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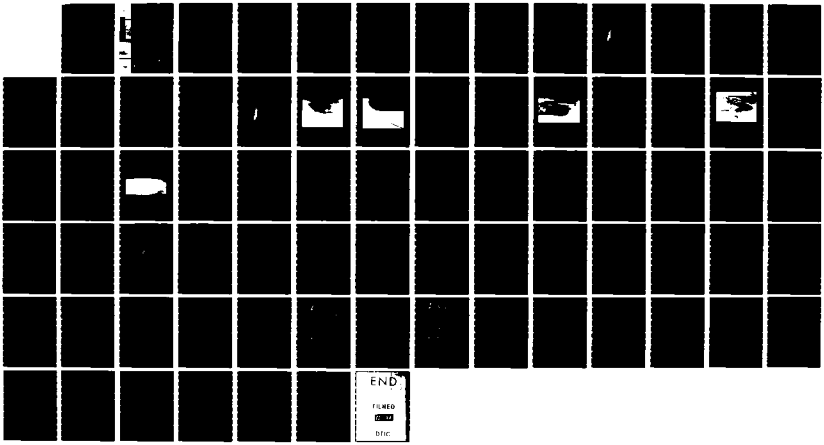

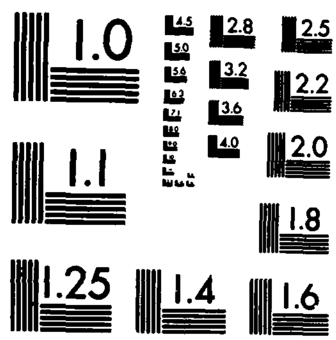

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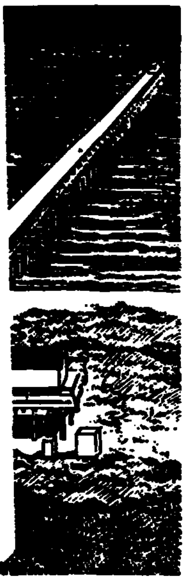

MISCELLANEOUS PAPER CERC-83-6

SEDIMENTATION INVESTIGATION AT MASIRAH ISLAND, OMAN

by

Craig H. Everts, Andrew W. Garcia, Edward P. Meisburger
Coastal Engineering Research Center
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study was conducted by the U. S. Army Corps of Engineers Coastal Engineering Research Center (CERC) to provide assistance to the Sultanate of Oman. After analyzing results of field observations and measurements made at Masirah Island, CERC investigators concluded the following:

a. The saltwater intake structure (groin) built in 1982 by the United States will not cause sediment to accumulate and cover either this

(Continued)

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or a nearby Sultanate of Oman Air Force (SOAF) intake structure.

b. The intake groin will not cause erosion but will create a slightly more stable beach.

c. If a proposed pier is built over the U. S.-built groin, or as near south of it as possible, pier length will be reduced to a minimum; if a compound pier--consisting of a rubble-fill section extending to the end of the existing groin and a pile-supported section extending to the pier's end--is constructed, sedimentation problems at the U. S.-built and SOAF saltwater intakes will be minimized and effects on nearby beaches will be acceptable.

In addition to presenting these conclusions, the report provides wave and current data for use in design of the proposed pier and presents a means of using current speed and wave height to predict percents of time the pier can be used for vessels with specific handling characteristics.

Appendices A-E provide background, describe data collection and analysis procedures used, and present more specifically the findings on which the report's conclusions are based.

PREFACE

This report is the U. S. Army Engineer Waterways Experiment Station Coastal Engineering Research Center's (CERC's) response to a request of the U. S. Army Engineer Division, Middle East (Rear) (MEDED), to provide coastal engineering assistance to the Sultanate of Oman. Contact between MEDED and CERC was carried on by Mr. Roger Thomas and Dr. Craig H. Everts, respectively. A visit to the study site was made between 18 and 29 May 1983 by CPT Tim Beally, MEDED, Mr. Albert Charmot, MEDED, Mr. Andrew W. Garcia, CERC, and Dr. Everts. Mr. Garcia wrote Appendix D, Mr. Edward Miesburger, CERC, provided the analyses in Appendix B, and Dr. Everts prepared the rest of the report.

On 1 July 1983, CERC became part of the Waterways Experiment Station (WES) under the direction of Dr. Robert W. Whalin, Chief.

Commander and Director of WES during the publication of this report was COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, INCH-POUND TO METRIC (SI) UNITS OF MEASUREMENT

Inch-pound units of measurements used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
knots (international)	0.5144444	metres per second
feet per second	0.3048	metres per second

SEDIMENTATION INVESTIGATION AT MASIRAH ISLAND, OMAN

OBJECTIVES AND CONCLUSIONS

This report is the U. S. Army Corps of Engineers Coastal Engineering Research Center's (CERC's) response to a request of the U. S. Army Engineer Division, Middle East (Rear) (MEDED), to provide coastal engineering assistance to the Sultanate of Oman. The six objectives given below are those specified by MEDED. Conclusions following each of the objectives were the result of a two-part approach involving observations and measurements made in the field and subsequent analyses conducted at the CERC. Justification and additional information pertaining to the conclusions are presented in the Appendices A-F.

1. To Determine whether the U. S.-built saltwater intake structure (groin) will create sedimentation problems.

Effects of the intake groin are and will continue to be small. The living coral reef between the narrow littoral zone and Masirah Channel (see Figure 1) is primarily responsible for the slight effect because the groin lies predominantly landward of the reef and the intakes are seaward of the reef. The two main concerns involving the intake groin were (1) whether the structure will act to trap sand against its northern side and, therefore, create sedimentation problems at the Sultanate of Oman Air Force (SOAF) and U. S.-built saltwater intakes and (2) whether the structure will act to accentuate erosion in front of the Beach Club and SOAF desalinization plant.

A sand fillet will not form in the littoral zone and cover the intakes. Sediment that enters the intakes is and will continue to be suspended in the tide- and wind-induced current in the channel. The only possible effect the structure could have on the intakes is to act as a flow deflector and increase (1) the amount of material that is suspended and (2) the distance the material is suspended above the bottom. While it is doubtful this will significantly affect the amount of sediment moving through the SOAF system, it would be useful to monitor future sedimentation rates in the SOAF sump and compare them to past rates.

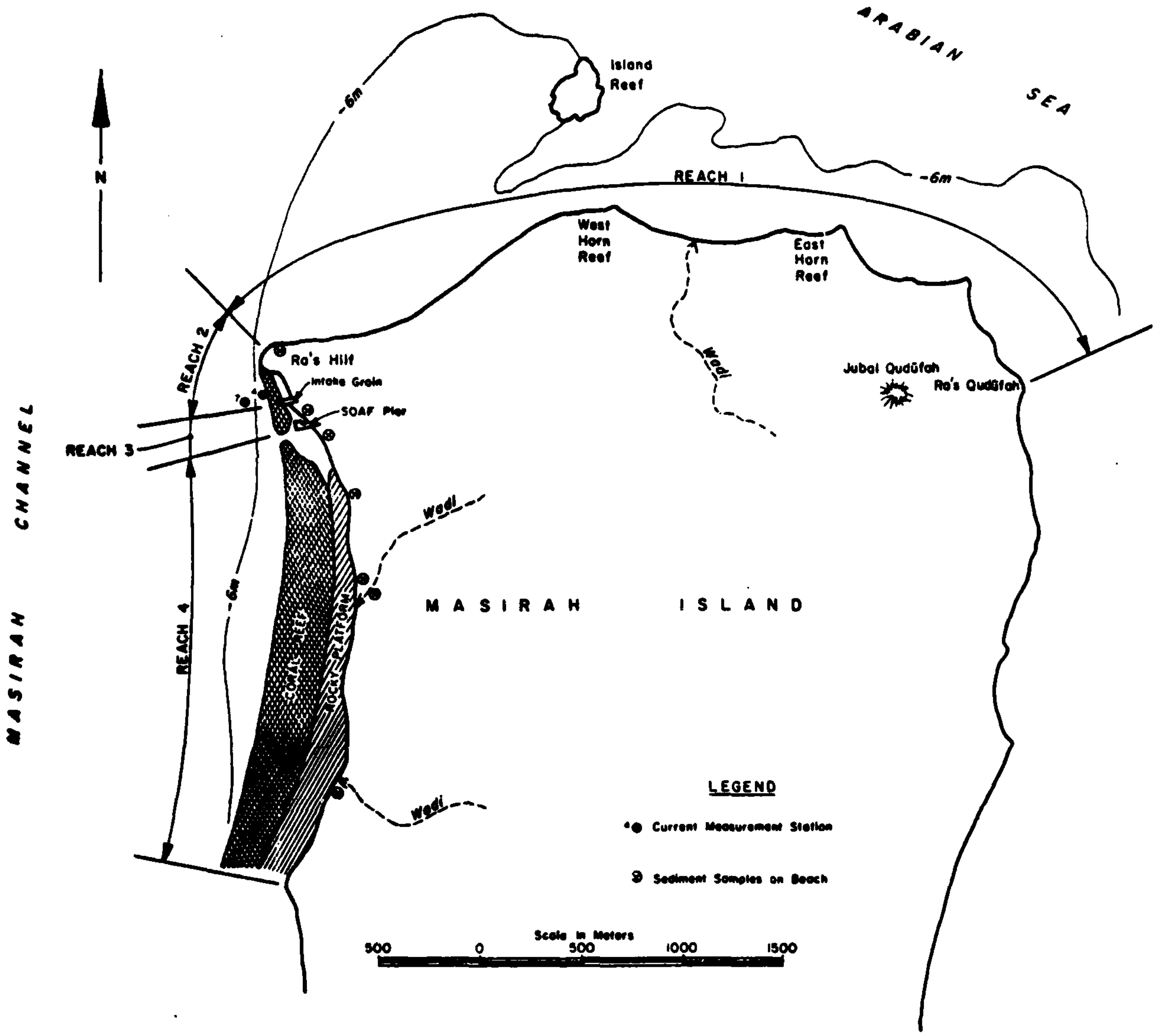

Figure 1. Location map showing features considered in the investigation of sedimentation at Ra's Hilf, Masirah Island, Oman

The intake groin will, if it has any effect, create a slightly more stable beach in front of the buildings. Note, however, that since the magnitude and duration of SW monsoon and nonmonsoon waves can vary greatly from year to year and since storm frequency also varies, changes can occur in shoreline position. These changes should not be attributed to the structure.

2. <u>To determine the effect of sediment redistribution caused by the following:</u>

a. A proposed 300-m-long pile-supported pier. A pile-supported pier in the northern one-half of Reach 3 (Figure 1) would have no effect on adjacent shorelines beyond that which has already occurred and is occurring as a result of the U. S.-built intake structure.

b. A proposed 300-m-long rockfill pier. The effect of a continuous rockfill pier out to the -7-m (MLW) contour could be great. While it would probably not cause beach sand to move onshore or offshore across the coral reef at the pier, it would likely produce major changes in longshore sediment transport, especially in Reach 2. The spit at Ra's Hilf would likely build east into Masirah Channel, thereby creating a permanent loss of Reach 1 beach sand during the non-SW monsoon period. In addition, sediment transport south over SOAF and U. S.-built saltwater intakes would probably occur. The fillet created against the north side of the pier would likely be permanent because the structure would prevent its destruction during the SW monsoon period.

c. A proposed combination rockfill (to -3-m or -4-m depths) and pile-supported (on out to -7-m depth) pier. This pier, if located in the north one-half of Reach 3 (Figure 1), would not affect adjacent shorelines or the saltwater intakes beyond that which has occurred and is occurring as a result of the U. S.-built intake structure.

3. To recommend a pier location and pier type in which sedimentation problems would be minimized.

The optimum pier location will be over the U. S.-built intake groin, or as near south of it as possible. Orientation would be near normal to the trend of the adjacent -7-m (MLW) depth contour in Masirah Channel. This location will reduce pier length to a minimum. If a rubble-fill pier section is constructed from shore to not beyond the present length of the U. S.-built intake groin and a pile-supported section is constructed further west, sedimentation problems at the U. S.-built and SOAF saltwater intakes will be minimized and impacts on nearby beaches will be acceptable. This type of compound pier can be successfully sited anywhere in the northern one-half of Reach 3 (Figure 1) without creating sedimenation and shoreline change problems; if the structure is built south of the U. S.-built intake groin, pier length must increase progressively with distance from the groin.

4. <u>To provide wave and current data to be used into pier design.</u>

Tables 1 and 2 represent maximum wave and current conditions for a 7-m water depth in Masirah Channel seaward of Reach 3 (Figure 1).

Table 1

Maximum Wave Conditions

Direction	Fetch km	Depth m[a]	Wind Velocity m/sec	Wave Height m[b]	Period sec
SW	75	10	25[c]	2.3	6.0
W	20	5	25	1.2	4.5
NW	15[d]	5	25	1.2	4.5
N	45	7	25	1.7	5.5
			45[e]	2.4	6.0
NE	100		25	4.0	8.5
			45[f]	7.2	10.2

[a] Characteristic depth for calculations using revised shallow-water theory (Coastal Engineering Research Center 1981a).
[b] Highest one-third of all waves.
[c] Maximum SW monsoon winds.
[d] Fetch could vary from 12 to 20 km, depending upon area of wave origin.
[e] Very infrequent cyclonic storms (such as that which occurred in June 1977).
[f] Assume deepwater conditions.

Table 2

Maximum Current Conditions

Direction	Wind Velocity m/sec	Current Speed, m/sec: Wind Component	Tide Component[a]	Total
N	25[b]	1.5	1.8	3.3
	45[c]	2.7	1.8	4.5
S	25[b]	1.5	1.8	3.3

[a] Spring tide range = 2.6 m.
[b] Maximum assumed noncyclonic winds most frequently (0.5/yr) from the south.
[c] Very infrequent cyclonic winds assumed only from north quadrants.

5. To provide information on percent of time the pier can be used based on ship criteria provided by Ministry of Defense, Engineering Division, Sultanate of Oman (MODED).

Figure 2 shows the percent of time as percent of tidal cycles in which a specific current speed is exceeded; i.e., at some time in the tidal cycle the current speed will reach the maximum given. Figure 3 shows the percent of time the given wave height will be exceeded. During a flooding tide when current is directed south and SW-monsoon-generated waves are directed north (i.e., during wave-current interaction), wave heights may be slightly larger than those in Figure 3. The MODED request can be addressed using Figures 2 and 3 when the MODED criteria are provided.

6. To review the Stanley Consultants, Inc. (1983) Report.

The report is well written and inclusive. Conclusions reached are technically accurate with the following exceptions:

a. Page 5. Spit growth is primarily the result of seasonal changes in longshore sediment transport directions, not the result of construction activity.

b. Page 6. There is no distinct NE monsoon at Masirah Island.

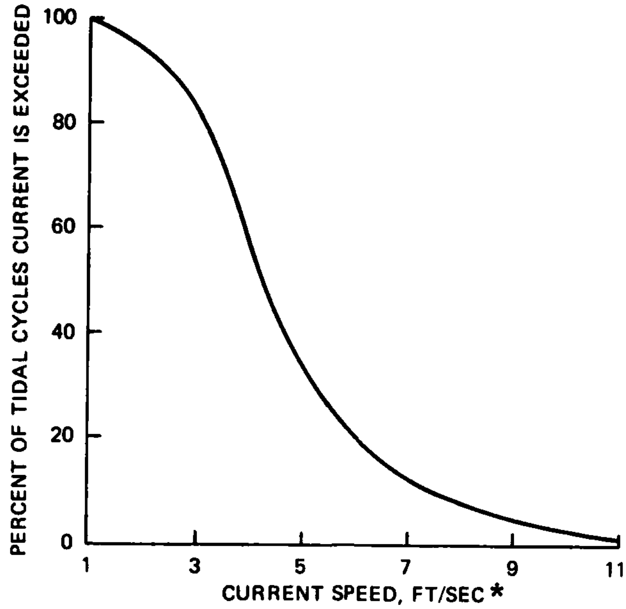

Figure 2. Percent of total tidal cycles each year in which the current speed at some time in the tidal cycle (direction north or south) exceeds that shown. Current is the combination of wind-driven current and astronomical tide-driven current. Maximum currents occur during times of the SW monsoon and spring tides. Maximum currents will be from south to north except perhaps, during cyclones

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* A table for converting the inch-pound units of measurement used in this report to metric (SI) units is found on page 3.

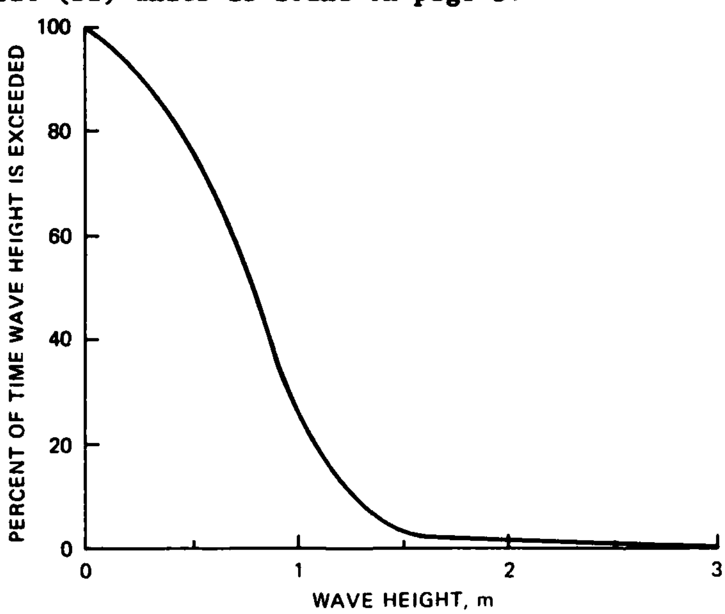

Figure 3. Percent of time the wind-generated wave height is exceeded at Ra's Hilf Anchorage for waves from all directions except for winds from the east, south, and southeast (1 m = 3.28 ft)

c. Pages 9-11. Wave analyses did not consider refraction, consequently the effective fetches presented in Table 3 are too short and design wave heights are too small. CERC suggests design wave data given in this report be used.

d. Page 14. Parallel bottom contours in the nearshore region should not be assumed. The coral reef along Reaches 2, 3, and 4 (Figure 1) and the rocky platform also fronting Reach 4 have a profound effect on the angle of breaking waves (See Appendices A and E, this report).

e. Page 17. Use of the constant 7500 in the energy flux factor method to estimate longshore sediment transport rates is incorrect; 7500 is much too large, at least for Reaches 2, 3, and 4 (see Appendices A and E, this report). The small volume of sand on the beach and the narrow littoral zone preclude use of that CERC (1972) value.

f. Page 18. Net longshore sediment transport rates shown in Table 9 are too large, and the directions appear incorrect in light of field evidence (see Appendices A and E, this report).

g. Figures 8, 9, and 10. See Appendix F, this report.

h. Page 20. Maximum currents in water depths of -4 m to -8 m (mlw) when used for design should be as given in this report. A maximum surface tidal current of 1.2 m/sec is much too low.

