CHAPTER 82

BEACH DEVELOPMENT BETWEEN HEADLAND BREAKWATERS

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ABSTRACT

Breakwaters in a series can be employed to protect sedimentary coasts. They are used to protect newly reclaimed land along the southeast coast of Singapore; they act as headlands between which sand beaches are formed. The development of these beaches takes place under conditions of low energy waves, a predominant wave direction from the southeast and an east-west littoral drift. The characteristics and development of three beaches over a one-year period are presented. Surveys of the reclaimed land show various beach types between the headland breakwaters. A relationship exists between berm orientation and headland breakwater orientation. Beach stability is tentatively indicated by the formation of a wide berm.

INTRODUCTION

One of the functions of the offshore breakwater is to protect the coast from wave action. By dissipating the wave energy along its entire length, the breakwater causes sediments in its lee to deposit and a shore salient is formed. If the breakwater is of sufficient length in relation to its distance from the shore and if the breakwater is built on a littoral drift coast, a tombolo will form joining the breakwater to the shore(1). If the offshore breakwaters are placed in a series along a coast with a gentle offshore slope and a substantial littoral drift, tombolos will form behind the breakwaters between which bays will be sculptured by waves to form stable shapes(2). These attached breakwaters would thus form a series of artificial headlands (Fig 1).

In nature, beaches between headlands are influenced by the position of the headlands. Where the headlands are closely spaced and a limited sediment supply exists, small pocket beaches are formed. Where the headlands are far apart and an adequate sediment supply exists, long and wide beaches are formed. Generally, between these two extremes most beaches between natural headlands take a shape that is related to the predominant wave approach; on the downcoast sector is a long and straight beach while on the upcoast end is curved beach. Such beaches

have been studied under various names; "zeta curve" bays (3), "half-heart shape" bays (2), "headland-bay beaches" (4), "J-shaped curves" (5) and "crenulate shaped bays" (6).

The curved segment of the beaches between natural or artificial headlands has attracted much attention. Krumbein (7) suggested that these beaches may approximate a logarithmic spiral. Yasso (4) confirmed this observation in his study. Silvester (6) in his modal study established a relationship between the logarithmic spiral constant and the angle of predominant wave approach. A quasi-permanent shape was reached when waves broke simultaneously around the model bay. As it is difficult to measure the curved sector in nature, Silvester and Ho (8) suggested the use of an indentation ratio to relate the bay's shape to wave approach.

EAST COAST RECLAMATION SCHEME

The afore-mentioned concepts of headland breakwaters and beach formation between them were applied in 1968 and are being applied on a large scale along the southeast coast of Singapore, where a series of headland breakwaters is used to protect newly reclaimed land. The reclamation which is officially known as the "East Coast Reclamation Scheme" is carried out by the Housing & Development Board which is a statutory board responsible for public housing, in a number of phases (Fig 2).

1 Phases I & II comprising 458 ha from Bedok to Tanjong Rhu were reclaimed between April 1966 and May 1971. The fill came from the nearby hills at Bedok and was conveyed to the sea by a continuous conveyor belt system.

2 Phase III, which is west of Phase II, comprises an area of 67 ha and involves the hydraulic placement of fill material behind an offshore stone bulkhead. It was implemented in April 1971 and scheduled for completion by the end of 1974.

3 Phase IV comprising 485 ha is an eastward extension of the earlier two phases. It was implemented in April 1971 and will be completed in early 1976. The same method of reclamation in the first two phases is used here.

The headland breakwaters used in Phases I, II & IV to protect the reclaimed land (Plate 1) are of two types:

a Gabion breakwaters constructed on the foreshore of the newly reclaimed land at low tide (Fig 3). The gabions used for the construction of breakwaters are PVC coated steel wire cages of 2x1x1 m, 3x1x1 m and 3x1x½ m in capacity and filled with stones ranging from 0.3 m to 0.2 m in size. Each breakwater is built up with these gabions in three layers rising from LWOST to approximately 0.9 m above HWOST. The length of the gabion breakwaters varies between 28 m and 46 m depending on the siting distance from the edge of the fill which is from 30 m to 60 m. The minimum length of the gabion breakwater is in the order of 1½ wave length. The breakwater spacing which varies from 120 m to 240 m is determined by the allowable shoreline recession between headland breakwaters. The limit of recession was estimated on the assumption that

the downcoast sector of the beaches will be oriented with the predominant wave approach. It varies from 25% to 30% of the headland breakwater spacing.

