beaches for the benefits of future generations and the tourist industry; and should not be of a Type which will erode and degrade these beaches and make them unusable.

D. It should not diminish the scenic value of the natural shorelines and should not degrade the coastal environment.

The Policy Paper is attached to this report as Appendix-A.

(2) Principles in Planning Coastal Protection

Meeting the above objectives is to mean satisfying acceptable engineering requirements as well as complying with certain political, economic, and social considerations and should be based on the following criteria:

1. It should be as cost effective in long term, and as maintenance-free as possible.
2. It should be as low as possible in height, allow lagoon and ocean views while at the same time greatly reducing wave height and wave velocity;
3. The protection should enhance the environment, not degrade it;
4. It should allow normal water flows to prevent lagoon degradation and stagnation yet be capable of calming hurricane-force seas when necessary;

5. It should be aesthetic, not an 'eyesore';

6. Especially in the Main Town foreshore it should produce usable foreshore recreation areas and a Marine Promenade. It should not form an impassable barrier;

7. Where necessary, it should protect and help to rebuild existing beaches; and not be the cause of eroding and degrading them.

In addition to the Policy Paper, a town planning for "A Capital Center At Avarua" prepared by University of Auckland in 1992 provides the concept of the coastal zone between the Avatiu and Avarua as follows:

"The Waterfront is the major feature of the Avatiu to Avarua coastal zone. It is proposed a timber boardwalk promenade along the lagoon edge giving people a feeling of being both at and on the waterfront. A number of viewpoints and activity nodes such as restaurants, cafes and a yacht club are suggested along the promenade. A major economic factor could be the creation of a leisure harbor adjacent to the harbor at Avatiu. A leisure harbor accessed at Avarua harbor would not only generate income through berthing fees but be a visual attraction and image maker of enormous significance.

To create a leisure harbor, a basin would have to be excavated. Marine engineering studies would have to be carried out to ascertain and mitigate the effects of any marine-related works."

(3) Coastal Protection Carried out on Avarua - Avatiu Coast

JICA recommended the widening of the coastal road protected with revetment works on shore in 1987. JICA simultanously recommended the construction of breakwaters to protect Avarua Port. The breakwaters were constructed in the same year.

Controversy had continued on the breakwater function till 1991; do they increase the wave set-up and consequently augment the wave attack onto Avarua - Avatiu Coast? Accepting the study results of Prof. Kirk (Canterbury University) in 1991, the Government of the Cook Islands concluded that the breakwaters would increase the wave set-up and bring about more damages. The breakwaters were removed and temporary coastal protection was constructed in 1992.

The armour rocks removed from the breakwaters were placed partly on Avarua - Avatiu Coast, east of Avarua Port, and along the coast road west of the meteorological station.

The rocks are basalt and thier size is large, approximately 1 ton to 6 ton, but they are rather round and not much interlocked each other. The slope of the rock revetment is rather tender and seems not much effective to decrease the wave run-up of a hurricane sea state.

The coastal protection works normally require a huge qunatitiy of rock. Particularly in the Cook Islands, all the cement is imported and fine materials of concrete (sands) are very scarce. Therefore, the existence of rock quarry is vital.

Ministry of Works has its own qaurry site at Nikao. However, the quarry can produce only small size of rock which are crashed to coarse aggregates of concrete works or for road works. (See Photo 3-36)

A quarry site exists on the upstream of a stream running to Manuia Beach. However, the rocks are much weathered and have many seams. They are not suitable for producing amrou rocks. (See Photo 3-37)

Huge rocks are scattered on the ground along the inner road at Apa Metua. They seem suitable as amour rocks. To be sure about the supply of a sufficient qauntity of rocks, a geological investigation is recommended. (See Photo 3-38)

After the disaster caused by Cyclone Sally, the coastal protection along the Avarua - Avatiu Coast had been discussed, and the present shore protection was completed in 1992.

Photo 3-36
Quarry site at Nikao owned by Ministry of Works.
It can only produce small size of rock.

Photo 3-37
Quarry site on the upstream near Manuia Beach.
The rocksare much weathered.

Photo 3-38 Huge rocks scatterd on the ground along the inner road at Apa Metua.