EXPLANATION OF APPENDICES

Appendices A-F contain a description of the approach used in collecting information and data, the analytical procedures which were used, and the interpretations that form the basis for the study conclusions. Appendices A-D deal with data and field observations and are entitled as follows: Appendix A: Coastal Geomorphology, Appendix B: Coastal Sediments, Appendix C: Currents, and Appendix D: Waves. Appendix E: Sediment Transport Without Structures at Ra's Hilf and Appendix F: Sediment Transport With Structures at Ra's Hilf rely heavily on Appendices A-D.

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APPENDIX A: COASTAL GEOMORPHOLOGY

The shoreline affected by and affecting the existing US-built intake structure, which acts as a groin, and the SOAF intake and which would be affected by the proposed pier is herein separated into four reaches. Each of the reaches has a considerably different cross-sectional shape and plan shape. In each reach, past shoreline changes have differed markedly, sediment input from land (wadis) differs, and the coastal processes causing longshore and cross-shore sediment transport differ . Figure A-1 is a location map of the reaches.

1. REACH 1.

This 1.4 x 10^4 - ft (4300-m) long reach extends west from Ra's Qudūfah on the Arabian Sea to Ra's Hilf which faces Masirah Channel. The shoreline along the eastern half of the reach is dominated by four points identified as reefs, but composed of blocky basalt as shown in Figure A-2. This appears to be the same material found on Jubal (hill) Qudūfah (Fig. A-1), suggesting that the "reefs" are in-place basalt. There may be coral reefs offshore, but that was not substantiated by this study. The western half of Reach 1 (West Horn Reef to Ra's Hilf) is sandy (Fig. A-3).

a. Coastal Shape. The "reefs" east of West Horn Reef (Fig. A-1) create headlands (Fig. A-2) with pocket beaches between. Sediments in the pocket beaches are relatively coarse (M_d = 0.3 to 0.4 mm) and composed of much shell hash. West of West Horn Reef the beach sediments are much finer (M_d = 0.1 to 0.2 mm) and the shoreline is slightly undulating (Fig. A-3).

East of West Horn Point the beaches are relatively stable. West of West Horn Point, however, the shoreline varies greatly and predictably by season, depending on wave approach direction. Long-term changes in this area are harder to determine, but the net is probably one of accretion. In the period September - May a spit usually forms west of West Horn Point. From May through September the spit is eroded and reduced in size. The profile seaward of the beach is very gradual, slightly convex up (indicating accretion) in Reach 1, and the offshore bottom is composed of sand.

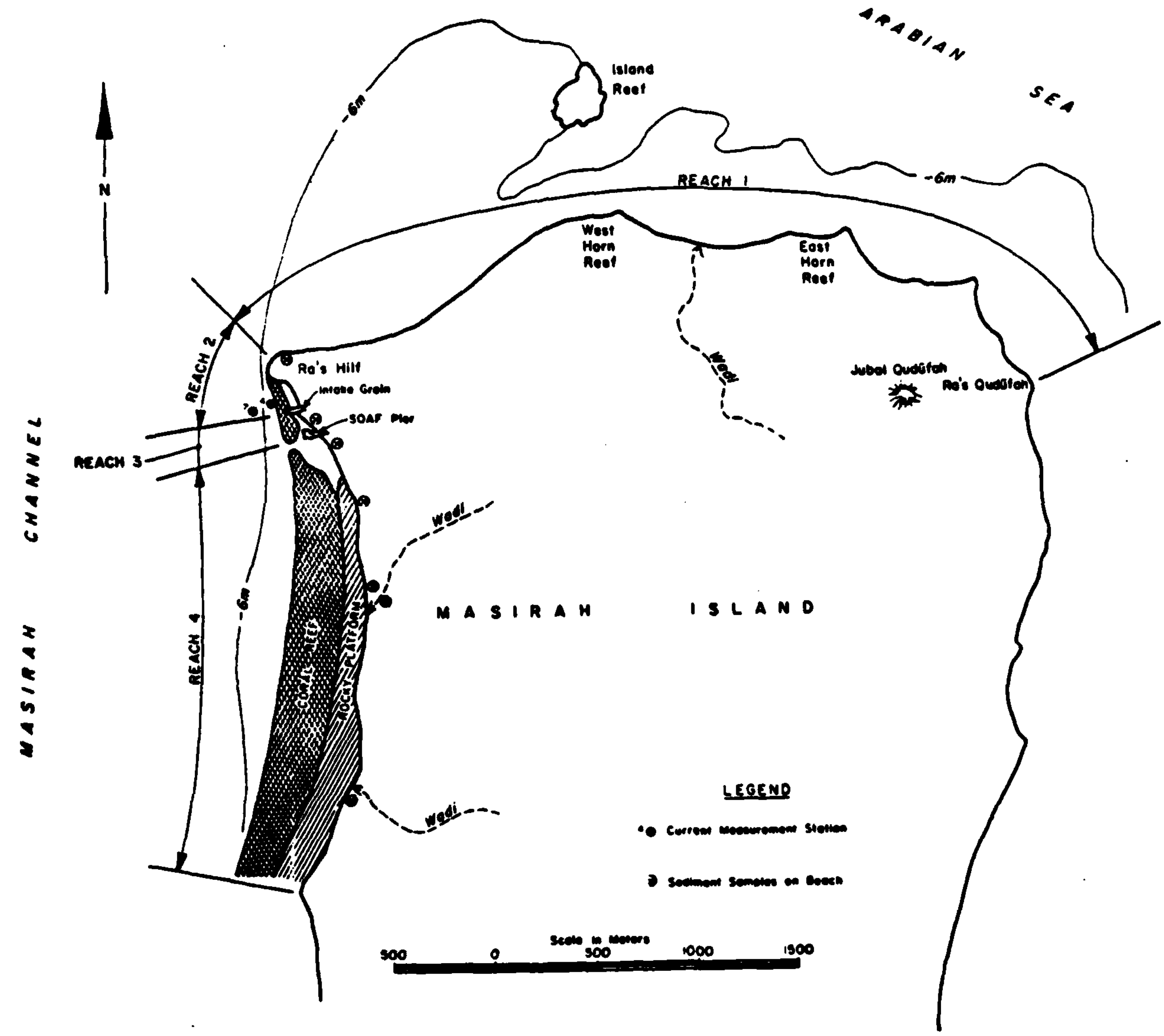


Figure A-1. Location map showing shore reaches considered in sedimentation investigation at north end of Masirah Island, Oman. Shoreline position is that of April 1980 a month before the Southwest monsoon began. Data are from a 1:5000 aerial mosaic by B.K.S. Surveys Limited, Mutrah, Sultanate of Oman. The shoreline shown is also approximately that which existed in May 1983 at the start of the Southwest monsoon. The intake groin was constructed in December 1982

Figure A-2. View east in eastern one-half of Reach 1. East Horn Reef is the prominant headland in the center of the photograph. Note: (1) the crenulate-shaped bay southwest of the headland indicates net longshore sediment transport is to the right (west) and (2) swell waves from the east are breaking at an angle such that littoral sand was being transported west when the photograph was taken (25 May 1983)

Figure A-3. View west in western one-half of Reach 1. Ra's Hilf is in the center background. Waves which origniated in Masirah Channel have refracted around Ra's Hilf and are breaking at an angle to the beach such that longshore sediment transport is to the east (bottom of photograph)

b. Coastal Processes. East of West Horn Reef the dominant direction of wave approach is from the east, which includes waves generated by the SW monsoon. Consequently, longshore transport is from south to north and/or east to west in this area. A series of indistinct beach ridges on an April 1980 aerial mosaic indicates a large accumulation of sand has formed over a long time period (>10^2 yr) between Ra's Qudūfah and the next reef to the north. The orientation of the ridges indicates transport was from the south coast. Material in the area east of West Horn Reef is on the east side of the headlands, again indicative of longshore transport to the west. During the beach reconnaissance (May 22, 1983) waves ($T = 7$ seconds, $H_b = 0.3$ m) were approaching from the east; the SW monsoon was about 15 knots at the time. Because the "reefs" are permeable (Fig. A-2), some sand passes through and around them.

Further west, between West Horn Reef and Ra's Hilf, SW monsoon-created waves on 22 May 1983 ($T = 3.4$ seconds, $H_b = 0.2$ m) were approaching from the west (Fig. A-3) and longshore sediment transport was to the east. This is likely typical of the SW monsoon that prevails from May through September in this area. During the remainder of the year when the wind direction is variable, the net transport is east to west. This is what produces the recurved spit at Ra's Hilf between October and May each year. West Horn Reef is, thus, alternately a longshore sediment transport convergence zone (May - September) and a partial divergence zone (October - May).

Since reefs, except possibly seaward of the basaltic headlands, are mostly absent in Reach 1, sand probably moves on and offshore depending on conditions; storms would carry it seaward; swells would return it. Very likely the net transport is onshore as evidenced by the large quantities of shell hash on the beach.

Quite likely the sediments west of West Horn Reef are derived from offshore sources and from Masirah Channel; i.e., as a result of a net transport from south to north in the channel. Channel velocities are certainly large enough to transport the sediment, and along the length of Masirah Channel there is an ample source of fine-grained material. At Ra's Hilf Anchorage the bottom is gravel and coarse sand. Currents are so swift there, fine material will not settle out. Very likely, however, much fine material is carried over the bottom from sources to the south. The large shoal (5 x 10^3-ft long by 4 x 10^3-ft wide) extending northeast into the Arabian Sea was probably created by sediment transport north from Masirah Channel.

Sediments east of West Horn Reef are likely a mixture of material which was transported onshore from the Arabian Sea and parallel to shore from sources along the east side of Masirah Island. Beach sediment adjacent to West Horn Point is a mixture of material from Masirah Channel which was transported north and west. A small quantity of sediment is infrequently carried into the system from a wadi just east of West Horn Point. But this does not appear to be a major source of sand on the north side of the island.

2. REACH 2.

This reach (Figs. A-1 and A-4) extends between Ra's Hilf and the US-built intake structure (hereinafter called the intake groin). It contains a highly variable, but predictable, shoreline and is the most dynamic reach in the study area.

a. Coastal Shape. South of Ra's Hilf a narrow reef effectively separates the littoral (beach) sediment transport zone from the channel sediment transport zone. From the south to the north in this reach, the distance from shore to the -7-m (mlw) contour decreases by one-third.

At present, Reach 2 is affected by the intake groin. According to Mr. Bill Little (SOAF) and others on Masirah Island, the recurved spit extended slightly south of its usual southern limit during the October 1982 to May 1983 non-monsoon period. This is reasonable since the intake groin, which was constructed in December 1982, tends to block waves which approach from the south.

Figure A-4. View of Ra's Hilf to the south showing the recurved spit which formed during the non-SW monsoon season, the US-built intake groin, and the SOAF pier. Dark irregular patches in the water on the upper part of photograph are cloud shadows. Note the photo was taken during the SW monsoon and wave refraction is such that waves breaking on the spit are eroding sediment and transporting it to the north and east

t. Coastal Processes. Seasonal changes in the plan shoreline shape in this reach are predictable. During the non-SW monsoon period (October - May) winds predominantly, but variably, blow from the north and eastern quadrants and generate waves that cause sediment to move west along Reach 1 and south for a short distance along Reach 2. The result is the recurved spit shown in Figure A-4. During the SW monsoon, sediment comprising this spit is moved north and slightly east, some of it to nourish the beaches in Reach 1 and some into the large shoal northeast of Ra's Hilf. The volume of sand moved into and out of the spit deposit over the period of a year is approximately 2.5×10^4 yd^3/yr (1.9×10^4 m^3/yr). This is based on a plan area change of 5.8×10^4 ft^2 (5.3×10^3 m^2) as shown on Figure A-5 and a depth of 4 m (MLW as shown on USNHO Chart* 62352). The depth is probably a good estimate because it represents the depth at the north end of the reef. The reef ends at the spit location (Fig. A-1). Possibly some, but not much, sediment is transported into the channel and lost to the beach system during the SW monsoon period. Sediment moved during the monsoon period likely all remains in the beach zone until it passes Ra's Hilf. Beach sand is fine to medium, shelly carbonate sand. Sand granule and gravel-sized basaltic rock fragments were observed on the beach on 24 May 1983.

Sediment moves in the channel west of Reach 2 but, because of swift currents, is not deposited. Surface bottom sediment in -4 to -7m in Reach 2 is gravel, cobbles and medium-to-coarse shelly carbonate sand (from boring data supplied by MEDED).

Wave approach direction during the SW monsoon season (24 May 1983) was normal to shore except at the recurved spit (Fig. A-4) where the approach was from south of shore-normal. This created a net north longshore sediment transport at the spit. Wave diffraction at the intake groin (Fig. A-6) caused the waves to approach in a shore-normal direction in the embayment at the Beach Club. Wave height in the embayment was 0.4 m and decreased to 0.2 m along the spit. Wave period was 3.4 m sec. with a 15-knot wind from the southwest. As the spit deposit retreats east, this embayment will likely deepen in the lee of the intake groin. The evolution of the embayment is treated in Appendix E.

* U. S. Navy Oceanographic Office Chart.

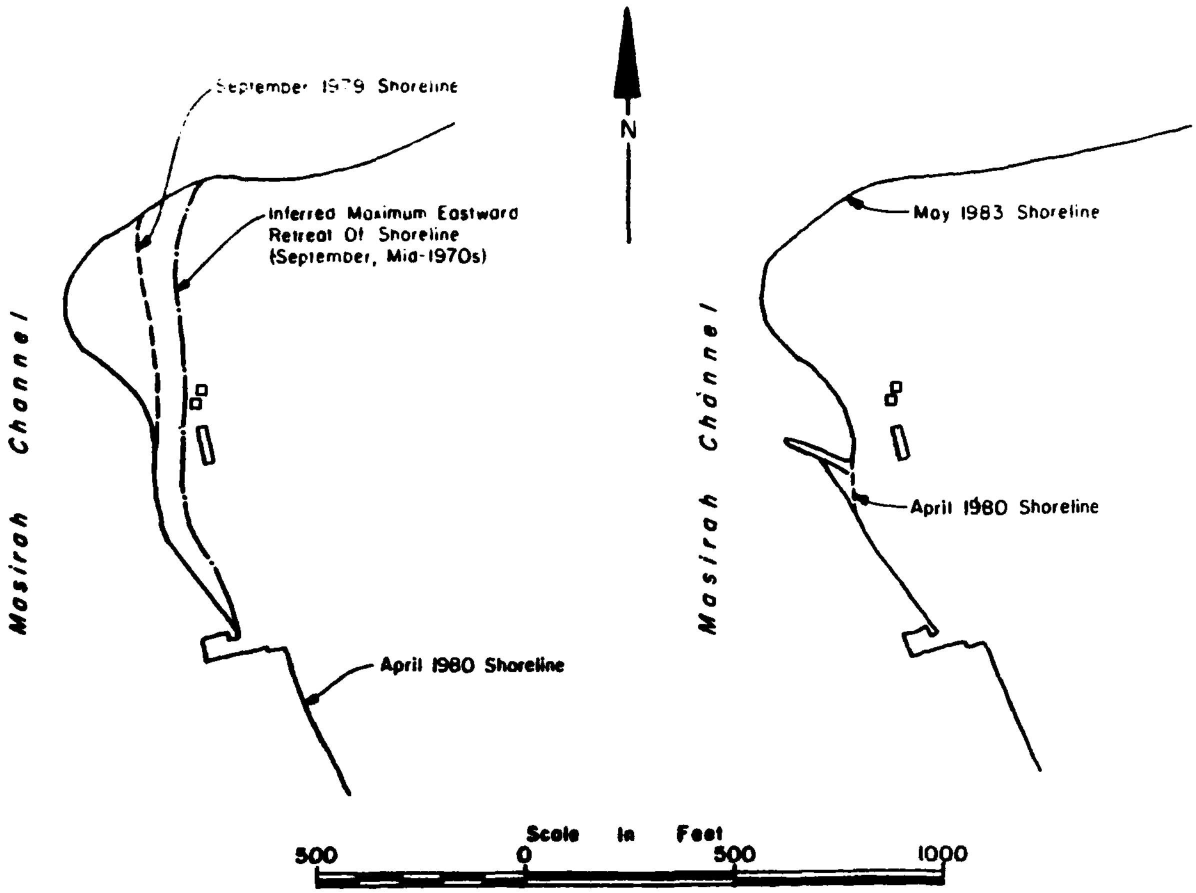


Figure A-5. Left-hand diagram shows pre-intake groin shoreline positions at Ra's Hilf for a post-SW monsoon period (September 1979) and pre-SW monsoon period (April 1980). Right-hand diagram shows post-intake groin shoreline position for a pre-SW monsoon period (May 1983)

Figure A-6. SOAF pier (right) and US-built intake structure (left). Note wave diffraction at end of intake structure, and general shore-parallel orientation of breaking waves. SW monsoon winds were about 15 knots when this photograph was taken (25 May 1983)

3. REACH 3.

Located between the intake groin and the SOAF pier, this reach is the prospective site of the new pier.

a. Coastal Shape. Like Reaches 2 and 4, part of this reach is bordered by a living coral reef (Fig. A-7). The shoreline of Reach 3 has always been oriented north-northwest (Figs. A-1, A-6) and since the intake groin was constructed the orientation has become even more northwest. However, it is not clear whether this is the result of artificial reorientation created during construction, or natural reorientation driven by a change in the net wave approach direction resulting from the structure. Quite likely Reach 3 is now in the process of slight clockwise rotation. Angular cobbles and pebbles on the beach along the northwest one-half of the reach appear to be construction material. During the SW monsoon of 24 May 1983, wave approach was slightly north of shore-normal in the northwest part of the reach indicating a net southeast sediment transport during monsoon conditions. Both lines of evidence suggest Reach 3 is in the process of reorientation.

b. Coastal Processes. This reach has historically been quite stable. A 26 September 1973 (post-SW monsoon) aerial photograph in the SOAF Operation Building shows the ramp at the Beach Club held the reach before the intake groin was constructed. That is, the ramp also acted as groin and, during the monsoon, net longshore transport was from south to north. The May 1980 (pre-SW monsoon) aerial mosaic supplied by MEDED also showed a south fillet at the boat ramp—about a 25-ft. (8-m) offset— which indicates non-monsoon transport is also south to north in Reach 3. Apparently the re-entrant of the received spit in Reach 2 is the nodal point for longshore transport south of Ra's Hilf.