b Rip rap breakwaters constructed dry in the fill material along a near straight edge of fill and subsequently become wet (Fig 4). The area upon which each rip rap structure is to be constructed is first overfilled, compacted and thereafter excavated in stages to form an earth mound with a seaward slope of 1:2 and a landward slope of 1:1½. A vynilon sheet used as a filtering medium to prevent removal of fill material by wave action is then spread loosely over the entire mound. On top of it are placed a 0.2 m layer of 0.15 m - 0.1 m stones, a second 0.3 m layer of 0.3 m - 0.15 m stones, and lastly a layer of 0.5 m stones properly pitched. The rip rap structure extends 0.4 m below LWOST to 1.6 m above HWOST. Subsequent wave action removes the fill material to expose the rip rap breakwater which are spaced at 300 m to 360 m. The length of the rip rap breakwater varies from 55 m to 67 m, which has to be such that it would not subsequently become an "offshore island". This can be predetermined using the Silvester's relationship between logarithmic spiral constant and the predominant wave approach angle(6).

Plate 1. High aerial oblique of Phases I & II Reclamation

Both types of headland breakwaters are used in Phases I & II. The rip rap breakwater is being used in Phase IV.

The objective of this paper is to present field data on beach processes and development of the beaches between the headland breakwaters of the project. Data monitored at the first four headland breakwaters of Phase IV from August 1972 to July 1973 are presented (Plate 2). The one-year data are analysed for the northeast monsoon (December 1972 - March 1973) and the remaining period (August 1972 - November 1972, April 1973 - July 1973), as the variation between these two periods is large. The results of the two surveys of Phases I & II in April 1972 and February 1974 are also included.

Plate 2. Low aerial oblique of the studied area

BEACH PROCESSES

Winds

Winds were recorded at the Changi Aerodrome at a point 1.2 km from the sea and 10 m above mean sea level. Sharp contrasts in direction and velocity of winds were recorded for the northeast monsoon and the other period (Fig 5). Winds during the northeast monsoon are predominantly from N-NNE and are less than 5 m/s. Winds during the other period are from the southeast quadrant with speeds of 2-3 m/s.

Tides

The tides are essentially semi-diurnal of a mixed type with a mean range of approximately 2.64 m. The maximum range recorded was 3.49 m on 11 February 1974.

Waves

A resistance wave staff coupled to a battery operated Rustrak recorder was used to record waves. The waves were measured in 3.5 m water at the end of an open jetty; they were sampled once every 2 hours between 0830 hours and 1700 hours during which their direction was also determined by a compass. The data from August 1972 to July 1973 were analysed in accordance with Draper(9) and reduced to deep water waves by linear wave theory and refraction diagrams(10), an example of which is given in Fig 6.

The cumulative distribution of significant wave height, H_s and maximum wave height, H_{max} for the recorded period is shown in Fig 7. This figure can be used to determine the proportion of time for which H_s or H_{max} exceeded any given wave height.

The frequency distribution of H_s, H_{max} and zero-crossing period, T_z, are also given for the northeast monsoon and the other period (Fig 8). During the northeast monsoon the highest value of H_{max} was 1.1 m and for more than 65% of the time, H_{max} did not exceed 0.6 m. During the other period H_{max} exceeded 0.6 m for less than 10% of the time. 90% of T_z fell between 2.5 and 4 seconds during the northeast monsoon while T_z was predominantly around 3 seconds during the other period.

The relationship between H_s and T_z for the period of northerly winds and southeasterly winds are given in Fig 9. The numbers represent the number of occurrences which fell within the range of H_s and T_z values. The dashed lines represent wave steepness (H_s/L_o). For the northerly winds, 0.2 - 0.3 m and 3-4 second waves prevailed. For the southeasterly winds, 0.2 m and 2.75 seoond waves prevailed.

The frequency of occurrence of various significant wave heights H_s for one year is given in Fig 10 which shows that predominant wave approach is from the southeast quadrant resulting in a nett westward drift.