3.3 Port Improvement

There are two ports, Avatiu Harbour and Avarua Harbour on the northern coast of Rarotonga Island.

The Previous Study proposed the following items as a Master Plan.

- To provide a container storage area to accommodate the increase of container cargoes.
- To expand the east breakwater, widen the entrance channel and turning basin and deepen the quay wall and the basin in Avatiu Harbour to ensure the safety of large vessels.
- To repair the existing quay wall.
- To prepare the facilities of the fishery port for the increase in both number and size of fishing boats to materialize more fish catches.
- To construct a marina for the increase in the number of pleasure boats, especially large yachts to enhance tourism industry development.
- To protect small fishing boats from high waves during a cyclone.

It is requested by Steering Committee of the Cook Islands that the Additional Study be concentrated on only Shore Protection including port areas and that a new marina be planned in Avarua Harbour to accommodate all cruisers to call from other countries as a short-term plan. The latter request is due to increasing problems at Avatiu Harbour caused by berthing of general cargo vessels and pleasure boats in the narrow water basin. (JICA previous study suggested a joint use of Avatiu and Avarua Harbours for marina as a Short-Term plan.)

The main port improvements to be planned in this Additional Study are:

- the improvement of the existing breakwaters at Avatiu Port,
- a new marina development at Avarua Port.

In this Section, the results of JICA previous study will be summarized and some comments will be made based on the new findings by the Additional Study.

(1) Avatiu Harbour

(a) Present Condition

i) International Shipping

The international & inter-island shipping service on the northern coast of Rarotonga is provided at Avatiu Harbour.

International shipping operations into the Cook Islands are mainly provided under the Joint Shipping Services Agreement between New Zealand, Niue and the Cook Islands. Under this agreement, two vessels, Aotea Link and Ngamaru III, are currently operated. And another vessel, Urte, operated by Hawaiian Shipping Service started in 1991. Those three vessels, for general cargoes, operate based on the following schedule and routes.

Table 3-3-1 Shipping Routes and Schedule at Cook Islands in 1991

Vessel Name	Service (days approx.)	Route
Aotea Link	21	Auckland - Papeete - Rarotonga - Auckland
Ngamaru III	31	Auckland - Niue - Apia - Rarotonga - Aitutaki - Auckland
Urte	31	Honolulu - Pagopago - Apia - Tonga - Rarotonga - Christmas Is. - Honolulu

Of these three vessels, Aotea Link and Urte mainly transport containerized cargoes though they are not full-container ships.

In addition to the above vessels, tankers are operated at irregular intervals. Pacific Rover and Pacific Explorer are principally used for the transportation of liquid petroleum products from Lautoka (Vuda Point) of Fiji, and Coral Gas for the transportation of LPG from Fiji. Dimensions of vessels are given in the following tables.

Table 3-3-2a Dimensions of General Cargo Vessels

	Aotea Link	Urte	Ngamaru III
D.W.T	2,671	3,035	2,181
G.T	1,829	2,696	1,464
Length overall (m)	79.6	92.5	72.4
Beam (m)	13.2	13.9	15.5
Full draft (m)	6.4	6.8	5.6
Speed (knots)	11.5	11.5	12.0
TEUs	118	166	60
Year built	1988	1985	1970

Table 3-3-2b Dimension of Tankers

	Pacific Rover	Pacific Explorer	Coral Gas
D.W.T	1,963	1,642	2,366
G.T	1,594	954	1,897
Length overall (m)	80.0	71.9	77.0
Beam (m)	13.3	11.7	12.7
Full draft (m)	4.8	4.2	5.9
Speed (knots)	12.5	12.0	12.9
Year built	1979	1973	1971

The number of ship calls at Avatiu Harbour from 1985 to 1990 is shown in Table 3-3-3.

Table 3-3-3 Number of Ship Calls at Avatiu Harbour

	1985	1986	1987	1988	1989	1990
Cargo Vessel	21	27	25	33	23	96
Tanker	37	28	28	23	18	9
Pleasure Boat	48	64	67	96	90	123
Others	2	5	6	17	11	17

Imports from overseas ports, mainly from New Zealand, but also from Japan, South East Asia and Pacific ports (Fiji, Western and American Samoa, Tahiti) are for consumption in Rarotonga or transshipment to the outer islands.