It is likely only small volumes of sediment were lost from Reach 3 at the north end before the intake groin was constructed. With the intake groin, which extends across the coral reef, little, if any, sediment passes that cross-shore barrier. At the south end of the reach the inboard portion of the SOAF pier acts as a littoral barrier. The fillet has always been

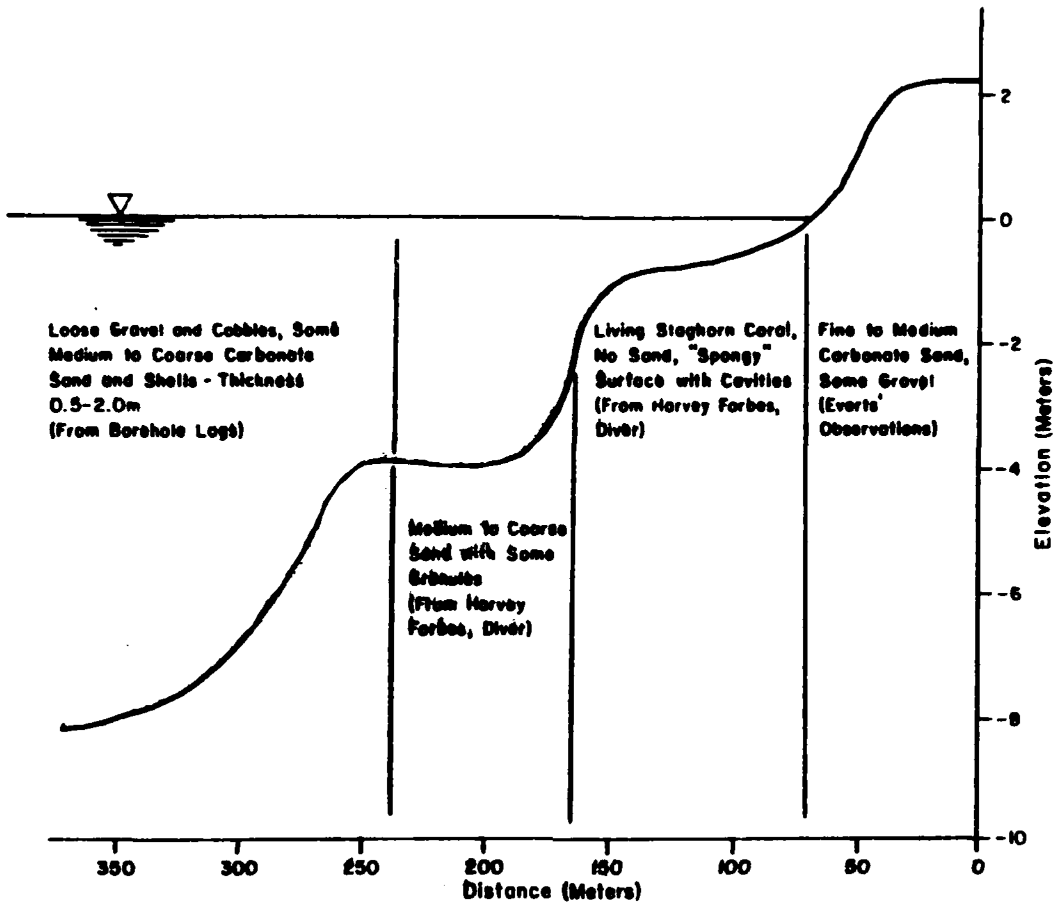


Figure A-7. Cross-section, showing surface sediment characteristics at the Stanley Consultant, Inc., proposed pier site near the middle of Reach 3 at the north side (Reach 3 side) of the pier. This is an area of accumulation of coarse shell fragments and coarse sand which suggests net longshore sediment transport is north to south.

The Reach 3 beach is, and in the past has been, held between two fixed shore-normal structures which probably allow little sand to pass downdrift. Very likely the net longshore sediment transport rates in Reach 3 (north at the north end, south at the south end) are very small. Therefore, since offshore transport is probably non-existant and onshore movement near the SOAF pier is small, this reach is relatively stable. In the future, this reach will likely remain stable with only a slightly clockwise rotation until it reaches a dynamic equilibrium.

4. REACH 4.

This reach extends north from the Omani Village of Hilf to the SOAF pier (Fig. A-1). Beach sands in this area appear to contain less calcium carbonate than those east of Ra's Hilf, probably because of the input of wadis.

a. Coastal Shape. The planview shoreline forms a gentle concave shape with a few slight undulations created because of differential sediment transport resulting from wave refraction around rocks and the offshore reef (Fig. A-1). A rocky zone extends south from a point about 250 m south of the SOAF pier to south of Hilf; Figure A-8 shows the rocky platform at low tide on 23 May 1983. That platform increases in width to the south reaching a maximum 150 m at Hilf. It extends from about +0.5 m MLW (mean low water) to about -0.5 m MLW. There was very little sand on the rocky platform on 23 May 1983 and little indication sand frequently moves across or along it.

The reef, composed of living staghorn coral according to Harvey Forbes, the Dillingham diver, extends about -0.5 m to -2.0 m MLW along almost the entire length of Reach 4. A small break in the reef exists seaward of the SOAF pier. The Dillingham - Stanley hydrographic survey (16 April 1983), entitled "Masirah Island Pier Survey" shows this non-reef area is without

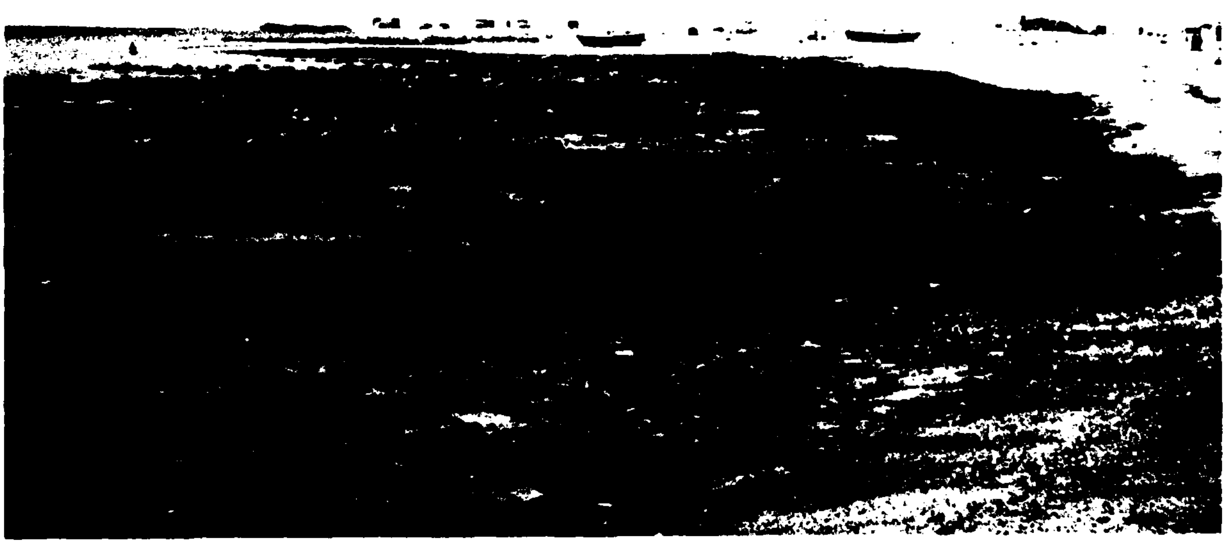


Figure A-8. Rocky platform between the sandy foreshore and the coral reef in Reach 4. View is north toward the SOAF pier. Note the small volume of sand available for longshore transport on the beach. Beach sand does not appear to pass across the rocky platform the steep profile gradient between -1.5 and -3.0 m (MLW) which is characteristic of the western (deep water) coral reef edge. The reef surface is porous and to some extent covered with brown easily-broken shells. Cavities in the coral area are preferred haunts of octopi, crayfish and finfish.

Bottom sediment beyond the coral reef (water depths in excess of -3 m MLW), according to Forbes, is medium to coarse sand with some granule and gravel-sized material. Borings made by a subcontractor to Stanley Consultants show similar material beyond the reef between the SOAF pier and the intake groin.

A clear progressive change in the foreshore and berm characteristics between Hilf and SOAF pier was measured on 23 May 1983. At Hilf the berm elevation was low, only about 0.5 m above the rocky platform; berm elevation then increased to the north reaching 2m just south of the pier. This corresponds to a narrowing of the rocky platform to the north. Breaking waves on the platform on 23 May were 0.1 m at Hilf and only reached 0.2 m at the north end of the rocky platform (Fig. A-1). Between the pier and the beginning of the rocky platform the waves were 0.3 m. Lower waves to the south were clearly a result of wave attenuation over the coral reef and rocky platform.

The beach in Reach 4 is stable. An Omani Fisherman (No. 3) said the beach at and north of Hilf does not change, either seasonally or year-to-year. Comparisons of vertical and oblique aerial photographs, ground photographs, and existing charts all indicate the beach in this reach is stable. During the SW monsoon a small fillet builds at the south side of the pier but does not overtop the ramp (Fig. A-6).

b. <u>Coastal Processes</u>. Reach 4 has two district sediment transport systems, the beach and the channel seaward of the coral reef (Fig. A-1). With the exception of the short (about 200 m) section just south of the pier, it appears there is little or no sediment transport in an onshore or offshore direction across the reef-rocky platform area.

Longshore transport also is minimal. Even during the period of the SW monsoon little sediment is transported to the north as evidenced by the small fillet that builds along the south side of the pier. During the 22-25 May 1983 visit to Masirah Island, SW monsoon winds varied from 5 to 25 knots. And, on eight separate occasions, with different wind velocities, waves were always observed to break parallel to shore south of the pier. This indicates wave refraction across the reef and rocky platform is substantial; it also indicates the Reach 4 shoreline is in near-equilibrium with waves created by the SW monsoon. Waves from the north during the October - May period probably have little effect on this reach because of protection afforded by Ra's Hilf. Also, because there is a relatively small volume of sand in the beach littoral system, longshore transport must be very low or a large relative quantity of the material would have moved.

Like sediment transport in Reaches 2 and 3, a large quantity moves seaward of -3 m (MLW). This current-transported sediment is not deposited in the channel seaward of Reach 4 because the current velocities are too large.

APPENDIX B: SEDIMENTS

During the beach reconnaissance efforts of 22-24 May 1983, visual observations were made of sediment size and sediment composition between Ra's Qudūfah and Hilf. These observations, which provided certain indications of sediment transport direction, are described in Appendix A. During the reconnaissance period samples were also collected at the sites shown on Figure A-1. Analyses of these samples were made to establish, if possible, containment boundaries for longshore sediment transport, especially between Reach 3 and Reach 4 (Fig. A-1), and the net direction in which the sediment moves. Coupled with wave and wind data, this information can be used to define sediment transport patterns. Results of the sample analyses are the subject of this appendix.

1. DATA.

a. Reach 2. Surface sediment sample collected from the mid-foreshore 60 m south of Ra's Hilf on 24 May 1983 (400 m north of SOAF Pier).

b. Reach 3. Surface sediment sample collected on the mid-foreshore 100 m north of the SOAF pier on 23 May 1983.

c. Reach 4.

(1) Surface sediment sample collected on the mid-foreshore on the north side of Hilf on 23 May 1983 (2000 m south of SOAF pier).

(2) Surface sediment sample collected on 23 May 1983 on the mid-foreshore about 800 m south of the SOAF pier at the outlet of a small wadi which drains the west airfield area.

(3) Surface sediment sample collected on 23 May 1983, 60 m inland in the wadi (about 800 m south of SOAF pier); collection site is probably inundated by spring tides.

(4) Surface sediment sample collected on the mid-foreshore 400 m south of the SOAF pier on 23 May 1983.

(5) Surface sediment sample collected on the mid-foreshore 100 m south of the SOAF pier on 23 May 1983.

2. DATA ANALYSIS.

The six beach foreshore samples were used in the analyses. The wadi sample was partially used to isolate land-derived components of the sediment population that could be expected to enter the littoral system.

Samples were sieved and separated into the four size fractions shown on Table B-1. Grains within each size fraction were analyzed, by count percentage, for (1) grain angularity; (2) grain roundness; (3) grain polish, i.e., the surface shine of the particle; (4) rock fragment content (land contribution) since most of the sediment was of marine carbonate origin; (5) quartz content; (6) foraminifera content (foraminifers are microscopic marine organisms with shells); (7) bryozoa content; and (8) barnacle content.

3. RESULTS.

Results are based upon analyses done by Mr. Edward Meisburger of the Coastal Engineering Research Center using grain counts of 300 to 600 for each analysis (Table B-1). Large differences in count percentages, which might indicate a littoral barrier or an indication of longshore transport direction, are underlined in the table. The following are interpretations of the data in Table B-1 and implications of those interpretations for each type of analysis:

a. Grain Angularity. The percentage of angular grains in a sample from samples north of the pier is generally much less than that south of the pier for the two smaller size fractions. This indicates the SOAF pier may be a partial or complete littoral barrier. All samples contain few angular grains in the coarser size fractions.

Table B-1. SEDIMENT GRAIN COUNT DATA

Sample and Location	Grains Counted	Angular	Rounded	Polished	Rocks	Quartz	Foraminifera	Bryozoa	Barnacles
Size: 0.125-0.250 mm									
2-400N	336	71.1	28.9	5.4	5.7	6.8	0.6	Not done	Not done
1-100N	300	76.7	23.3	6.3	5.3	7.6	2.7		
3-100S	301	93.0	7.0	1.7	1.0	2.7	17.6		
6-400S	304	93.1	6.9	1.6	1.6	4.3	26.0		
4-800S	338	82.5	17.5	3.0	8.9	6.7	0.6		
5-2000S	234	94.9	5.1	0.4	6.0	8.1	0.4		
Size: 0.250-0.425 mm									
2-400N	540	14.6	85.4	11.1	18.7	5.4	0.2	Not done	Not done
1-100N	580	14.3	85.7	12.1	16.0	4.0	0		
3-100S	508	40.3	59.7	4.1	4.9	1.6	9.6		
6-400S	373	12.9	87.1	1.1	2.1	0.8	36.7		
4-800S	656	16.8	83.2	3.8	8.7	2.7	0.7		
5-2000S	401	58.9	41.1	2.5	7.5	2.5	0.2		
Size: 0.425-0.850 mm									
2-400N	332	2.4	97.6	14.8	19.9	17.8	0	0.3	Not done
1-100N	433	6.2	93.8	19.6	21.7	18.7	0	1.1	
3-100S	451	5.3	94.7	7.9	14.2	29.7	0	5.1	
6-400S	343	2.3	97.7	5.0	6.7	15.5	0	14.9	
4-800S	409	5.1	94.9	5.9	8.3	10.8	0	6.1	
5-2000S	354	1.4	98.6	5.4	13.8	38.1	0	0.8	
Size: 0.850-2.00 mm									
2-400N	361	2.8	97.2	14.1	21.9	17.5	0	0	2.2
1-100N	341	2.3	97.7	21.1	20.5	19.6	0	0.6	2.1
3-100S	276	2.5	97.5	12.3	16.7	13.0	0	8.0	2.5
6-400S	302	2.3	97.7	4.0	7.6	4.6	0	18.5	6.6
4-800S	251	2.4	97.6	2.0	11.2	9.6	0	12.7	3.2
5-2000S	334	2.4	97.6	4.8	19.5	41.9	0	0.6	0.6

b. Rounded Grains. In the smallest size fraction, rounded grains are 3+ times more plentiful north of the SOAF pier than south of the pier. This partially indicates the pier may be a littoral barrier. Since the larger fractions are quite uniform in roundness, it also indicates the smallest grains north of the pier may exist in a more energetic region; i.e., have been subjected to more wave-caused abrasion.

c. Polished Grains. North of the SOAF pier polished grains average two to three times the average abundance found south of the pier in the all size fractions. This is a strong indication the pier is a littoral boundary. If the polishing occurs in the coastal zone, it also indicates the north end of Reach 4 is more energetic than the area further south. Because the rocky platform and coral reef are absent seaward of the north location (Fig. A-1), this is a reasonable deduction.

d. Rock Fragments. There is again a difference north and south of the SOAF pier. Rock (vs minerals, mostly carbonates) material is more abundant north of the pier, especially in the smaller size fractions. This indicates the pier is a littoral boundary. It also indicates wadi contributions of land-derived sediment are more important north of the pier; i.e., sediment has moved from the north side of the island around Ra's Hilf. This movement probably occurred over a long time interval. A well mixed sediment population north of the pier suggests that there are no complete littoral barriers in that area. Note that the net longshore sediment transport directions identified in Appendix A are the difference between transport north and south. Sediment moves in both directions, but one is dominant.

e. Quartz. This is a major constituent in all samples. It is indicative of a land source of sediments. In general, the samples north of the pier contain more quartz than those south of the pier. This substantiates the conclusions drawn from the distribution of rock fragments that land contributions are more important north of the pier.

f. Foraminifera. In the two smallest size fractions, there is only a small amount in all samples except Sample 3 (9.6%) and Sample 6 (36.7%), both of which are just south of the pier and in the area where the rock platform is narrow (Sample 6) or absent (Sample 3). This suggests there is onshore sediment just south of the pier but not across the rock platform. The high counts in this area are probably also due to favorable conditions for their preservation at the time of collection; i.e., at least 36% of the beach sediment at Site 6 has not moved far in the longshore transport system (foraminifer tests do not last long in the energetic littoral environment because of mechanical abrasion).

g. Bryozoa. North of the pier the average abundance in the larger size fractions is 0.8% and south of the pier it is about 7%. Bryozoa came from offshore. This variation in bryozoa suggests some onshore transport south of the pier and possibly a slight transport south away from the pier. Bryozoa, because they are fragile, may not remain on the higher energy beaches north of the pier.

h. Barnacles. Barnacle distribution is not diagnostic in the study area.