The relationships computed for wind speed, U, vs H_s and T_z suggest a stronger link between waves and southeasterly winds (ie on-shore winds) than between waves and northerly winds (ie offshore winds) (Fig 11). This suggests that the southeast coast of Singapore is washed by refracted swell from the South China Sea.

For onshore winds, the empirical relationships

$$H_s = 0.087\ U \text{ and}$$

$$T_z = 3.154\ U^{-0.2}$$

are being used for planning purposes on the southeast coast.

Currents

Drogue experiments and a current meter measurement were carried out at Phase IV. The details of the two types of drogues used are shown in Fig 12. The drogues were released from a boat and their movements were picked up by two theodolite stations from the shore. Their positions were later plotted on large scale plans and the velocity of current computed. Simultaneously, tide, waves and winds at hourly intervals were recorded throughout the period of observation.

May 2, 1973 experiment:

Drogues seeded 300 m offshore decelerated towards high tide and immediately after high tide they changed in direction and accelerated (Fig 13). The change in direction is clockwise.

May 3, 1973 experiment:

The change in direction was not immediately after high tide for drogues seeded 1000 m offshore (Fig 14). Within 50 m of the shore, the velocity of drogues fluctuated due to the effect of reflection of oblique waves from the headland breakwaters.

In-situ current measurement at 1000 m offshore and in 15 m depth of water was carried out for 25 hours on October 18, 1973 to determine the speed and direction of current at various depths. The current velocity was resolved into north and east components. These were plotted against time and smooth curves obtained. The north and east components of current at each lunar hour were extracted from the curves for the construction of a tidal current ellipse. An example for the current is in the east-west direction (Fig 15). The current flows eastward for approximately 11 hours with a maximum velocity of 1.1 m/s and westward for approximately 14 hours with a maximum velocity of 0.5 m/s. The values of the westward flow are of the same magnitude as those in the May 3, 1973 experiment.

From the data collected so far it appears that the tidal current in the Singapore Straits flows eastwards during the first main ebb between the highest high water and the lowest low water for about 11 hours and the remaining 25 hours the tidal current is westwards and that the change in current flow is not related to tide.

BEACH DEVELOPMENT

Grain Size

The fill material for Phases I, II & IV is Older Alluvium, which is of Quaternary age and consists of semi-consolidated gravels, sands and clays(11). Under wave action, the fines are removed leaving behind sands and gravels between the headland breakwaters.

The grain size characteristics of the fill material between the first four headland breakwaters (A-D) in Phase IV are given in Fig 16. The fill material was sampled along 20 stations on July 1972. The median size varied from 0.03 mm to 0.66 mm and the average median size along the three bays was 0.19 mm.

Subsequently, after wave action samples of beach material at mid-tide were taken on May 1973 and at the upper foreshore, mid-tide and lower foreshore on August 1973. The characteristics of these samples are shown in Fig 17.

May 1973 Mid-tides Samples:

The median size varies from 0.5 mm to 1.9 mm with an average of 0.97 mm. Coarser sediments are found around the headland breakwaters. Sorting is generally poor except between the headland breakwaters.

August 1973 Samples:

(a) Upper foreshore: The median size varies from 0.26 mm to 0.4 mm with an average of 0.3 mm. The sediments are coarser at the headland breakwaters than between the breakwaters. Sorting is good varying from 1.2 to 1.6.

(b) Mid tide: The median size varies from 0.4 mm to 1 mm with an average of 0.63 mm. Similarly, coarser sediments are found around the headland breakwaters. There is a slight improvement in sorting between the headland breakwaters.

(o) Lower foreshore: The median size varies from 0.25 mm to 1.9 mm with an average of 0.76 mm. In contrast, finer eedimente are found around the headland breakwaters. Sorting in thie zone ie poorer.

Beach & Offshore Changes

Beach ohanges along the firet four headland breakwaters in Phase IV were monitored for a year. As the beach forms between each pair of headland breakwaters a J-shaped bay develope. The beach geometry variee along the bay and ohangee with the seasone. 20 beach profilee along the beach between headland breakwater A and headland breakwater D were surveyed on Ootober 1972 and April and Ootober 1973. Data are given for profiles 14, 16 and 18 in the third bay (Fig 18) to illustrate the following pointe:-

(a) During the northeast monsoon, erosion across the foreshore occure at the upcoast section and accretion at the downcoast eector to form a straight berm in each bay. The mean beach gradient on the upcoast curved sector and downcoast straight sector is 1:10 and 1:8 respectively.