The cargo volume handled at Avatiu Harbour for recent five years is shown in Table 3-3-4. Cargo volume handled in 1990 in Avatiu Harbour was recorded at approx. 39,200 freight tones.

Table 3-3-4 Past Records of Cargo Volume handled at Avatiu Harbour

	1986	1987	1988	1989	1990
Freight Ton	40,353	56,260	29,983	36,131	39,238

Main imported commodities are foods, construction materials, motor vehicle/parts and petroleum products. Among those commodities, petroleum products such as gasoline, diesel oil, aviation gas and LPG, etc. have been increasing every year excluding the year 1988 after cyclone Sally attacked the Cook Islands.

Most cargoes are well containerized except liquid fuel and long and/or heavy construction materials such as cement, steel bars and plates, plywood, etc. The cargo volume handled and the ratio of containerization by main commodities are shown in Table 3-3-5.

Table 3-3-5 Ratio of Containerization in 1990 Excluding Break Bulk

Commodities	Total Frgt. ton (x1,000)	Breakdown Containerized (x1,000)	Ratio of Contnr.
Foods	10.0	9.5	0.95
Construction Materials	3.7	0.4	0.10
Vehicles	3.8	0.0	0.00
Motorcycles & Parts	0.9	0.6	0.71
Others	9.3	6.4	0.69
Total	27.7	16.9	0.61

All cargoes are handled by the Waterfront Commission (W.F.C.) under the control of Ministry of Trade, Labour and Transport (T.L.T).

ii) Inter-island Shipping

Regular inter-island shipping services are provided by Cook Islands Shipping & Development Co., Ltd. using Manava II, approx. 400 G.T. Cargoes to and from the outer islands are all non-containerized. Inward cargoes are mainly agricultural products and empty fuel drums for local consumption or transshipment to overseas ports respectively mainly from Aitutaki and Mangaia. Outwards cargoes are mainly fuel, construction materials and equipment, fertilizers and agricultural supplies, foods and beverages. Outward cargo volume has been consistently recorded at approx. 2,000 to 2,200 freight tons in the last few years.

iii) Other Traffic

No regular ferry or passenger boats are plied in the Cook Islands at present. Passengers are transported by the above-mentioned inter-island vessel when demand arises. As shown in Table 3-3-3, more than 50 % of total number of ship calls is accounted for by pleasure boats, mainly small cruisers and yachts. Those pleasure boats are principally moored at the cargo wharves in Avatiu Harbour and moved as requested when a cargo ship arrives. It is undesirable to utilize the harbour this way.

Four large passenger ships called at Avatiu Harbour in 1991 (up to October), but could not enter the harbour due to the shallow basin. The passengers were transported by small boats to the wharf.

iv) Port Facilities

As shown in Table 3-3-6 and Figure 3-3-1, there are two quay walls; one is located on the east side with a length of 226 meters and depth of -6.2 m below M.S.L. for international & inter-island shipping, the other is on the south side (the end of the port), with a length of 116 meters and depth of -4.0 m, mainly used for pleasure boats. Some small fishery boats now use the rubble-mounded jetty located on the west side of the port.

Table 3-3-6 Existing Major Port Facilities at Avatiu Harbour

Facilities		Quantity	Owner	No.
Civil, Building & Utilities				
Quay Wall (-6.2 m)		226 m	TLT	1
(-4.0 m)		116 m	TLT	2
East Breakwater	About	220 m	TLT	3
West Breakwater	About	270 m	TLT	4
Cargo Shed No. 1		580 m^2	WFC	5
No. 3		1,056 m^2	WFC	6
Container Freight Station Container Yard		880 m^2	WFC	7
Maintenance Shop		170 m^2	WFC	8
Canteen		135 m^2	WFC	
High-tension & Low-tension Substation		60 m^2	TLT	13
LPG Tank Area		2,580 m^2	Cook Is. Gas	9
Fisheries Office and Shed		230 m^2	Marina Resources	10
TLT Work Shop		380 m^2		11
Slipway		1 m^2		12
Waterfront Commission Office		226 m^2		14
<u>Cargo Handling Equipment</u>				
Forklift 25 tons		1		
8 tons		1		
3 tons		2		

Note) The numbers on the right column of this table correspond to the numbers indicated in Figure 3-3-1.