4. SUMMARY.

This sediment analysis effort provides information on longshore and cross-shore sediment transport and possibility of sand passing around the SOAF pier, a littoral barrier; land contributions of sediment to the beaches; and the energetics of different reaches.

a. From the perspective of sediment characteristics, the study area has two littoral segments: Reach 4, south of the pier; and Reaches 1, 2, and 3, north of the pier. The SOAF pier is clearly a littoral boundary.

b. Longshore transport is low in Reach 4, but higher in Reaches 2 and 3. These data provide little information on net transport direction.

c. Some onshore sediment transport is indicated in the region of the SOAF pier. The amount cannot be quantified.

d. The wadi sample is high in quartz, indicative of land-derived sediment, but the beaches are low in quartz. This suggests land contributions of sediment to the coastal zone are less than 5% of the total littoral sediment in the system in Reach 4. Wadi contributions are slightly higher on the north side of the island.

e. Reach 4, especially more than several hundred meters south of the pier, is clearly less energetic than the rest of the study reach.

APPENDIX C: CURRENTS

Relationships between the mechanisms that drive the currents and the current velocity at Ra's Hilf Anchorage are established in this section. Using available information and data collected on-site, an empirical methodology to estimate current velocity under any condition, including maximum event, is established for use in sediment transport analyses and structure design. While these procedures can be applied elsewhere the empirical relationships cannot because they are unique to the north end of Masirah Channel.

Two mechanisms predominate in driving currents at Ra's Hilf Anchorage. These are the astronomical tides and wind-created shear stress on the sea surface. The development of an empirical methodology to separately predict the tide-driven and the wind-driven components of current velocity is described.

1. DATA.

The following constitute all available current data and observer estimates of currents at and near Ra's Hilf Anchorage.

a. Field Measurements. On 23 May 1983, current, wind, and wave measurements were made from a small anchored boat at the 7-m and 4-m stations located in Figure A-1. Current speeds were measured using a Gurley current meter, Model 665. Current direction was obtained using the orientation of the wire supporting the current meter. Wave height and wind velocity were visually estimated. Figure C-1 illustrates the results of the field measurement effort.

Tide values at Masirah Island were based on an extrapolation of Muscat, Oman, predicted tidal values. No time difference exists between tide turns at Muscat and Masirah Island. The tidal elevation difference at Masirah Island relative to Muscat is given on US Navy Hydrographic Office (USNHO) Chart 62351. Tidal information at Ra's Hilf Anchorage is given in Table C-1, which was obtained from USNHO Chart 62352.

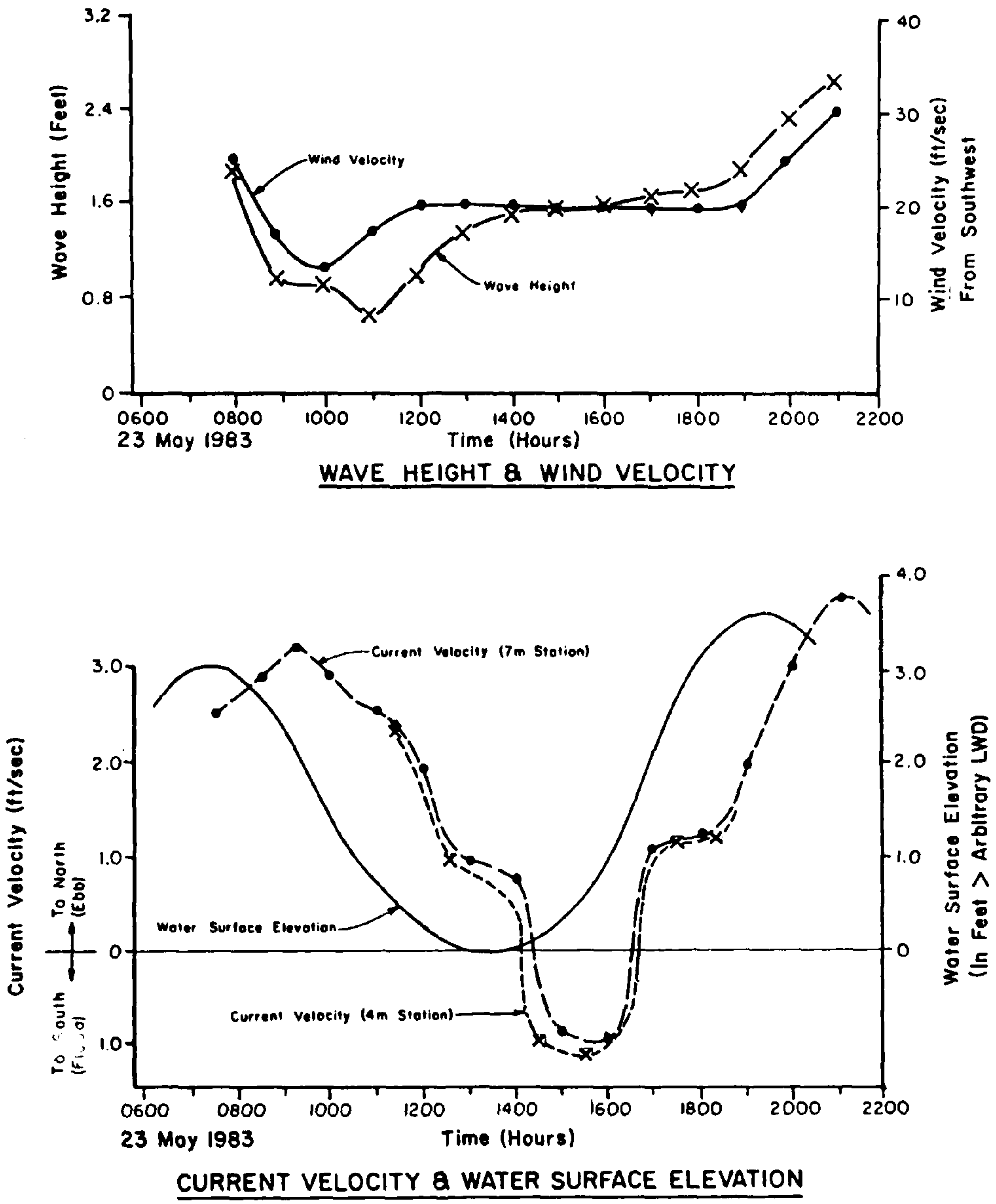


Figure C-1. Wind, wave and current data obtained on 23 May 1983, at a location 200 m (650 ft) north of the SOAF pier at Ra's Hilf, Masirah Island. Current, wind and wave data were taken at a station in the channel (Fig. A-1) where the water depth is 7 m (22 ft); current data only were also taken at a 4-m depth (13 ft) station sited at a permanent buoy near the SOAF salt-water intake structure (Fig. A-1). The 7-m station was located approximately 60 m (200 ft) west of the SOAF buoy

Table C-1. TIDAL INFORMATION AT STUDY SITE

AVERAGE TIDES			SPRING TIDES		
MHHW[1]	MLLW[2]	Range[3]	MHHW	MLLW	Range
6.5 Ft	0.9 Ft	5.6 Ft	7.6 Ft	-1.0 Ft	8.6 Ft

[1]MHHW = mean higher high water.

[2]MLLW = mean lower low water.

[3]Range = MHHW - MLLW (average maximum daily vertical water surface excursion).

b. Data From Charts. Figure C-2 illustrates current speeds over a complete tidal cycle from two locations in Masirah Channel, near the south end of the island and near the island middle. These data, when integrated over the complete tidal cycles, show there is little difference in the volume of water which moves north and south in the channel, i.e., there is no residual current. Data came from a table on USNHO Chart 62351.

Current speed and direction are given on USNHO Chart 62352 at Ra's Hilf Anchorage. Flood current direction is south (180°), ebb current direction is north (005°), and in each situation the maximum current speed is given as 3.5 knots (5.9 ft/sec). This is probably the maximum current speed that exists during a spring tide period without influence from the wind.

c. Local Visual Observers. The following are comments by local observers. None reflect instrument-devised current values.

(1) Mr. Bill Shields, a knowledgeable observer who has been working on Masirah Island since 1966, said the maximum current he observed in the study area was 6 knots (about 10 ft/sec) which occurred during spring tides and with a strong monsoon wind from the south. Mr. Shields said there was no NE monsoon on Masirah Island.

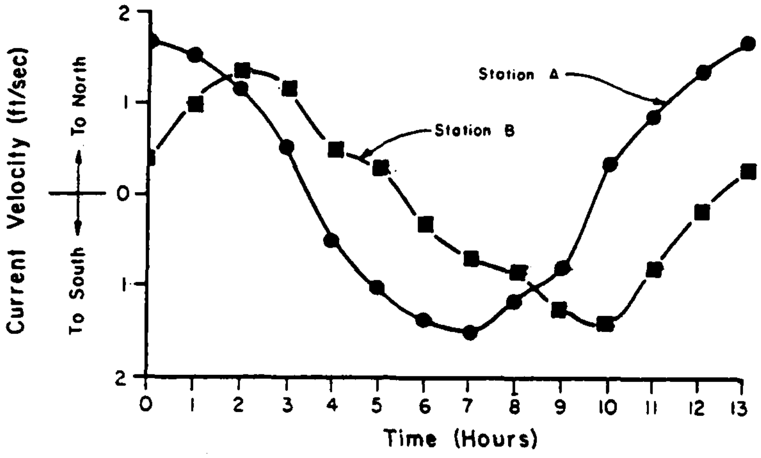


Figure C-2. Current velocities in Masirah Channel. Data were taken from the U.S. Navy Oceanographic Office Chart No. 62351 (Masirah Channel). Station A, located in a channel with a water depth of 13.8 m (45 ft), is at the south end of Masirah Island about 40 km (25 mi) south-southwest of the study site. Station B is located at the island midpoint (north of Jazirat Shagha) about 18 km (11 mi) south of the study area in a channel with a depth of about 13 m (43 ft). The channel off Ra's Hilf is a continuation of the channel in which Stations A and B are located. Currents were in a nearly north-south orientation

(2) Mr. Shields noted a counter-clockwise gyre was set up near shore between the US-built intake structure and the recurved spit to the north during the flooding portion of the tide. This only occurs, according to Shields, before the SW monsoon begins. He noted fishing dhows sometimes anchor in the gyre area.

(3) Omani Fisherman No. 1 observed current speed varies with tidal range and wind speed. He noted tides do not reach very low stages during the SW monsoon, but during non-monsoon times they did experience periods when the water surface elevation was very low. This fisherman also noted currents under the SOAF pier were less than in the channel.

(4) Omani Fisherman No.2 said currents were consistently greater to the north during the SW monsoon. He also said he observed no net current to the south or north during non-monsoon periods.

(5) Omani Fisherman No. 3 said he felt that even during non-monsoon times the ebb (north-directed) current was largest.

d. Data from Stanley's Report.* Stanley references (p. 11, 12) a surface-float study of currents done in October 1961, a non-monsoon period. Maximum currents observed were 3.9 ft/sec (ebb flow) and 3.0 ft/sec (flood flow). Stanley also provided wind data (p. 8, 9, Table 2, Figure 7). Their wind rose is at Figure C-3, and extreme storm data at Table C-2.

Table C-2. EXTREME STORM PARAMETERS[1]

Maximum Sustained Wind:	90 knots
Maximum Wind Gusts:	120 knots
Precipitation (24 hours):	430.6 millimeters
Core Diameter:	24 kilometers
Storm Track:	North Tip Masirah Island

Source: Masirah Island Meterological Office.

[1] Meterological data from a cyclonic storm that crossed Masirah Island 13 Jul 77.

* Stanley Consultants, Inc. 1983

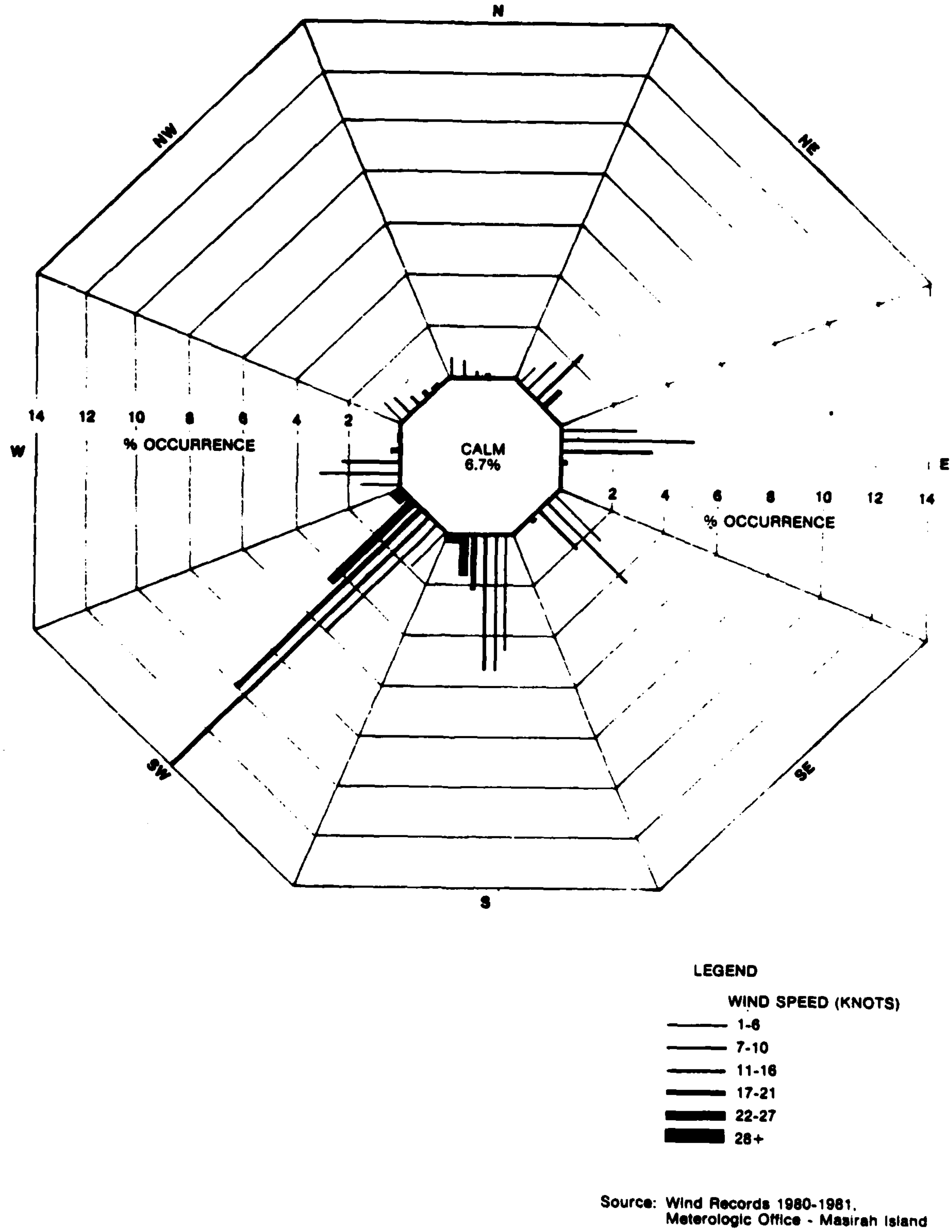


Figure C-3. "Long-Term" wind data for a two-year period, Masirah Island, Maximum wind of record (1981 & 1982) was 49 knots from 220° (wind rose from Stanley Consultants, Inc. 1983)

2. RESULTS.

Based on the data available for this study, the following results seem applicable to the estimation of wind- and tide-driven current velocities at Ra's Hilf Anchorage:

a. Current direction is nearly north-south (0° - 40° & 180° - 220°) under both wind and tide forcing functions.

b. Maximum measured current velocities are 5.9 ft/sec (north and south) during spring tides (USNHO Chart 62352). These velocities apparently only represent tidal effects. If wind were included it would be evidenced in a non-equal north and south directed maximum current.

c. There appears to be no residual current either north or south in Masirah Channel (Figure C-2). When flow is integrated through time over an ebb and flood cycle at the south end and near the middle of the island, again when wind effects are absent, the net flow north is about equal to flow south, and the period of the ebb cycle equals the period of the flood cycle (each about 6.2 hr).

d. Wind is a major factor in currents at Ra's Hilf Anchorage. This was certainly the case during the field measurement effort on 23 May 1983. Winds are generally from the south and southwest (Fig. C-3).

e. As a result of the 23 May 1983 field measurement program, during which the SW monsoon was active and about average in intensity (about 20 ft/sec), the following observations are pertinent:

(1) An ebb tide phase shift of about one hour was measured; i.e., the actual maximum current velocity occurred one hour before the predicted time of maximum velocity. A similar shift of about 0.7 hour was measured for the flood tide. Friction changes in Masirah Channel are probably responsible for the phase shift; at a higher water surface elevation, the bottom friction effect is usually less and current velocity is larger, all

other conditions being equal. No data, however, were obtained to substantiate or to quantify the friction effect.