(b) During the other period, erosion ocours at the downooast etraight eector and accretion at the upcoast curved sector of the bay. The mean beach gradient for both the upcoast and downooast sectors ie generally 1:9.

(o) There is marked alongshore variation in the maximum height of the beach acoording to the seasons. At the end of the northeast monsoon, the height of the beach at the downcoast straight sector is 0.5 m higher than the upcoast curved eector. During the other period, the height of the beach at the downcoast end ie 0.9 m lower; this reflects the degree of exposure to wave action.

The offshore topography also varies. Echo soundings were also carried out in October 1972 and April and October 1973. The changes in the offshore topography of the three baye between theee periode are given in Fig 19 and 20.

A oomparison between October 1972 and April 1973 seabed contours shows eroeion of the offshore during the northeast monsoon when predominant wavee arrive from the southeast quadrant. Further, due to diffraction and refraction around the downcoast end of the headland breakwater, the upcoast portion of the bay retrograded to form a J-shaped bay (Fig 19).

A comparison between April 1973 and October 1973 seabed oontours indicatee a general accretion of the offshore topography in the period after the northeaet moneoon when waves oome from the SSW to SE. The ehape of the bays remains unchanged (Fig 20.)

Although the J-shaped bay prevails throughout the year between each pair of headland breakwatere in Phase IV, changes in the beach geometry and offshore topography suggest that an equilibrium shape has not been reached. For land-use planning purposes, it is neoessary to

determine the limit of erosion. Silvester(6) has suggested that the relationship between the logarithmic spiral constant and the wave obliquity can be used to determine the equilibrium shape of beaches between headlands. The probable shapes based on this criterion of the three bays for wave approach from the southeast are given in Fig 21. This assumes that the westward littoral drift is reduced or cut off.

Beach Types

A survey of Phases I & II in April 1972 shows that beaches between headland breakwaters take various shapes(12). Based on the development of the beach, the formation of the berm, the shape of the beach and the character of the sand projection behind the headland breakwaters, several beach types were identified (Table 1). The various shapes of the beaches reflect the complexity of other factors at work such as the original position of the fill line in relation to the headland breakwater alignment and the orientation of the headland breakwaters to littoral drift and wave approach.

TABLE 1. BEACH TYPES BETWEEN HEADLAND BREAKWATERS, PHASES I & II (12)

TYPES	FEATURES
NEW BEACHES	(1) Beach is not fully developed; marine clays underlying the sand prism are exposed. (2) Curvature of the bay is from crescentic to J shape. (3) Sand projection forms on the lee of the downcoast breakwater and is the nucleus for berm construction. (4) Scarp along the fill material is common.
DEVELOPING BEACHES	(1) Beach is sufficiently formed. (2) Typical curvature of the bay is J shape with a downcoast straight sector. (3) Berm develops from the downcoast breakwater towards the opposite end. It varies from a triangular form which tapers upcoast along the bay to an almost continuous formation between the breakwaters. (4) Scarp along the fill material varies from isolated sections to an almost continuous one along the bay.
BEACHES INTERRUPTED BY DRAINS	(1) As beach formation progresses, the drain becomes increasingly important; the sequences of beach development are as follows: (a) No effect by the drain on beach formation; the features are as for developing beaches. (b) Deposition becomes pronounced on the upcoast side of the drain. (c) Distinct development of an upcoast J-shaped bay and a downcoast straight sector, generally characterized by a scarp. (2) Silting in drains Becomes an increasing problem as the upcoast sector develops, thus necessitating dredging.
DEVELOPED BEACHES	(1) Beach and berm are well formed. (2) Typical curvature of bay is a J shape with a long downcoast straight sector. (3) Berm varies in width along the bay. (4) Little or no sand transport in the lee of breakwaters.
UNBAYED BEACHES	(1) Beach is characterized by a well-formed berm with varying width. (2) Straightness of beach is interrupted by a (a) concavity when surface runoff impounded behind the berm cuts channels across it and the material from the foreshore is removed by the littoral drift; (b) convexity when eroded material from the berm and foreshore forms a small delta offshore.