WFC : Waterfront Commission

TLT : Trade, Labour and Transport

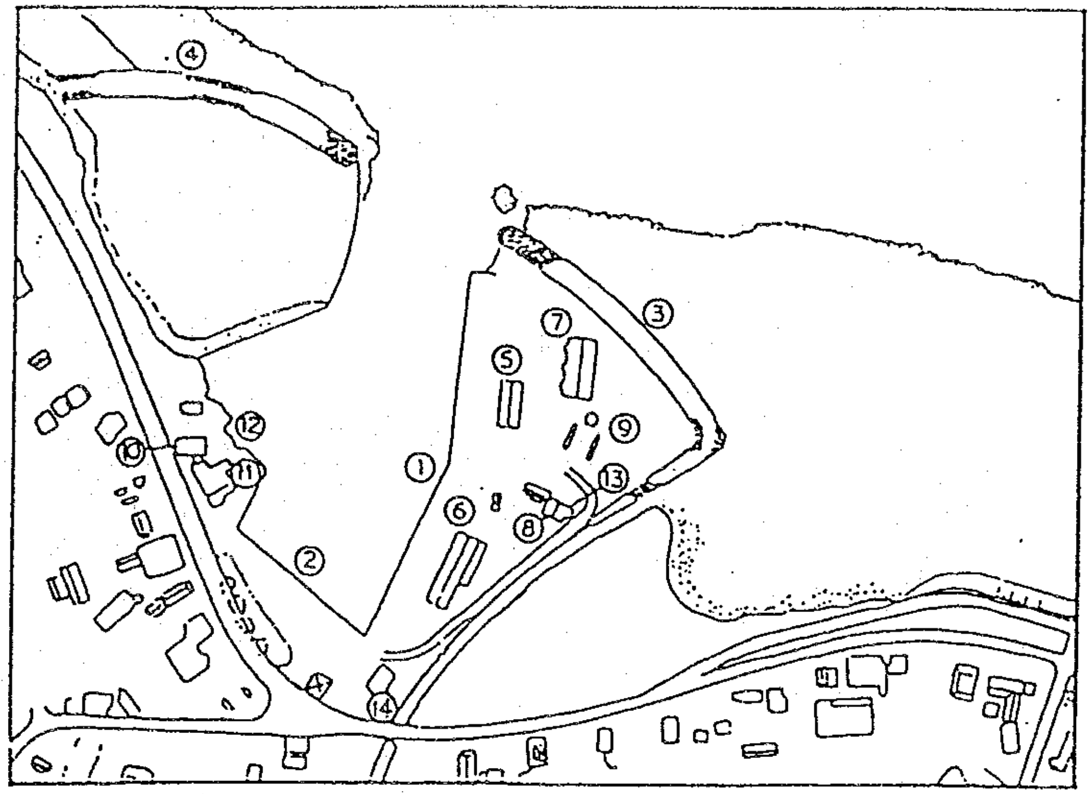


Figure 3-3-1 Location of Existing Facilities at Avatiu Harbour

The present joint berthing of general cargo vessels and pleasure boats in the narrow water basin has produced some problems that require improvement; this basin should be used exclusively for general cargo and the construction of a new marina is necessary.

(b) Long-term Plan (Review of the Previous Study's Master Plan)

Table 3-3-7 shows the summary of the demand forecast on overseas cargo in the JICA previous study.

Table 3-3-7 Forecast of Overseas Cargo Volume by Commodities in 2010

Commodities	Frgt. ton (x1,000)	In Cont. (x1,000)	Non-Cont. (x1,000)
Foods	13.9	13.2	0.7
Construction Materials	4.8	0.5	4.3
Vehicles	5.0	0.0	5.0
Motorcycles & Parts	1.2	1.1	0.1
Fuel	15.9	-	-
Others	12.3	11.1	1.2
Total	53.1	25.9	

Domestic Cargo Volume (outward) in 2010 is estimated to be 2,800 freight tons (those in 1989 and 1990 were 2,300 and 2,100 tons respectively).