(2) The wind component, U_w, of the total current, U, can be extracted from Figure C-1. Without wind, the current very likely is balanced to the north and to the south (Figure C-2). When the total flow over that tidal cycle illustrated in Figure C-1 is balanced between north and south flow and compared to the actual flow on 23 May 1983, the difference reflects the wind component. Wind shear stress on the sea surface prior to 1300 hours and 1700 hours, for example, created a wind component, U_w, in the total current of 0.9 ft/sec. and 1.2 ft/sec., respectively.

(3) Only a small time lag (less than one hour) exists between the time the SW monsoon reaches a specific velocity and the time the current driven by that wind reaches an equilibrium velocity."

f. Current measurements were made at 0.2, 1.0, 2.0, 4.0, 6.0 and 8.0 m above the bottom. Above 1.0 m from the bottom on both flood and ebb cycles, the current velocity was constant; i.e., there was no surface current stronger than the currents at depth. Below 1.0 m above the bottom the velocity distribution was logarithmic, as one would expect.

g. Currents velocities at 7-m and 4-m stations (Fig. A-1) were the same in magnitude and phase (Fig. C-1). Therefore, currents in depths beyond the reef can be assumed equal. Currents landward of the reef edge will decrease.

h. Winds from the south, and especially the southwest, predominate at Ra's Hilf Anchorage (Fig. C-3). These winds occur during the period late May through September. The mean wind velocity is about 15 knots from 207°.

i. The Coriolis effect may be disregarded in the study area because Masirah Island is located at a low latitude, the water depths are shallow, and distance scales at Masirah Channel are small.

3. METHOD TO PREDICT CURRENT VELOCITIES.

This section presents a methodology to predict the magnitude of currents at Ra's Hilf Anchorage under all forcing conditions to wind and tide. The method is empirical and results only apply to that location. Current direction is assumed to be constrained to 0° to 40° or 180° to 220° under all conditions.

a. Wind Component of Current, U_w. Currents caused by shear stress in the sea surface produced by wind, especially during the SW monsoon (Fig. C-3), can equal or exceed the tide-created component of the total current. For a wind that has been flowing in the same direction for a long enough time to produce a steady current (about four hours) the relationship between the wind-produced current, U_w, and wind velocity, S_w, is

$$U_w = k_w S_w \qquad \text{(C-1)}$$

in which k_w = 0.06 for current velocities at 1330 hr and 1730 hr (Fig. C-1) when the current is assumed to be completely wind created (0.9 ft/sec and 1.2 ft/sec, respectively) and using the average wind velocity for the preceding four hours (15 ft/sec and 20 ft/sec, respectively). This assumes the current was generated by "local" winds; i.e., that the SW monsoon wind was steady over the 75-km fetch to the southwest from which the wind was blowing. The assumption is probably a reasonable one because the monsoon is known to be relatively steady and the fishermen note it blows throughout the fetch area. Orientation of the monsoon is also that of Masirah Channel so corrections are not needed for direction.

Use of the empirically-derived k = 0.06 rather than the commonly assumed 0.03 value (CERC 1977; Stanley Consultants 1983) is warrented in the special case of Masirah Channel because it is shallow and flow is constrained between the mainland of Oman and Masirah Island. The k = 0.03 value is applicable for surface currents in deep water (i.e., no bottom friction), while in the study area the current was found to be fully developed to the bottom. The k = 0.03 assumption is that there is an exponential decay in current speed with depth. Therefore, k = 0.06 value for shallow water in Masirah Channel is the result of a situation where the net flux is less, but the k value is greater, because k is depth-integrated.

b. Tidal Component, U_t. The method to predict the tide-forced component, U_t, of the total maximum current for a tidal cycle, U, at Ra's Hilf Anchorage is a simple relationship between U_t and H_t, the tidal range high-tide elevation minus the previous low tide elevation

$$U_t = k_t H_t \qquad \text{(C-2)}$$

in which k_t = constant. The measured maximum U on 23 May 1983 was 3.9 ft/sec (Fig. C-1) of which U_w = 1.5 ft/sec (k_w = 0.06, S_w = 25 ft/sec which is the average of the 4 hours between 1700 hr and 2100 hr). Therefore, U_t was 2.4 ft/sec for a tidal range of 3.6 ft (Fig. C-1) and k_t = 0.67. For a spring tide range of 8.6 ft (Table C-1), the current, without a wind component, was 5.9 ft/sec (USNHO Chart 62352) and k_t = 0.69. For the purpose of this analysis we assume k_t = 0.7.

4. PREDICTION OF CURRENT VELOCITY AT RA'S HILF ANCHORAGE UNDER ANY WIND AND TIDE CONDITION.

A combination of equations 1 and 2 produces

$$U = U_t + U_w \qquad \text{(C-3)}$$

or

$$\bar{U} = 0.7\ h_t + 0.06\ S_w \qquad \text{(C-4)}$$

in which all values are in ft and ft/sec.

a. Maximum Current Velocities. Using Table C-2, and assuming a maximum wind of 90 knots (150 ft/sec) for four hours which has blown from the south or southwest, or north or northeast, U_w = 9 ft/sec and U = 13 or 14 ft/sec. This is probably the best available design maximum current velocity for a cyclone. For a SW monsoon with a maximum velocity (Fig. C-3) of 49 knots or 83 ft/sec, U_w = 5 ft/sec and the maximum current velocity from the southwest during a period of spring tides would be U = 10.9 ft/sec or about the maximum velocity of 6 knots (10.1 ft/sec) observed by Bill Shields.

b. Frequency Distribution of Current Velocities. Table C-3 and Equation C-1 were used to determine the percent of time a wind-driven current was exceeded at Ra's Hilf. Winds from the west and east were disregarded because they approach normal to Masirah Channel. Tidal tables for Muscat (1982) and Equation C-2 were used to estimate the percent of time a tide-driven current was exceeded at Ra's Hilf. Figure C-4 shows the percent of time the combined current was exceeded at Ra's Hilf.

Table C-3. Wind Speeds at Masirah Island Oman

Speed Category, Knots	M/Sec	Direction	% Percentage of Total
1-6	(3.0)	N	1.0
7-10	(5.2)	N	1.0
11-16	(8.2)	N	0.5
17-21	(10.8)	N	0.2
1-6	(3.0)	NE	1.0
7-10	(5.2)	NE	2.0
11-16	(8.2)	NE	2.5
17-21	(10.8)	NE	1.0
1-6	(3.0)	E	3.0
7-10	(5.2)	E	5.0
11-16	(8.2)	E	3.5
17-21	(10.8)	E	-
1-6	(3.0)	SE	2.5
17-10	(5.2)	SE	4.5
11-16	(8.2)	SE	2.0
17-21	(10.8)	SE	-
1-6	(3.0)	S	4.5
1-10	(5.2)	S	5.5
11-16	(8.2)	S	5.5
17-21	(10.8)	S	2.0
22-27	(13.9)	S	1.5
28+	(25)	S	0.5
1-6	(3.0)	SW	2.0
7-10	(5.2)	SW	6.0
11-16	(8.2)	SW	14.0
17-21	(10.8)	SW	10.0
22-27	(13.9)	SW	4.5
28+	(25)	SW	0.5
1-6	(3.0)	W	1.5
7-10	(5.2)	W	3.0
11-16	(8.2)	W	2.0
17-21	(10.8)	W	0.5
22-27	(13.9)	W	-
1-6	(3.0)	NW	1.0
7-10	(5.2)	NW	1.0
11-16	(8.2)	NW	0.5
17-21	(10.8)	NW	-
			95.7

NOTE: 28+ knot category taken as 49 knots - 25 m/sec.

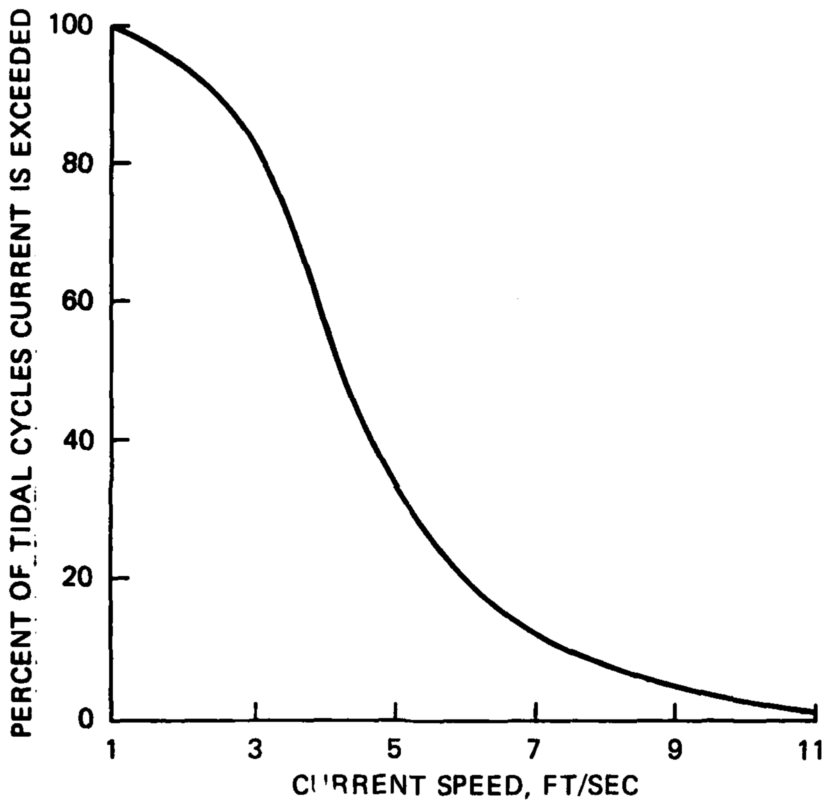


Figure C-4. Percent of total tidal cycles each year in which the current speed at some time in the tidal cycle (direction north or south) exceeds that shown. Current is the combination of wind-driven current and astronomical tide-driven current. Maximum currents occur during times of the SW Monsoon and spring tides. Maximum currents will be from south to north, except perhaps during cyclones

APPENDIX D: WAVES

Waves must be considered in pier design, ship mooring, and sediment transport in the littoral zone. Wave data obtained from gages or by visual observations over long time periods do not exist at Masirah Island. This appendix establishes the wave climate for the island using shallow-water wave hindcasting procedures. Qualitative observations of wave conditions were solicited from local people to check the hindcast data.

1. SHALLOW-WATER WAVE HINDCASTS.

The shallow-water wave hindcasting procedure was used in all but the NE wind case, because for 25-m/sec wind speeds waves generated are classed as shallow-water in 5-m depth after 20 minutes' wind duration. Most depths in the study area are 5 m or less. For lower wind speeds and shorter fetches, comparisons with deep water calculations show small differences (∿ 0.2 m). For higher wind speeds, shallow water conditions are achieved in even shorter durations.

Refraction effects of about 10 degrees between Bayādh Dimnah and Bayādh bin Juwaisim cause waves generated in Masirah Channel from southwest to propagate to Ra's Hilf. This estimate dictates a 75-km reach be used.

A 75-km fetch was used in the computation of waves generated by southwest winds. The actual fetch could be estimated at about 100 km; but within 25 km of Ra's Hilf, bathymetry is shoaling, and for typical depths in this region (3 m to 4 m) and wave periods generated in 75 km fetch (6 sec), wave growth assymptotically approaches zero for a 25-m/sec wind speed. In other words, energy being supplied by wind is nearly balanced over the last 25 km by energy being dissipated as bottom friction.

a. Wave Climate for Ra's Hilf, Masirah Island. The following procedure and data were used to determine the wave climate:

(1) The highest observed wind speed for two years of record (1980, 1981) = 49 knots (25 m/sec).

(2) CETN I-6 (Revised Method for Shallow-Water Wave Hindcasting*) values tend to be lower than previous modified SMB method. Therefore, the assumptions are a 75-km fetch, 25-m/sec wind speed, 10-m water depth in which H_s = 2.3 m, and T_s = 6.0 sec.

(3) The estimation of the (expected) refraction angle of 6.0-second waves around the coral shoal (Bayādh bin Juwaisim), from Shells Law is

$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{C_1}{C_2} \qquad \text{(D-1)}$$

in which, α_1 = incident angle of wave crest over contour, α_2 = transmitted angle of wave crest over contour, C_1 = wave celerity at d, and C_2 = wave celerity at d_2. From the 8-to the 7-m contour, α_2 = 3 degrees. From the 7-to the 5-m contour, α_2 = 6.2 degrees. Therefore, from 8-m depth to 5-m depth with incident angles of 45°, a 6.0-sec wave changes direction by about 10 degrees and 10° of refraction can be expected around the coral shoal.

For the following calculations shallow-water wave generation is assumed because water depths are shallow enough that for prevailing wind conditions waves become shallow-water types within a very short fetch.

(a) For north winds, 7-m water depth, 45-km fetch:

1) 25-m/sec wind

T_s = 5.3 sec, H_s = 1.7 m

2) 45-m/sec wind

T_s = 5.9 sec, H_s = 2.3 m

(b) For northeast winds use deep water hindcast tables—(CETN I-7**), 100-km fetch:

* CERC 1981a.

** CERC 1981b.

1) 25-m/sec wind

T_s = 8.5 sec, H_s = 4.0 m

2) 45-m/sec wind

T_s = 10.2 sec, H_s = 7.2 m

(c) For southwest winds, 10-m water depth and 75-km fetch:

1) 25-m/sec winds

T_s = 6.0 sec, H_s = 2.3 m

2) 40-m/sec winds

T_s = 7.0 sec, H_s = 3.0 m

(d) For west winds, 5-m water depth and 20-km fetch:

1) 25-m/sec winds

T_s = 4.2 sec, H_s = 1.4 m

2) 40-m/sec winds

T_s = 4.1 sec, H_s = 1.2 m

(e) For northwest winds, 5-m water depth, 15-km to 20-km fetch, (20 km used for calculations):

1) 25-m/sec winds

T_s = 4.2 sec, H_s = 1.4 m

2) 45-m/sec winds

T_s = 4.6 sec, H_s = 1.7 m

b. Computation of Expected Maximum Wave Conditions at Ra's Hilf due to Tropical Cyclone. Maximum wave conditions at Ra's Hilf are expected to occur during passage of a tropical cyclone. The storm of record used for the computation is the tropical cyclone (TC-18-77) of 11-13 June 1977 (see pp D7-D12). This cyclone reached a maximum intensity of 5.0 on the Dvorak Satellite Classification Scheme which is equivalent to a maximum wind speed of 90 knots. That speed is in excellent agreement with the 90-knot maximum sustained wind speed measured on Masirah Island. Examination of the area of cyclogenesis of storms likely to affect Masirah Island indicates the probable storm track would be from east to west with passage of the storm's center just to the north or south of the island generating the highest waves.

Passage to the north would result in maximum waves from the northeast generated in the northeast quadrant of the storm. Assuming deepwater conditions, a fetch of 100 km, and a wind speed of 45 m/sec, the result would be waves of 7.2-m significant height and 10.2-sec significant period (CETN I-7, 3/81).

Passage to the south of Masirah Island would result in maximum waves from the southwest generated in the southwest quadrant of the storm. Assuming shallow-water conditions, a fetch of 75 km, a depth of 10 m and a wind speed of 45 m/sec the result would be waves of 3.2 significant height and 7.2-sec significant period (CETN I-6, 3/81).

c. Percent Exceedance for Waves at Ra's Hilf. Wind speeds used in calculations are adjusted wind speeds (Fig. C-3). Winds from the east, southeast and south were not considered in computations of percent exceedance. East and southeast winds would produce waves propagating offshore, while south winds have a very short fetch. Moreover these wind direction classes would produce waves that would have no significant effect on the "tail" of the percent exceedance curve. Figure D-1 shows the percent of time the wave height at Ra's Hilf will be exceeded for wave heights up to 10 ft (3.0 meters). Waves greater than 10 ft (3.0 m) may occur during cyclones for which frequency-of-occurrence data are available.