Berm

In the April 1972 survey of Phases I & II, a relationship was found to exist between berm orientation and headland breakwater orientation (Fig 22). In February 1974, when an exceptional high tide occurred due to the moon, earth and sun ooming almost in a straight line, the beach geometry was modified. However, the relationship between berm orientation and headland breakwater orientation remains almost constant (Fig 22). Beaches with developed berms were less affected by this exceptional high tide.

CONCLUSION

The southeast coast of Singapore is a sheltered area and winds from the north during the northeast monsoon do not have a large influence except through refracted swell from the South China Sea. It is essentially a low energy coast throughout the year with the waves coming from the southeast quadrant, so that westward littoral drift is present.

Beach development between the headland breakwaters of the reclaimed land is therefore under a low energy regime and a westward littoral drift. Wave action effectively removes the fines and leaves ooarser material behind to form the beaches.

Under such conditions, headland breakwaters constructed in a series on a gentle sloping littoral drift shore provide an economic solution for the protection of the ooast and for the formation of beaches. While the headland breakwater system is effective in minimising littoral drift in this low energy environment, it can be effective as a shore protection measure in high energy area since the growth of bay to equilibrium is independent of wave period(13). Tentatively, beach stability between the headland breakwaters is suggested by the presenoe of a wide berm in the absence of an equilibrium shape determined according to the criteria of Silvester(6).

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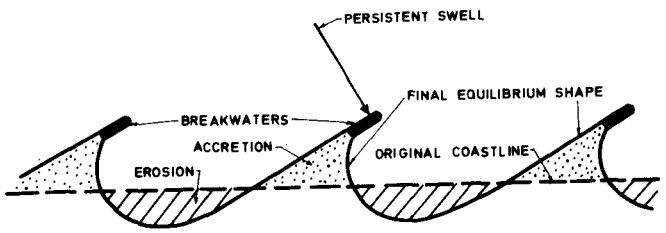
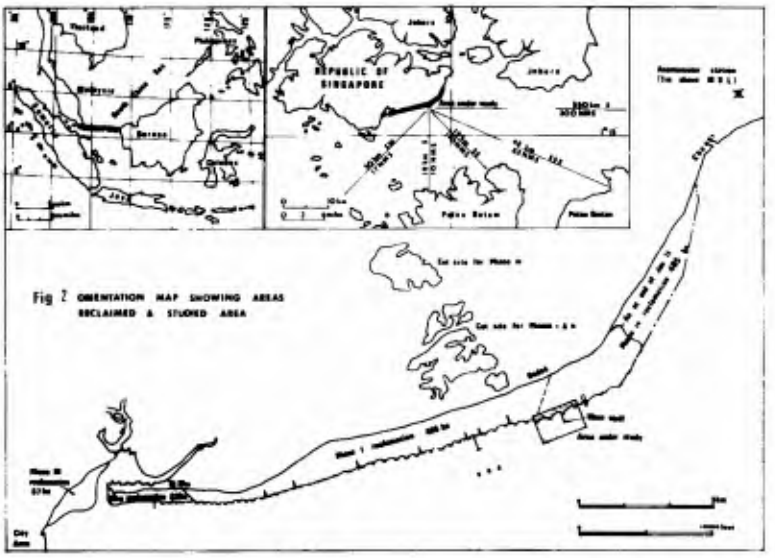
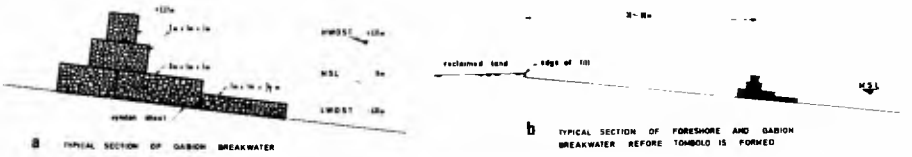


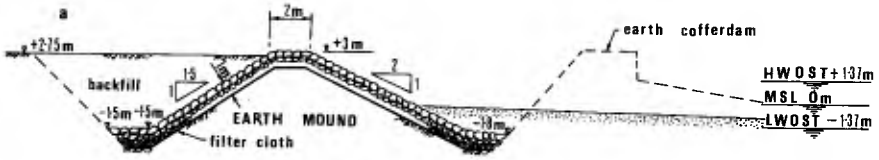
Fig 1 A METHOD OF PREVENTING LONG TERM MOVEMENT OF SEDIMENT ALONG THE COAST (AFTER SILVESTER, 1960)





c

Fig 3 a, b and c. Gabion breakwater



b

Fig 4 a and b. Rip rap breakwater.