Based on the demand forecast on the volume of seaborne cargoes to Rarotonga, the berth occupancy rate of the international wharf has been estimated in the previous study to be only 0.31 even in 2010, which requires no extension of the berth in the long term.

The JICA previous study has estimated the required area for cargo handling facilities in 2010 as follows:

- the area of the existing transit sheds (1,060 + 580 m^2) is sufficient for sorting and storage in 2010,

- the estimated area for container freight station (CFS) required in 2010 is 145 m^2, which is smaller than the area of the existing CFS and no extension is required,

- the required area for container storage yard in 2010 is 6,750 m^2 and that for container marshaling yard is 5,100 m^2. The existing container marshaling and storage yard is approximately 8,000 m^2 wide and the extension of container yard is needed as the number of containers handled increases in the future.

As shown in Table 3-3-6 and Figure 3-3-1, there is a LPG tank area. The JICA previous report recommended in the Master Plan that " The LPG tanks, which handle dangerous stuff, should be moved from the center to outside of the port. This measure would eliminate the possibility of major damage in the event of an explosion". Furthermore it mentioned in the Short-Term Development Plan as follows:

"The LPG tanks should be moved from the center of the port to out-side the port area. But, according to the contract between the Cook Islands government and the owner of the LPG tanks, the LPG tanks can be moved only with the consent of the LPG tanks owner. Therefore, if consent isn't granted before beginning of the construction works for Short-Term Development Plan, the LPG tanks can not be moved from their present location."

Based on the discussion with Steering Committee of the Cook Islands, the Additional Study will plan only the reinforcement of the breakwaters with new design wave conditions in Avatiu Harbour. However, the problem mentioned above is essential for safe and efficient port operation and it is recommended that the LPG tanks be moved to the appropriate area in near future from the view point of safety. In case that the LPG tanks were not moved, the area for container yard will become insufficient before 2010.

The JICA previous study planned two areas for container storage to cope with increase of containers in the future: one is the back area of the relocated East Breakwater extended offshore and the other, newly reclaimed area on a lagoon on the east of Avatiu Stream. (See Appendix-B of this report) It has been often said that breakwaters/jetties projected far into the lagoon may obstruct the littoral current and cause the rising of water level and the increase of volume of wave overtopping across the coast.

The JICA previous study proposed the introduction of such cargo handling equipment as large forklifts and tractor-trailers.

Based on the analysis on the necessity of developing fishery port facilities, the previous study planned a new fishery port and its facilities behind the west breakwater of Avatiu Harbour as follows:

- Landing Wharf: 50 meters for 30 fishing boats per day
- Lay-by Wharf: 180 meters for 60 fishing boats per day
- Sorting Facilities: 70 m^2 for 700 kg of fish catch per day: Ice Making Plant and its Office: 75 m^2 with the capacity of 1 ton/day
- Repair Shop: 80 m^2 for 60 repair boats per year

It seems difficult to relocate and extend the existing east breakwater to protect the new fish landing area against easterly waves as mentioned before. Therefore the area just behind the west breakwater could be possibly used for landing and lay-by wharfs.

As the nominal depth of Avatiu Harbour is 6.2 m below M.S.L., vessels having more than a 5.5 meter full draft must be controlled before port entry. The JICA previous study planned deepening the basin to -7.5 m and widening it to 140 m for large vessels, assuming provision of a new tugboat sufficient for safe and easy maneuvering of vessels in the aforementioned turning basin.

According to the previous study, the existing quay wall (concrete sheet piles) was severely damaged by Cyclones Val/Wasa and Gene and was recommended to be repaired. The steel sheet piles built from the tip of West Breakwater to north-west side of the slipway (See Figure 3-3-1) are severely damaged and deteriorated and it is recommended to repair them to maintain the channel.

There are two breakwaters at Avatiu Harbour, that is, East Breakwater and West Breakwater. These were damaged by Cyclone Sally in 1987, especially the West Breakwater which was under construction when Cyclone Sally attacked Rarotonga Island have not yet been repaired.

According to the previous study, the present layout of the two breakwaters is insufficient, especially in terms of protecting the water basin in front of the newly planned fishery wharf and securing wave calmness and workability needed there in normal climatic conditions (excluding rough sea condition by cyclone and hurricane). However, the present layout provides enough wave calmness needed for the international and inter-island shipping berth located on the east side of the Avatiu Port, which will be analyzed later.