2. OBSERVATIONS OF WAVE CONDITIONS.

Using an interpreter, three groups of Omani fishermen from Hilf (Fig. A-1) were interviewed. Their comments are as follows:

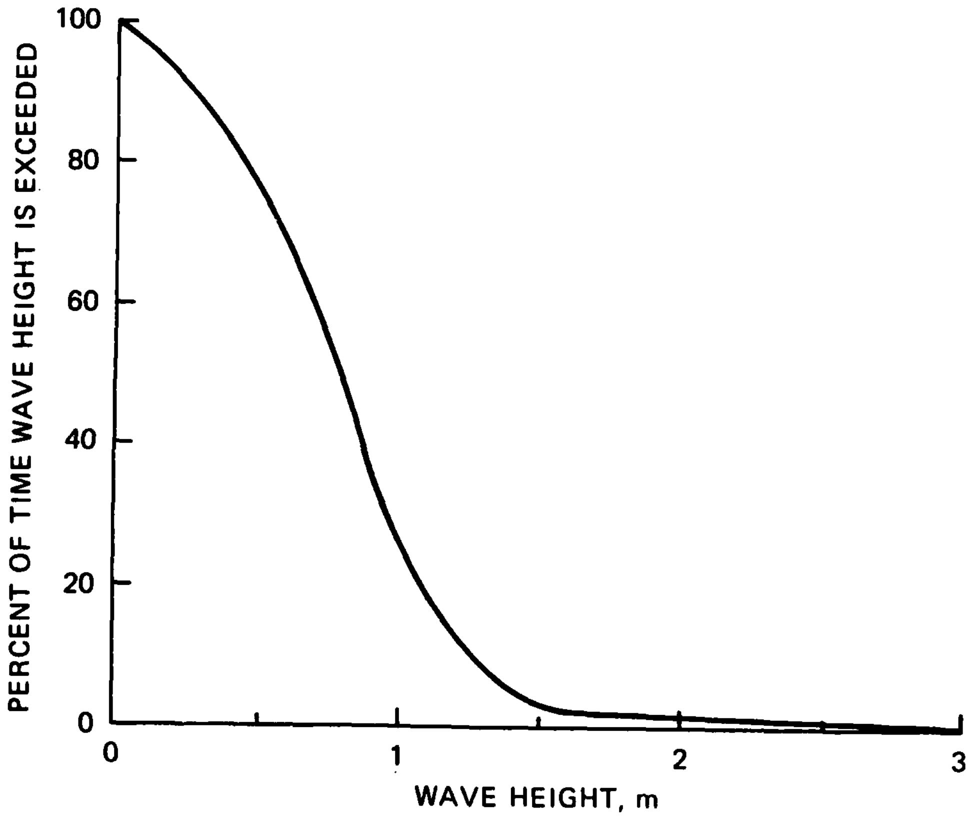


Figure D-1. Percent of time the wind-generated wave height is exceeded at Ra's Hilf Anchorage for waves from all directions except for winds from the east, south, and southeast (1 m = 3 28 ft)

a. Fisherman No. 1. He said the largest waves he had seen were 4 to 5 ft high in Masirah Channel during the SW monsoon. Waves were steepest during a flooding tide; i.e., when the current was moving toward the direction from which the waves were coming. He also said he saw waves on the SOAF pier deck during the cyclone of June 1977. This would require a wave height in excess of 7 ft.

b. Fisherman No. 2. He reported waves exceeding 16 ft (5 m) approaching from the north at the channel buoys north of Ra's Hilf. Maximum waves he saw on the reef near Hilf (deepwater edge of reef) were 10 ft (3 m) high. At the beach in Reach 4, he reported a 2-ft (0.6-m) highest wave, while at the SOAF pier he had seen waves 8 ft (2.5 m) high. Of interest, he also reported the highest waves correspond to maximum tide range; i.e., currents which oppose the waves steepen and heighten wind waves in Masirah Channel.

c. Fisherman No. 3. The maximum waves he reported seaward of the reef (Fig. A-1) in Masirah Channel during the SW monsoon were greater than 10 ft (3 m) and they occurred in August. He said waves on the beach at Hilf have never exceeded 2 ft (0.6 m).

d. Comparison With Hindcast Results. These subjective visual observations agree quite well with calculated maximum waves. The maximum cyclonic wave (7.2 m) from the northeast was, of course, not observed at sea during the 1977 cyclone.

1977 Cyclone Data for Masirah Island, Oman

1. North Indian Ocean fix data (data from North Indian Ocean Weather Atlas)

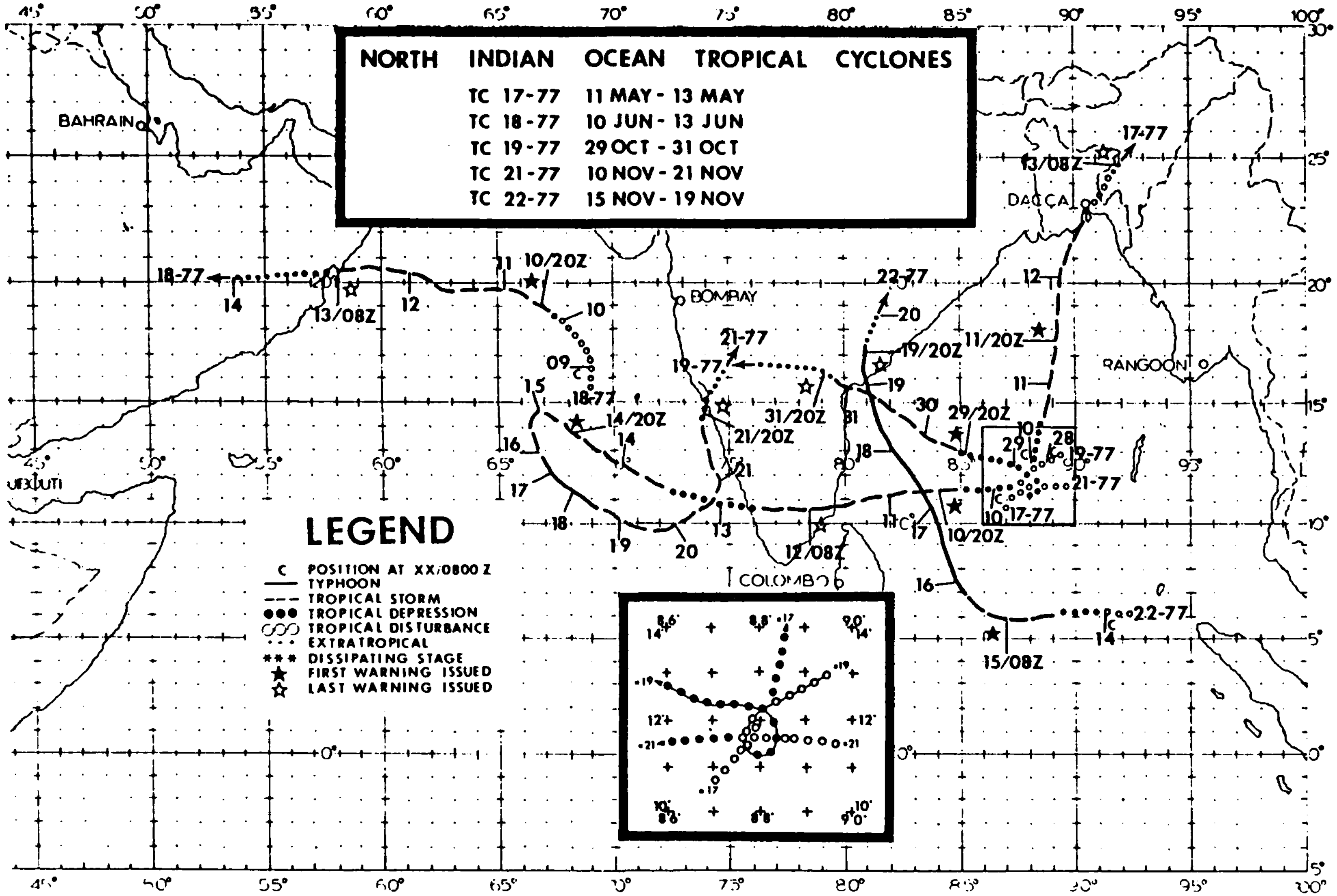
FIX POSITIONS FOR TROPICAL CYCLONE NO. 18-77
2000Z 10 JUN TO 0800Z 13 JUN

FIX NO.	TIME	POSIT		FIX CAT	ACCRY NAV-MET	FIX LVL	MAX OBS FLT LVL WIND DIR VEL BRG RNG	MAX OBS SFC WIND VEL BRG RNG	OBS MIN SLP	MIN 700MB HGT	FLT LVL TT/TD	EYE FORM	ORIEN-TATION	EYE DIA	POSIT OF RADAR	MSN NMBR
1	090329Z	16.0N	69.0E	SAT	(T1.0/1.0 / / HRS)			NOAA-5	(CONF 01)							
2	091617Z	16.9N	69.4E	SAT	(IR DATA)			NOAA-5	(CONF 02)							
3	100440Z	17.9N	68.3E	SAT	(T2.5/2.5 /D1.5/25HRS)			NOAA-5	(CONF 01)							
4	100448Z	18.7N	68.6E	SAT	(T3.5/1.5 / / HRS)		PCN 4	UNSP								
5	101540Z	18.3N	66.8E	SAT	(IR DATA)		PCN 6	UNSP								
6	102008Z	19.2N	66.1E	SAT	(T3.5/3.5 / / HRS)		PCN 6	UNSP								
7	110242Z	19.5N	66.6E	SAT	(T4.5/3.5 /D1.0/24HRS)		PCN 3	UNSP								
8	110357Z	19.7N	66.0E	SAT	(T3.5/3.5 /D1.0/23HRS)			NOAA-5	(CONF 01)							
9	110404Z	20.2N	65.6E	SAT	(IR DATA)		PCN 4	UNSP								
10	110700Z	19.6N	64.8E	SAT	(IR DATA)		PCN 3	UNSP								
11	111528Z	19.7N	65.9E	SAT	(IR DATA)		PCN 6	UNSP								
12	111955Z	19.6N	61.8E	SAT	(IR DATA)		PCN 5	UNSP								
13	120234Z	20.1N	62.6E	SAT	(T3.5/3.5 /S /24HRS)		PCN 3	UNSP								
14	120251Z	20.1N	61.4E	SAT	(T4.0/4.0 /D0.5/24HRS)		PCN 1	UNSP								
15	120500Z	20.2N	62.3E	SAT	(T5.0/5.0 /D1.5/25HRS)			NOAA-5	(CONF 01)							
16	121515Z	21.1N	60.5E	SAT	(IR DATA)		PCN 6	UNSP								
17	121602Z	20.3N	59.8E	SAT	(IR DATA)			NOAA-5	(CONF 02)							
18	121933Z	20.6N	59.9E	SAT	(IR DATA)		PCN 2	UNSP								
19	130219Z	20.8N	59.1E	SAT	(IR DATA)		PCN 6	UNSP								
20	130425Z	20.5N	58.5E	SAT	(T3.0/4.0 /W2.0/23HRS)			NOAA-5	(CONF 01)							
21	140534Z	20.1N	58.0E	SAT	(T1.0/1.0 /W2.0/25HRS)			NOAA-5	(CONF 01)							

Legend

(T.2.5	2.5	D1.5	25 hrs)
T-number	Dvorak Intensity No.	Forecast Index D - Developing S - No change W - Weakening	Forecast Period

2. North Indian Ocean tropical cyclone chart for 1977 (data from North Indian Ocean Weather Atlas)

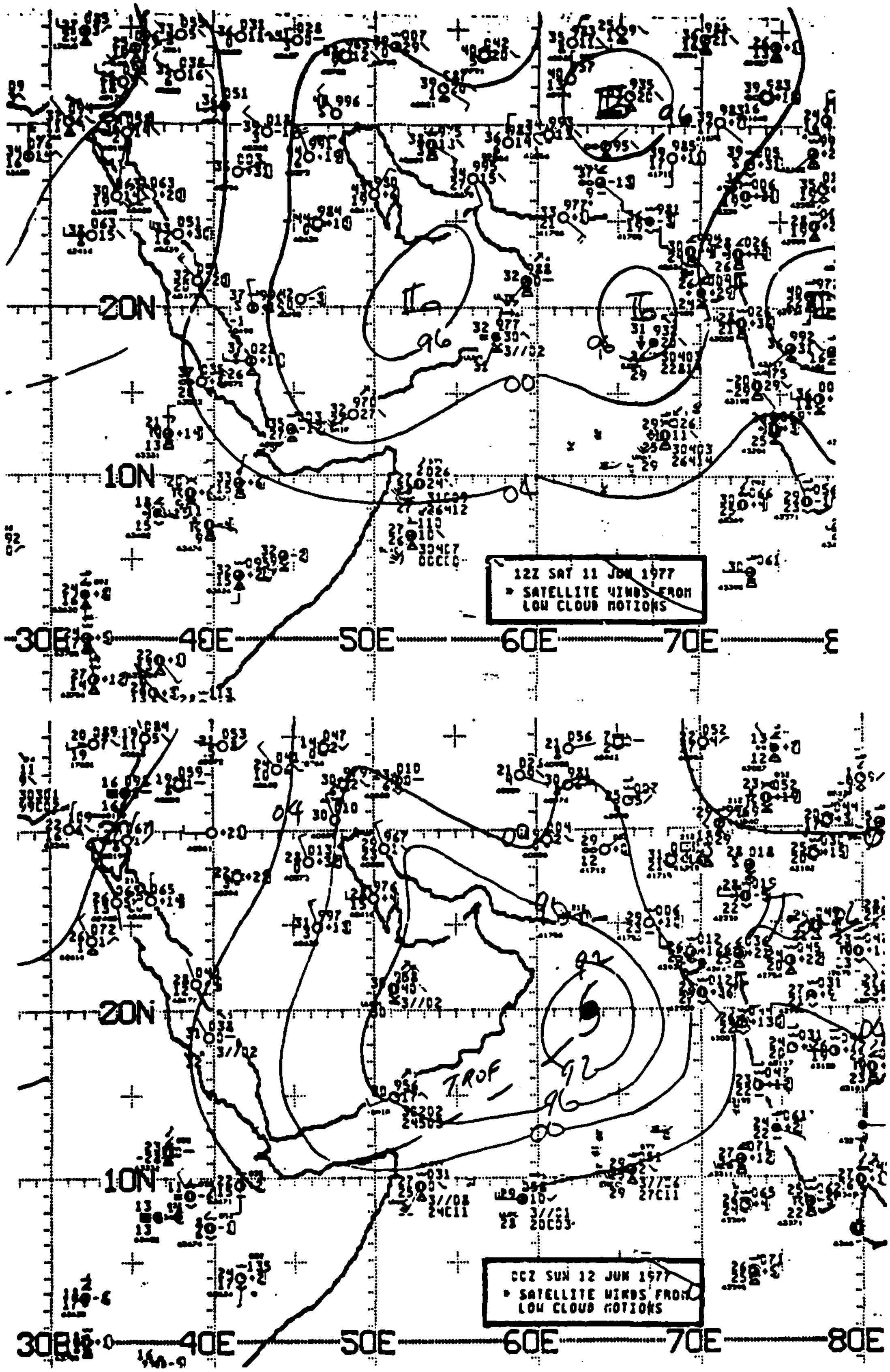


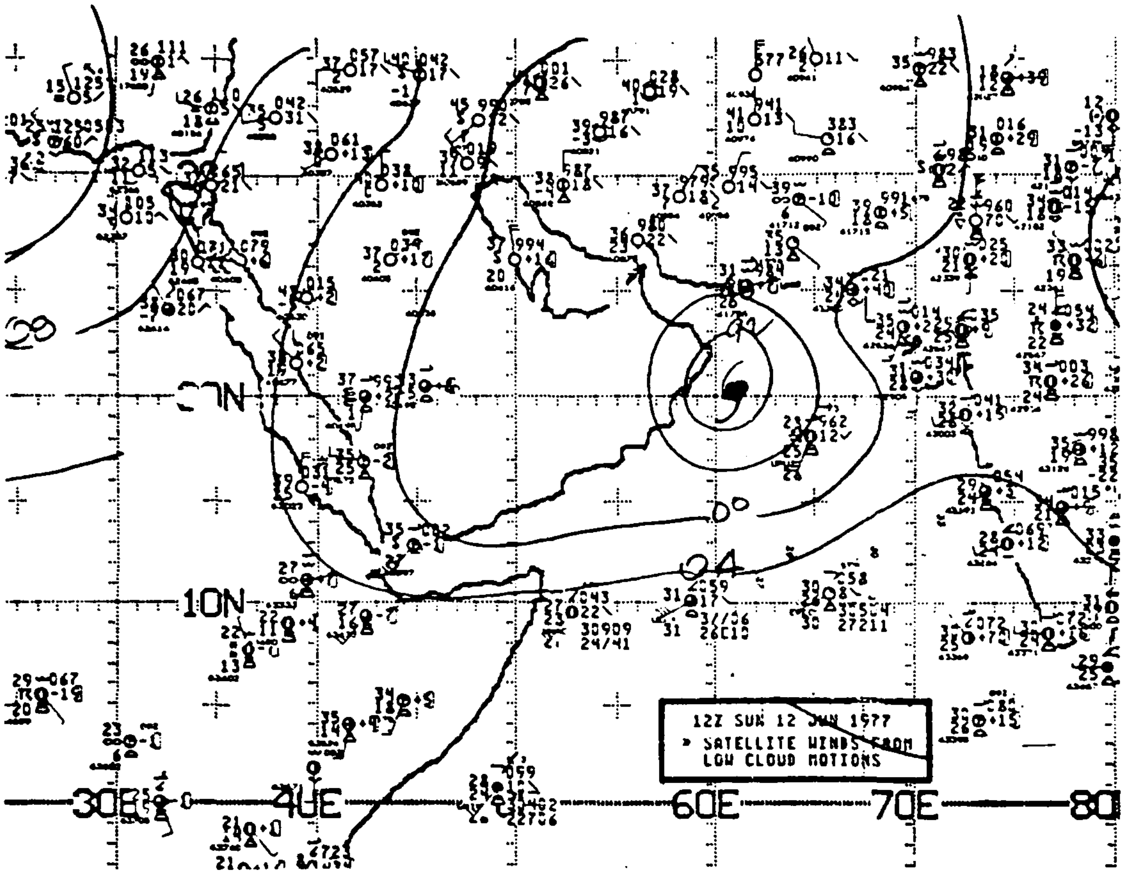
3. Dvorak Satellite Classification Scheme