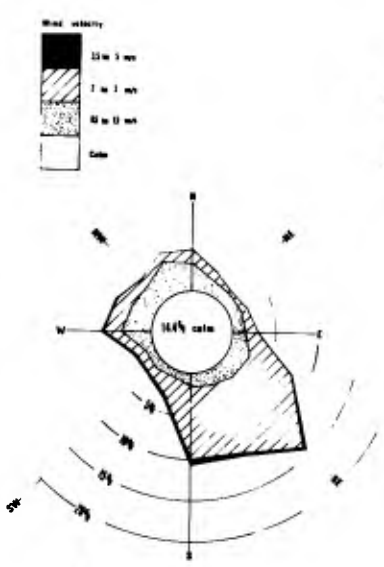
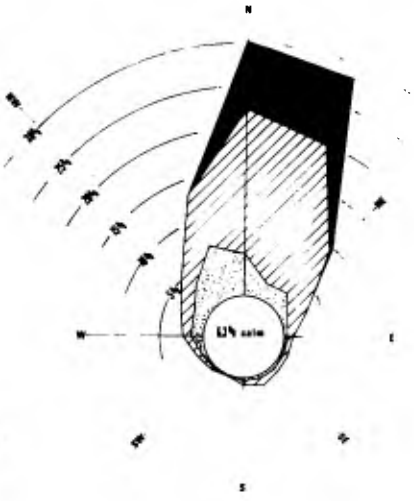


Fig 5 WIND ROSE FOR AUG. TO NOV 1972. APR. TO JULY 1973



WIND ROSE FOR DEC 1972 JAN FEB AND MARCH 1973

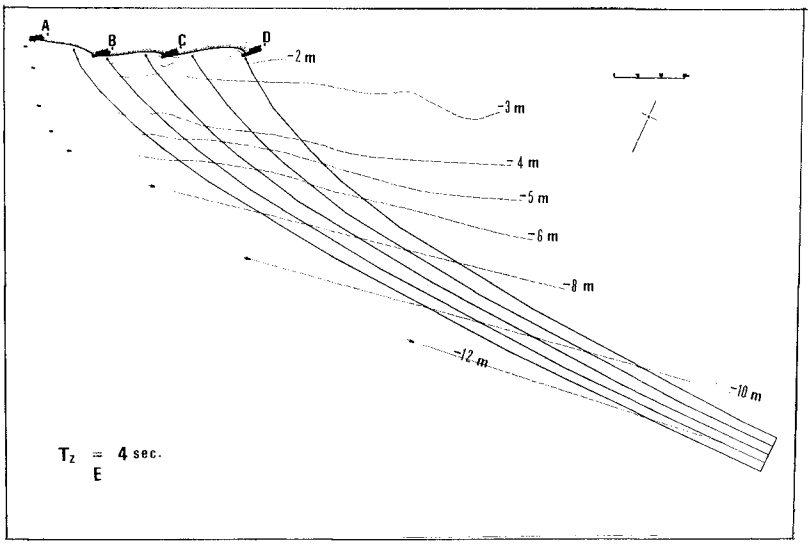


Fig 6. Refraction diagram

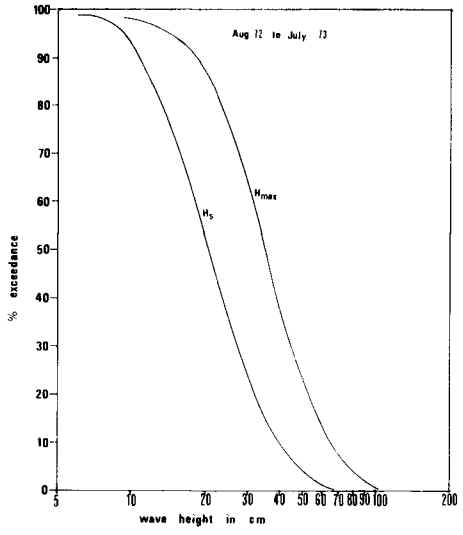


Fig 7 CUMULATIVE DISTRIBUTION OF SIGNIFICANT WAVE HEIGHT (H_s) AND MAX. WAVE HEIGHT (H_{max})