(2) Avarua Harbour

(a) General

There is a berth for small pleasure boats between two small rivelets flowing into the Avarua passage. The berth is heavily damaged and deteriorated. There used to be two breakwaters; the West Breakwater and the East Breakwater. The West Breakwater has been completely removed and the tip half of the East Breakwater has been removed. The -2.5 m pier is steel sheet pile type and severely damaged and deteriorated and the apron behind the pier caves in. These facilities should be rehabilitated as soon as possible. The offshore breakwaters for shore protection at both sides on Avarua Passage will increase the wave calmness in front of the pier.

4. COASTAL PROTECTION OF NORTHERN COAST OF RAROTONGA

4. COASTAL PROTECTION OF NORTHERN COAST OF RAROTONGA

4.1 Coastal Protection of Northern Coast of Rarotonga

(1) Principles in Designing Coastal Protection Works

Principles are the following;

- To protect the coast including the assets there against the wave and storm surge.
- To allow normal wave action on the lagoon and the normal transport of sediments across the lagoon from the reef to the shore.
- To provide the amenity to the coast when the protection works are completed.
- To minimize the cost and maintenance.
- To apply sound and tested technical means.

In line with the Government Policy on the coastal protection of the northern coast of Rarotonga Island, the following design principles are set forth:-

- Design Principle 1: Coastal protection works are to protect the coast including the assets there against the wave and storm surge generated by 100-year offshore waves. (The design offshore significant wave height (H1/3) is estimated at 12.0 m and the design wave period (T) is 13.5 sec.) Inundation of the low area, however, is permissible.
- Design Principle 2: During the normal sea conditions, they allow wave-induced currents to flow into the lagoon and maintain the transport of sediments across the lagoon from the reef to the shore.
- Design Principle 3: Coastal protection works should augment the amenity of the coast so that people will be able to enjoy the coast and should not prevent people from accessing to the coast.
- Design Principle 4: Coastal protection works should be cost-minimized in construction and maintenance.
- Design Principle 5: Their design is to be based on reasonable engineering methods recognized at present.

(2) Offshore Waves

The risk involved in a chosen design wave condition is determined by one of various functions such as normal, log-normal, Weibull, and Gumbel distributions. Generally, the extreme value of offshore wave height has forecasted by the Weibull function which is expressed as:

$$P(H) = \exp[-(\frac{H - c}{a})^b] \text{ ---------- } (1)$$

where P(H) = non-exceedance probability for variable H, and a, b, c = constants. For an application of the theory on wave height distribution, the constant c takes zero and the range of the constant b falls from 0.75 to 2.0. This reduces the fitting problem even further since the distribution is plotted by a straight line on a semi-logarizmic paper. In order to express the chance of occurrence in year other than a pure probability, the following form is often suggested to combine the return period and the chance:

$$Y = 1/M\ P(H) \text{ ---------- } (2)$$

where Y = return period having an unit of year, and M = the number of storm in one year.

Insufficient data for long-term cyclones in Rarotonga is available at present. The previous JICA team (1991) estimated the offshore wave height and period of 30 ~ 50 years return period based on Cyclone "Sally", which passed over Rarotonga in January, 1987. Another extreme value was obtained by Kirk (1992), relating the offshore significant wave height and the return period using some wave data incident on the north coast of Rarotonga. Figure 4-1-1 shows the distribution of the extreme event by the Weibull function based on 3 cyclones occurred from 1978 to 1992. Listed in Table 4-1-1 is the calculated significant wave height for several return periods. Kirk pointed out that the wave height previously obtained by the JICA team is 15 years return period if fitted on his distribution curve. Although the determination of 100 year offshore wave in 3 samples for 15 years is inadequate, the lack of data makes it impossible to make improvements of the confidence. In this study thus a wave height of 12 m is adopted as the 100 years significant wave off Avarua coast.

Kirk did not analyze the wave period corresponding to the 100 year significant wave. Wilson method, however, predicts not only the significant wave height but also wave period in the moving cyclone, once the central air pressure, radius of maximum wind, maximum surface wind, forward speed, and moving track are given as an input data.