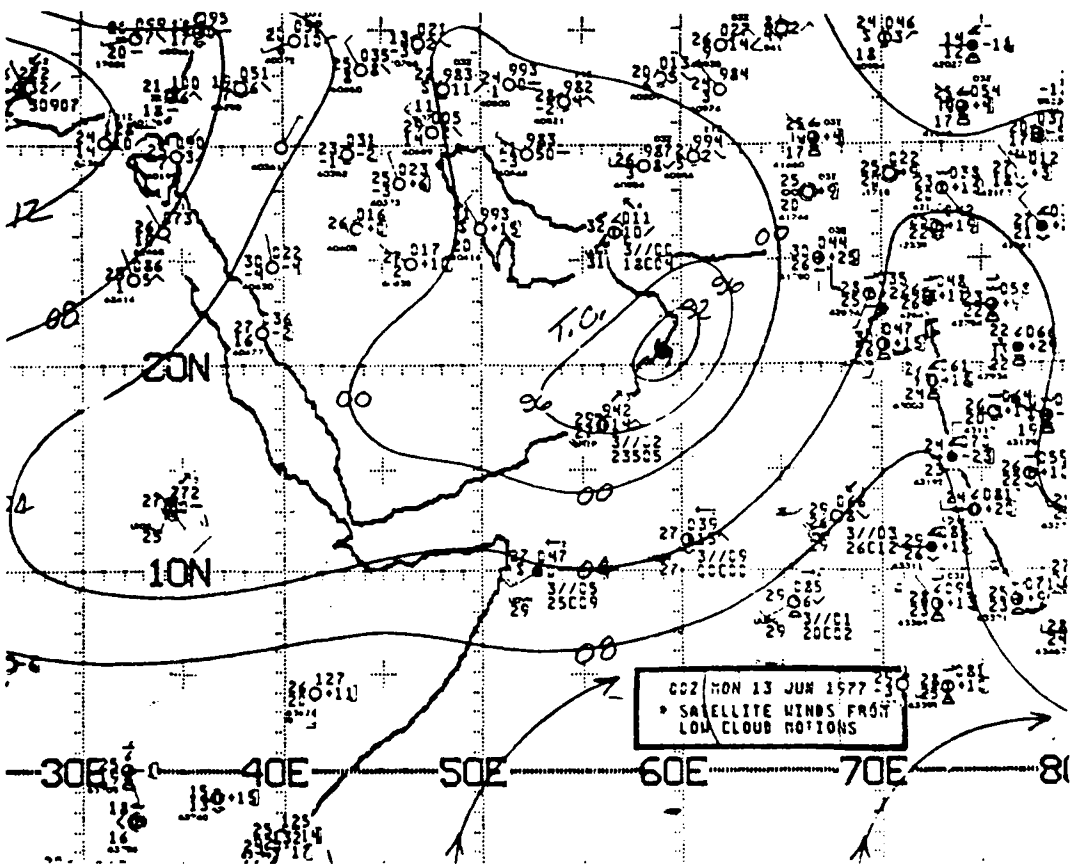
CI* Number	MWS (Knots)	MSLP (Atlantic) & E Pac.	MSLP (NW Pacific)
1	25 K		
1.5	25 K		
2	30 K	1009 mb	1000 mb
2.5	35 K	1005 mb	997 mb
3	45 K	1000 mb	991 mb
3.5	55 K	994 mb	984 mb
4	65 K	987 mb	976 mb
4.5	77 K	979 mb	966 mb
5	90 K	970 mb	954 mb
5.5	102 K	960 mb	941 mb
6	115 K	948 mb	927 mb
6.5	127 K	935 mb	914 mb
7	140 K	921 mb	898 mb
7.5	155 K	906 mb	879 mb
8	170 K	890 mb	858 mb

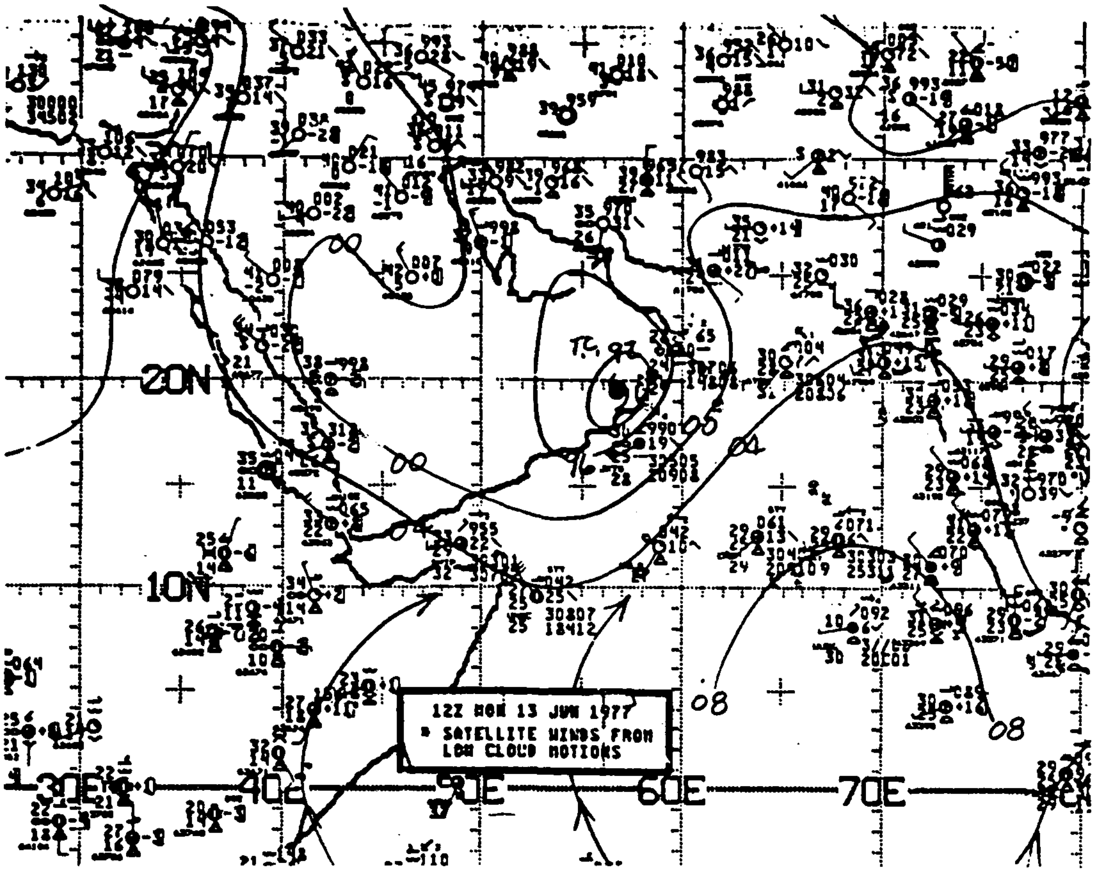
* Current intensity.

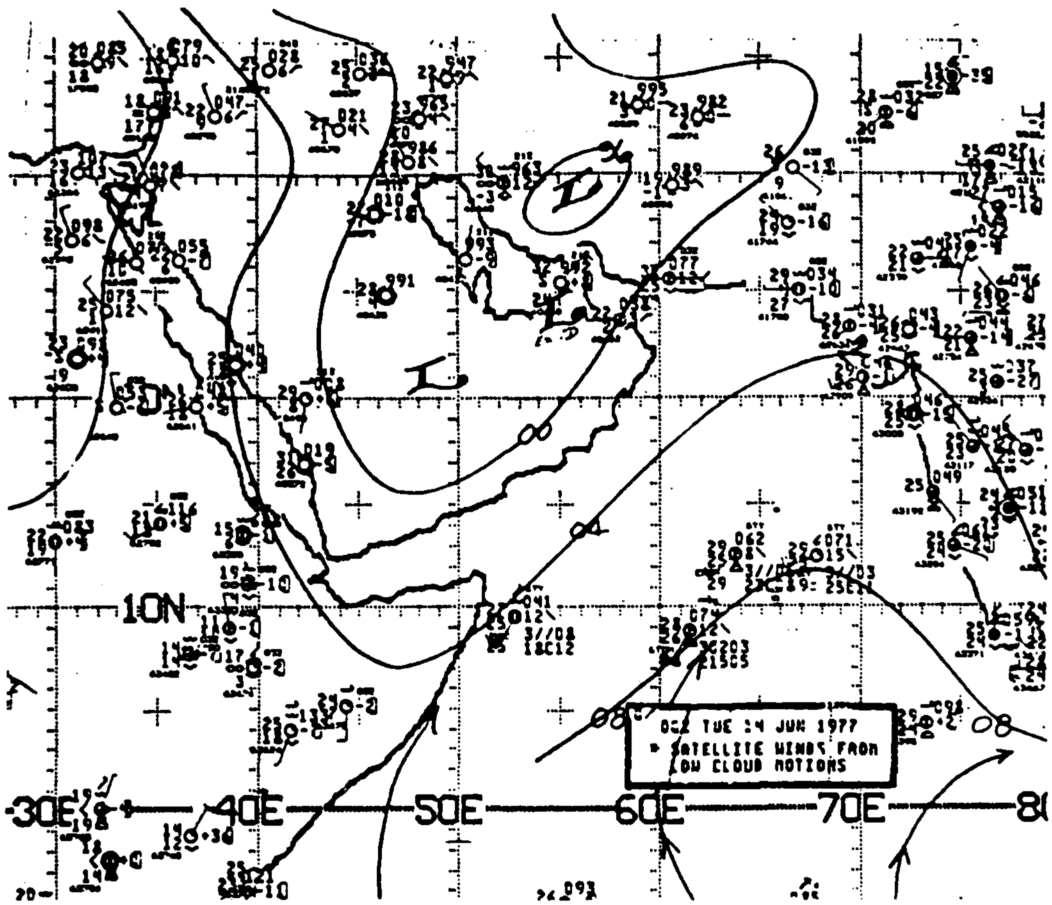
4. Surface pressure analysis for the northern hemisphere (data from National Climatic Center, Ashville, N. C.).




12Z SUN 12 JUN 1977
* SATELLITE WINDS FROM LOW CLOUD MOTIONS
20N
10N
30E
40E
60E
70E


00Z MON 13 JUN 1977
* SATELLITE WINDS FROM LOW CLOUD MOTIONS
T.C.
20N
10N
30E
40E
50E
60E
70E


12Z MON 13 JUN 1977
* SATELLITE WINDS FROM
LOW CLOUD MOTIONS
20N
10N
30E
40E
50E
60E
70E


00Z TUE 14 JUN 1977
* SATELLITE WINDS FROM
LOW CLOUD MOTIONS
10N
30E
40E
50E
60E
70E

APPENDIX E: SEDIMENT TRANSPORT WITHOUT STRUCTURES AT RA'S HILF

In this appendix all previous data and interpretations are summarized to provide an overview of shore-normal and shore-parallel sediment transport in the past, and coastal processes that caused some of the changes. Because of the risk involved in an interpretation of causes based on a few days' observations, sediment data as described in Appendix B allow a less quantitative, but longer term, analysis of sediment movement. Appendices C and D (Currents and Waves, respectively) provide quantitative information on what caused the changes and methods whereby those limited data can be used to predict changes in the future. All reaches are referenced in Figure A-1.

1. REACH 1.

Both longshore and cross-shore sediment transport are important in the distribution of sediment in this reach. Longshore sediment transport east of West Horn Reef is predominantly to the west and directionality is not seasonal. One-directional transport to the west is supported by the results of a cursory wave refraction analysis, evidence of coarse sediment build-up on the east side of headlands, crenulate-shaped bays west of headlands, coarse sand east and fine sand west of West Horn Reef, and the results of a seasonal sediment volume balance.

West of West Horn Reef a different situation prevails. During the SW monsoon West Horn Reef is a longshore transport convergence point. Sand from the spit at Ra's Hilf moves east along the shore to near West Horn Reef; this eastward movement obliterates coastal features, such as spits, along the northwest side of the island that formed during the non-monsoon period when transport was to the west. Wave approach directions observed during the monsoon period show waves from the south in Masirah Channel are refracted around Ra's Hilf and move sand to the east.

Although West Horn Reef is a convergence nodal point during the SW monsoon, sand is probably not lost offshore during the monsoon period. During the non-monsoon times it may be a location where fine-grained sand from the shoal northeast of Ra's Hilf is carried ashore. This is evidenced by size and compositional characteristics of the beach and shoal material.

While the shoal is probably gaining volume, it is unlikely it occurs at the expense of sand on the beaches in Reach 1. Thus, although Reach 1 is dynamic with large seasonal changes, it is probably a reach with a near-constant volume of sand above MLW.

2. REACH 2.

This is the most dynamic of the study reaches. Shoreline changes primarily involve the progressive construction of a recurved spit at Ra's Hilf during non-SW monsoon times (October - May) when waves approaching from the north and east predominate, and subsequent destruction of the spit by SW monsoon (May - September) waves from the south. That part of Reach 2 south of the recurved spit is more stable than the spit.

Longshore sediment transport during non-SW monsoon times is from east to west at Ra's Hilf, thence south along the spit. During SW monsoon times, longshore transport on the spit is in the opposite direction. That location where the recurved spit intersects the north-south oriented shoreline at the southern half of Reach 2 is a convergent nodal point during non-SW monsoon times. The spit configuration produces a counter-clockwise gyre driven by a flooding tide between the intake groin (or previously the boat ramp which acted as a groin) and the southern base of the spit. Thus longshore sediment transport along the beach of this southern part of Reach 2 is predominantly south to north at all time of the year.

Some of the sediment transported north from the spit during SW monsoon times may be carried offshore and onto the shoal northeast of Ra's Hilf; this is probably the only cross-shore transport that occurs in this reach. In the south and central portions of Reach 2 the coral reef prevents onshore transport. No evidence exists that sand is transported offshore across the reef.

The position of the shoreline in front of the Beach Club and SOAF desalinization plant is tied to the position of the sandy point at Ra's Hilf. During years when the effects of the SW monsoon are particularly severe (i.e., monsoon winds are abnormally energetic) this point where the north-south shoreline changes orientation to east-west may be moved to a more easterly location than usual. When this happens, the entire north-south-oriented shoreline south of the point may retreat east. This was the case in the mid-1970's when Mr. Bill Shields reported the shore in front of the Beach Club and desalinization plant had retreated to the fence. Sand bags were required to protect the buildings.

This situation shown in Figure E-1 could, and probably will, happen again when SW monsoon winds are abnormally strong or of abnormally long duration during the monsoon season, or when non-monsoon processes produce a smaller than normal recurved spit which is then readily removed during the subsequent SW monsoon. This potential for shore retreat is based solely on natural factors. Figure E-2 shows an idealized view of sediment in the study area.

3. REACH 3.

The proposed pier will be constructed within this reach. The Reach 3 shoreline has been historically quite stable and with the proposed pier (a gravity structure to -3 m MLW) and the new intake groin, it will likely remain stable in the future. The volume of sediment in the beach system has remained near constant through time (at least since 1973), and the orientation of the beach has not changed. A living coral reef bounds most of this reach, and sediment transport primarily by wind and tide-driven currents seaward of the outer reef edge does not appreciably affect the shoreline. The shoreline is affected by wave action landward of the reef. Little sand enters or leaves the reach in across-shore direction, and what sand does move in a shore-normal manner probably moves onshore near the SOAF pier.

This reach is stable for several reasons: (1) it is bounded by littoral barriers (the SOAF pier on the south, the intake groin and previously the boat ramp on the north) which contain the sand and (2) SW monsoon-generated waves

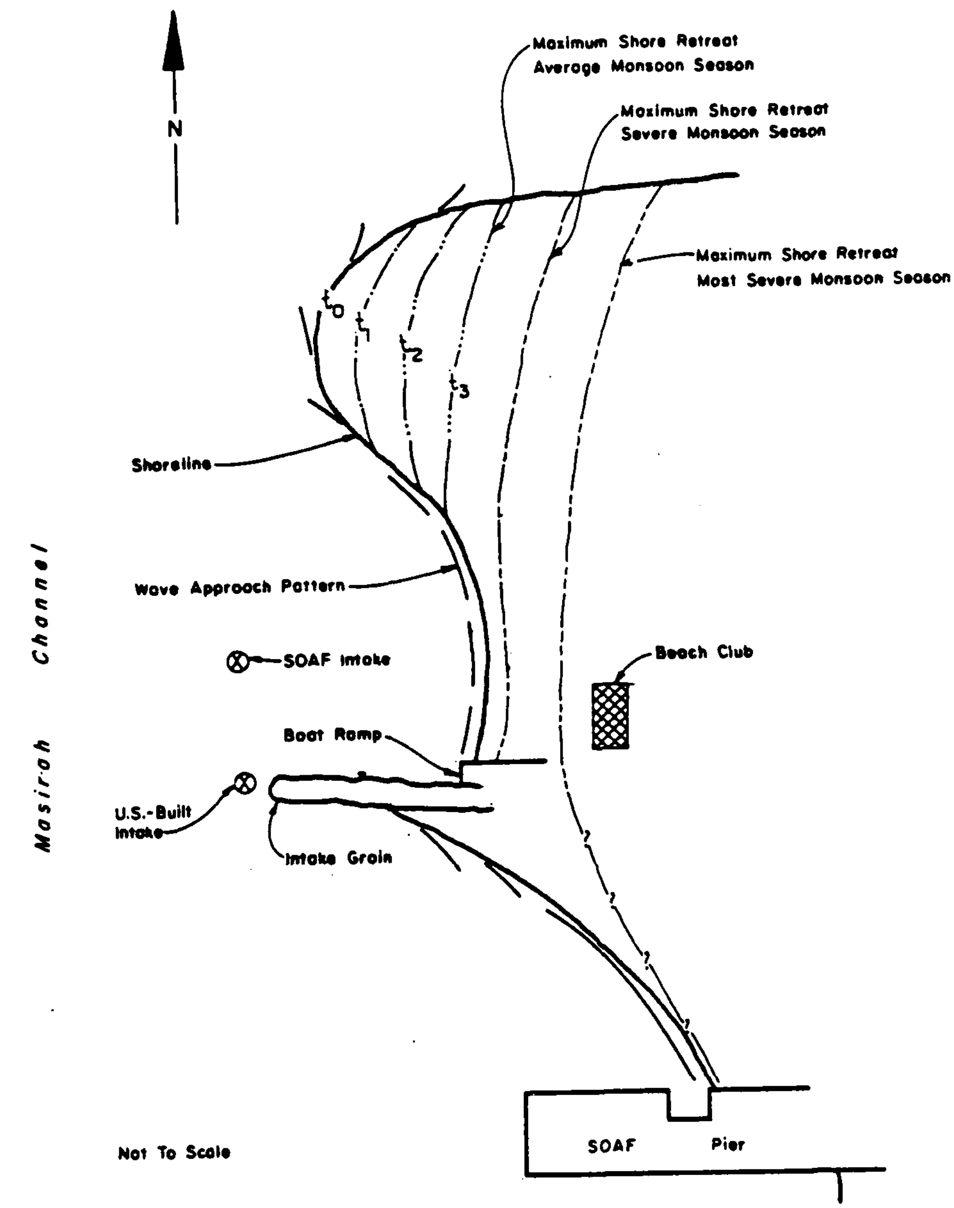


Figure E-1. Idealized sequence of shoreline changes that could take place in Reach 2 from the beginning through the end of the SW monsoon season (t_0 through t_3). Wave approach pattern is as existed at the beginning of the May 1983 SW monsoon. Longshore sediment transport is in the direction away from the open angle of wave approach with the shoreline. When wave approach and the shoreline are parallel, sediment is not transported alongshore unless a non-wave-driven current carries it. Maximum shore retreat is inferred from lineations on historic vertical aerial photographs. Diagram shows maximum shore retreat during different SW monsoon seasons. The spit volume created by pre-monsoon processes is assumed constant for all cases. The line with question marks south of the intake groin is the predicted shoreline if the intake structure is flanked on the landward end