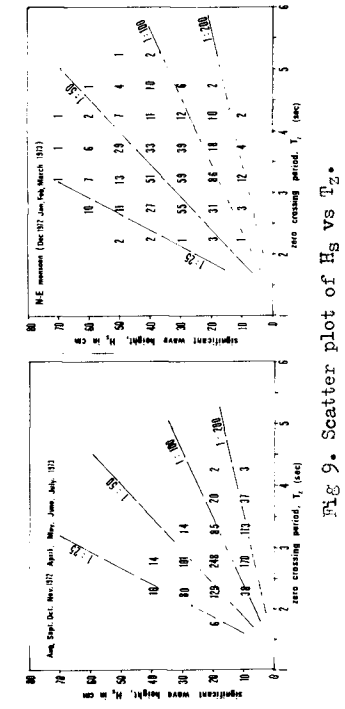


Fig 9. Scatter plot of H_s vs T_z.

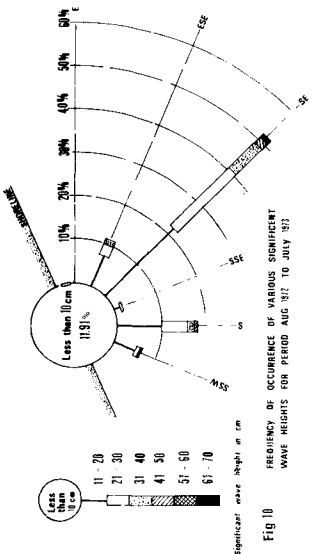
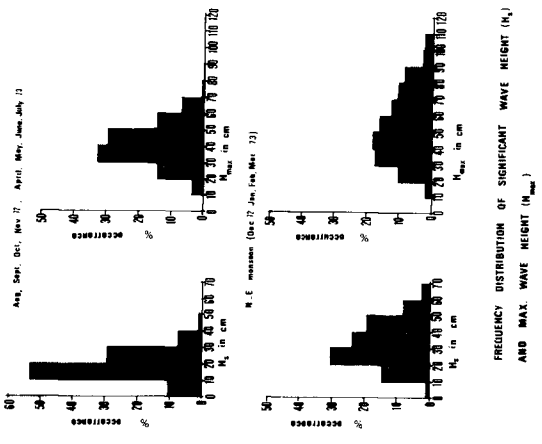
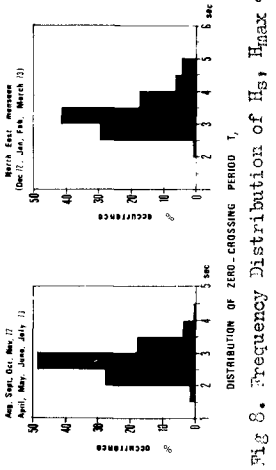


Fig 10 FREQUENCY OF OCCURRENCE OF VARIOUS SIGNIFICENT WAVE HEIGHTS FOR PERIOD AUG 1972 TO JULY 1973



FREQUENCY DISTRIBUTION OF SIGNIFICANT WAVE HEIGHT (H_s) AND MAX. WAVE HEIGHT (H_{max})