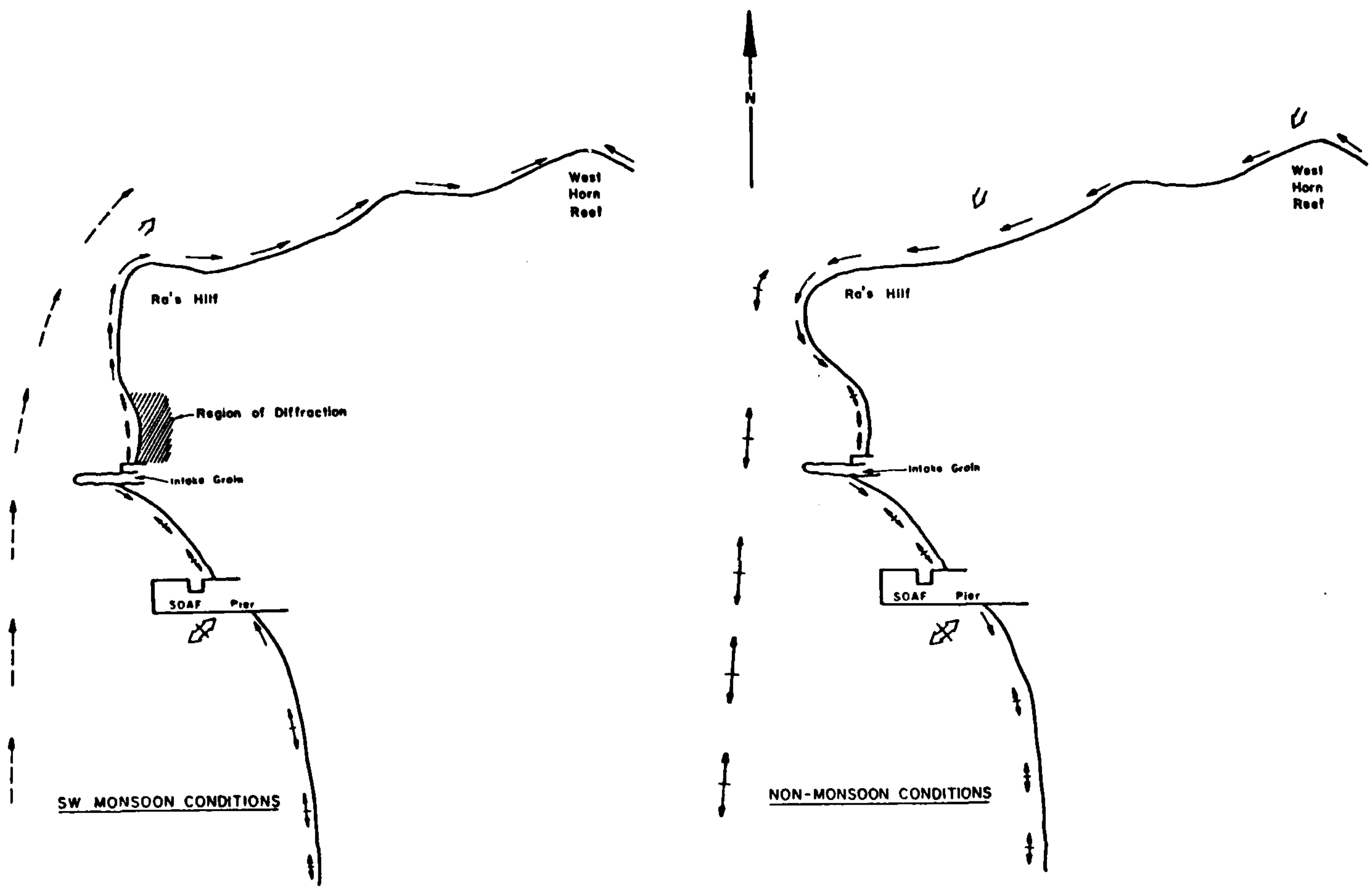


Figure E-2. Idealized sediment transport direction and relative transport rates at Ra's Hilf, Masirah Island, Oman. Solid single arrow = longshore sediment transport direction at beach; broken single arrow = sediment transport direction in Masirah Channel; length of single arrows indicates relative rate of transport; opposing-direction arrows indicate net longshore transport is near zero. Double arrows signify cross-shore transport dominate longshore sediment transport on the beach and they are refracted across the reef in such a way that they break parallel to the shoreline; hence longshore transport is minimized.

Sediment analyses and visual observations indicate little, if any, sand moves south to north or north to south past the SOAF pier. Net transport at the pier appears to have been slightly south before December 1982. At the boat ramp, net transport was slightly to the north, but it was mostly contained by the ramp which acted as a groin. (Presently the intake groin is modifying incoming waves in such a way that the shoreline is rotating back toward the pre-intake groin orientation; however, it will probably never quite reach that orientation. The final shape will be an embayment with a slight seaward bulge in the center caused by wave refraction, wave reflection off the intake groin (this is what will cut the fillet back), and wave diffraction from the intake groin when waves approach from the north.)

4. <u>REACH 4</u>.

This reach which lies south of the SOAF pier has been , is presently, and will continue to be stable. Throughout its length, except at the SOAF pier, it is protected by a near-beach rocky platform and further seaward by a living coral reef. No transport appears to occur across the platform/reef system. That system also appears to modify waves in such a way that net longshore transport rates along Reach 4 are near zero. Consequently, little sand enters or leaves the beach and the beach sand volume remains near constant (some wadi input may occur occasionally, but based on sediment analyses it is not of major importance). Also, because longshore transport is small, beach orientation remains relatively constant. The only place there is any noticeable seasonal shore retreat (October - May) or progradation (May - September) is within a few hundred (at most) meters south of the SOAF pier. The maximum shore-normal shoreline excursion then is only 10-15 meters. Sand from Reach 4 does not appear to pass around the pier, although some onshore or offshore transport may occur at the breach in the reef seaward of the pier.

APPENDIX F: SEDIMENT TRANSPORT WITH STRUCTURES AT RA'S HILF

This appendix describes the effect of changed natural sediment transport paths which have resulted from the existing US-built saltwater intake groin and which could result from three types of pier constructed in Reach 3: (1) a pile-supported structure, (2) a rockfill structure, and (3) a combination rockfill (near the shore) and pile-supported (near the channel) structure.

1. US-BUILT SALTWATER INTAKE GROIN.

This shore-normal gravity structure, which affects adjacent shores in exactly the same manner a groin would, was completed in December 1982. It extends from shore to about -4-m (MLW) depth, slightly west of the seaward end of the coral reef. The intake groin is flat, with an 8-m wide crest which is awash at high tide (Fig. A-6). Construction was of angular basaltic rock. Side slopes are about 1:1.5.

a. Reach 3. Longshore sediment transport has been little affected by the groin. Before December 1982, the net longshore sediment transport was directed north in all seasons, but the rate was very low. Even with the low and short boat ramp (Fig. A-6) which acted as a groin, very little sand passed to the north. The much longer and higher intake structure probably allows no sand to pass north or south in an alongshore direction on the beach (the littoral system — east of the coral reef).

Cross-shore sediment transport has also been little affected by the structure. Because wave refraction across the reef appears to cause most waves to break nearly parallel to the beach there is probably little opportunity for water to build up on either side of the structure. Tide and wind-created currents in Masirah Channel do not appear large in shallow water depths and therefore these currents, as they are deflected by the structure, probably do not carry much beach sand across the reef. If the structure were extended into deep water, that would probably not be the case.

Thus, longshore and cross-shore sediment transport into and out of the north end of Reach 3 has not changed much with the intake groin. Reach 3 remains a nearly closed beach system with the possible exception of some cross-shore transport near the south end where there is a breach in the reef. The volume of beach sand will stay quite constant, although some clockwise reorientation of the shore may occur because the north Reach 3 beach was apparently built seaward during intake structure construction. Reach 3 will, therefore, be little affected in the future by the intake groin.

b. Reach 2. This leaves Reach 2 (Fig. A-1) with the most potential to be affected by the intake structure. Two main problems must be addressed: (1) Will the intake groin act to trap sand against it's northern side and therefore create sedimentation problems at the SOAF- and US-built saltwater intakes? (2) Will the structure act to accentuate erosion in front of the beach club and SOAF desalinization plant?

(1) Sedimentation at Intakes? Sand deposition at the intakes, if it was to occur, would reach a maximum at the end of the non-SW monsoon season. This is the period when the spit builds as sand moves west and south from Reach I. A gyre is produced in the lee of the spit during the non-SW monsoon period which would preclude deposition of sand from the beach at either intake during that period. The southern one-half of Reach 2 (intake area) is relatively stable compared to the northern one-half (spit area). The intakes are west of the coral reef and located where the net yearly longshore sediment transport is slightly to the north.

Cross-shore sediment transport in this area is small or negligible. The beach system is separated from the intakes by the reef. Sand does not pass over the reef. Even if the intake area were tied to the beach by a continuous sandy bottom, the longshore transport patterns are such that a fillet of sand would not form against the north side of the intake groin and plug the intakes.

This does not mean that sediment moved by strong tide and wind-induced currents seaward of the reef will not move sand into the intakes. These currents are, on every tidal cycle, strong enough to carry all sizes of silt and sand. The bottom at the intakes is composed primarily of gravel and cobbles with some coarse sand because finer material is unstable on that bottom. The volume of finer material that moves in suspension over it is unknown, but may be appreciable. The large shoal northeast of Ra's Hilf probably received most of its volume from Masirah Channel to the south. Sediment entering the intakes would be suspended by the currents.

The only effect the intake groin would have on the SOAF intake would be to increase the amount and especially the vertical distance the material is suspended as it moves north on an ebbing tide. Without data on suspended sediment concentration and a model of the flow past the end of the intake groin it is not possible to quantify this factor. The same possibility, of course, holds for the US-built intake.

Monsoon-driven waves from the south diffract around the end of the structure (Fig. A-6) and create a small crenulate-shaped bay in the south one-jalf of Reach 2. The plan indentation depth of a crenulate-shaped bay (Everts 1983) is initially determined by the position of the downdrift "headland", in this case the point at Ra's Hilf. Since this "headland" moves a maximum 80 m east and west each year, the slower-evolving updrift end of the bay (at the intake groin) will respond at a slower rate. This means the south one-half (diffraction zone) of Reach 2 will probably not change much (± 10 m) from its position in May 1983 under average SW monsoon conditions. Wave reflection off the structure during non-monsoon times will probably have little effect on the Reach 2 shoreline. Refraction across the coral reef will tend to bend waves parallel to the shore so that the angle waves from the north make with the intake groin will be small.

(2) <u>Shore Erosion in Front of Buildings?</u> Shore erosion in front of the Beach Club and SOAF desalinization plant would be maximum at the end of the SW monsoon season. As previously stated, the position of this is tied to the position of Ra's Hilf (the point) after the SW monsoon destroys the spit (Fig. E-1). When the effect of the SW monsoon is particularly severe, the point will probably move to a more easterly

location than usual and the shoreline south of the point will retreat east. The eastward retreat of Ra's Hilf (the point) is a function of the balance between the amount of sand transported west and then south to the recurved spit during non-SW monsoon times, and the amount of sand returned north and east during the SW monsoon season as the spit is destroyed. When the latter exceeds the former, Ra's Hilf will retreat and shoreline retreat will occur in front of the buildings.

During the non-SW monsoon period, the intake groin may act to prevent a small part of the wave energy coming from the south from reaching the spit area. If this is the case the effect would be to enhance spit growth from the north. Similarly, the intake groin would slightly inhibit spit destruction during the SW monsoon period.

The overall effect of the intake groin will, therefore, be to slightly promote spit growth and inhibit spit destruction. Thus, the point at Ra's Hilf will retreat east a slight lesser distance than it would without the intake groin, and shore erosion in front of the buildings will be slightly less. A qualitative observation (Mr. Bill Shields) that the spit grew further south than usual between December 1982 and May 1983 supports this interpretation.

2. PILE-SUPPORTED PIER.

A pile-supported pier may act to attenuate part of the wave energy approaching shore. In some cases, but probably not in the Ra's Hilf area, this can affect adjacent beaches by decreasing the down-drift component of the longshore sediment transport rate. A pile-supported pier may also decrease offshore directed sediment transport in the wave-shadow of the pier. This is usually only a problem when waves approach shore at a small angle to shore-normal; i.e., when wave refraction is large. Differential longshore sediment transport may then create a bulge in the shoreline at and just updrift of the pier and a slight depression just downdrift of the pier. Wave attenuation is large because approaching waves must travel through a large number of piles before they reach shore; i.e., "wave permeability" is significantly decreased by the apparent density of the piles normal to shore.

At Ra's Hilf, the effect of a pile-supported pier section on adjacent beaches will be slight, and for pier design purposes it may be disregarded. The pile-supported section of a pier will probably be constructed seaward of the coral reef (west of the -3-m to -4-m (MLW) depth contour) and normal to the -7-m contour. Waves in this water depth will approach nearly normal to the pier axis—i.e., in a north-south direction—and with little refraction will pass normal to the pier. Hence, the apparent "wave-permeability" will be slight and the waves will be little affected by the pier piles. In designing the pier, the lowest density of piles vs open space when viewed from the side will be best, but a variation of a few percent will be inconsequential.

A pier supported by piles along its entire length, when constructed in Reach 3, will have approximately the same effect on adjacent shores as a compound gravity and pile-supported pier. This situation exists because the effects of the totally "wave-impermeable" existing nearby intake groin will be dominant when compared to a moderately "wave-impermeable" open pile "groin"; i.e., the pier section from shore to -4 m (MLW).

3. ROCKFILL PIER.

A rockfill pier will extend out into the high flow velocity portion of Masirah Channel (beyond the coral reef, Fig. E-2). Sediment moving in the channel is carried by tide- and wind-induced currents. The effect of a solid structure would be to act as a barrier to those currents and to the sediment they carry. Possible effects of the pier would be: (1) to create a shadow zone behind which some of the channel-carried suspended sediment would be deposited, (2) to change the littoral longshore sediment transport pattern in Reach 2, (3) to change the littoral transport patterns in Reach 3, and (4) to cause littoral sands to be moved into the channel by cross-shore transport.

Quite likely a depositorial site for suspended material would be created over and just seaward of the coral reef if the structure were constructed to the 7-m depth contour. Currents that move sediment at the western edge of the coral reef would be muted, and quite possibly much of the sediment carried in suspension would settle out near the pier; i.e., the pier would act as a headland. The size of the shoal off the northwest tip of Masirah Island attests to the large quality of fine- to medium-sized sand which is predominantly carried from south to north in Masirah Channel.

Major changes in sediment transport in an alongshore direction would also occur in Reach 2. The non-monsoon-produced spit at Ra's Hilf would be shadowed from the effects of SW monsoon waves. This does not exist today with the intake groin because its extension west is not great enough; i.e., the north sector-of-influence of the intake groin does not reach the spit. Shadowing of the spit would have two effects. The spit would build west into deep water at Ra's Hilf and sand from Reach 1 would be lost to the current-transport system in Masirah Channel. This would occur because a mechanism would no longer exist to remove the spit each year; i.e., SW monsoon waves would no longer reach the spit and carry its sand to Reach 1. The second effect would be that the spit would progressively grow south over the coral reef and ultimately fill in the region of the SOAF and US-built saltwater intakes. Littoral transport patterns in Reach 3 would probably not be significantly changed. Likewise, cross-shore transport from the beach to deep water, which presently is small, would probably not increase.

4. COMBINATION ROCKFILL (TO -3 or -4m DEPTHS) AND PILE-SUPPORTED (THEN OUT TO -7m) PIER.

At any location in the north one-half (Fig. A-1) of Reach 3, this structure would have little effect. The shore-tied, rockfill part, if its length seaward of the shore does not exceed that of the intake groin, will not affect the channel transport system. Its effect as the littoral transport system will be masked by the effect the US-built intake structure. That is, the combination of the intake structure and rockfill pier section will be nearly the same as that of the existing intake structure alone. The seaward pile-supported section would have little effect for the reasons outlined in Section 2 of this appendix.

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