DISTRIBUTION OF ZERO-CROSSING PERIOD T_z

Fig 8. Frequency Distribution of H_s, H_{max} & T_z

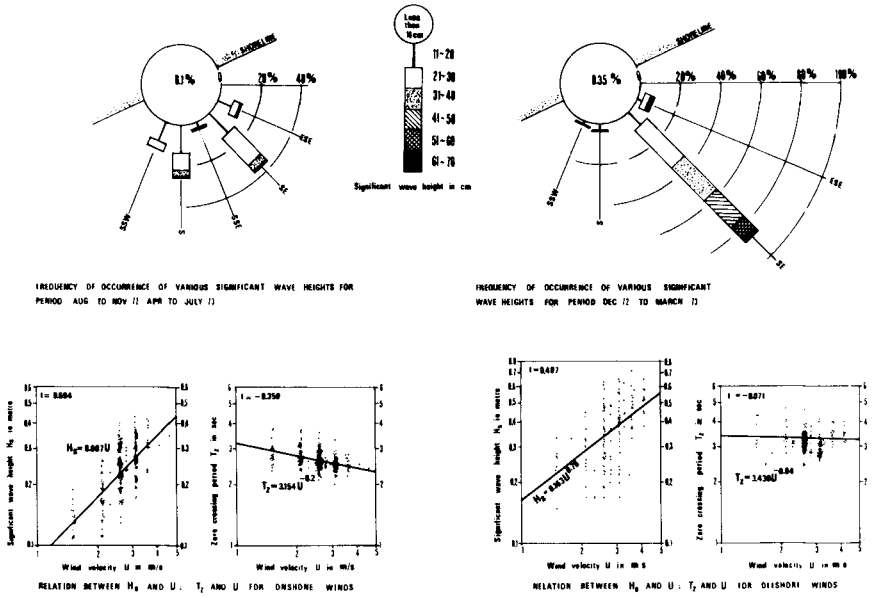


Fig 11. Relationships between H_S and U; T_Z and U

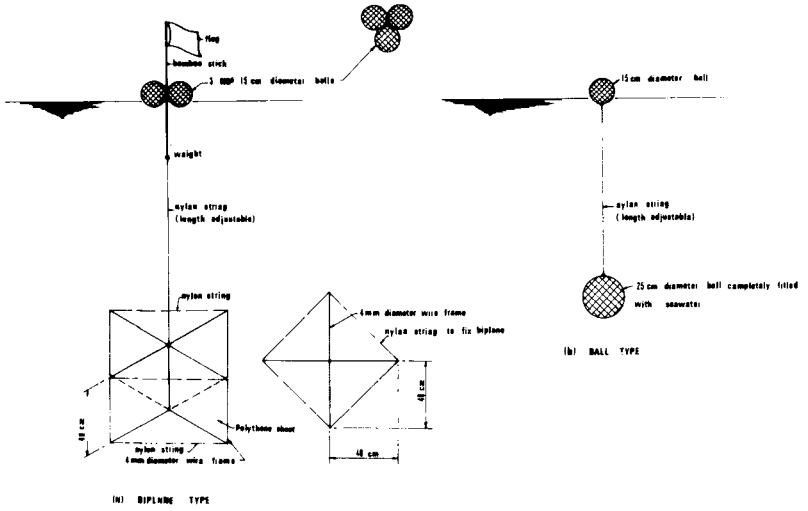


Fig 12. Details of Drogue

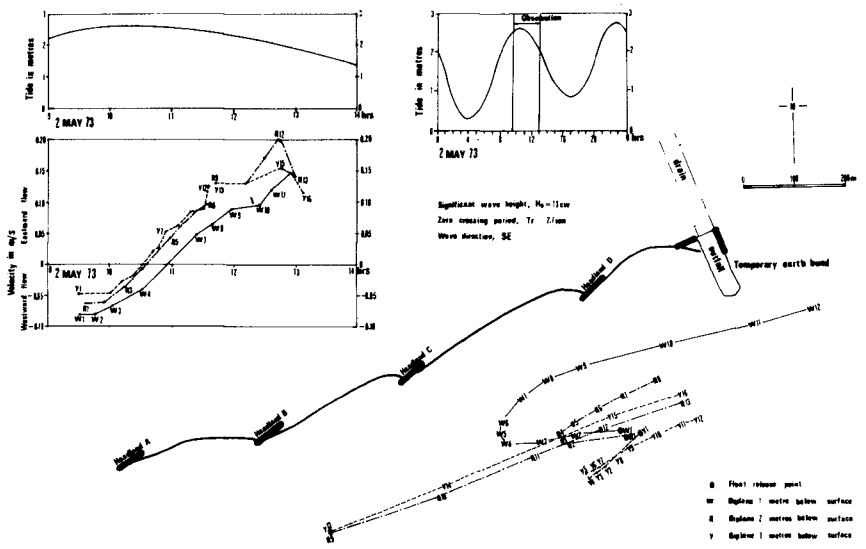


Fig 13 CURRENT OBSERVATION BY FLOATS ON 2 MAY 1973

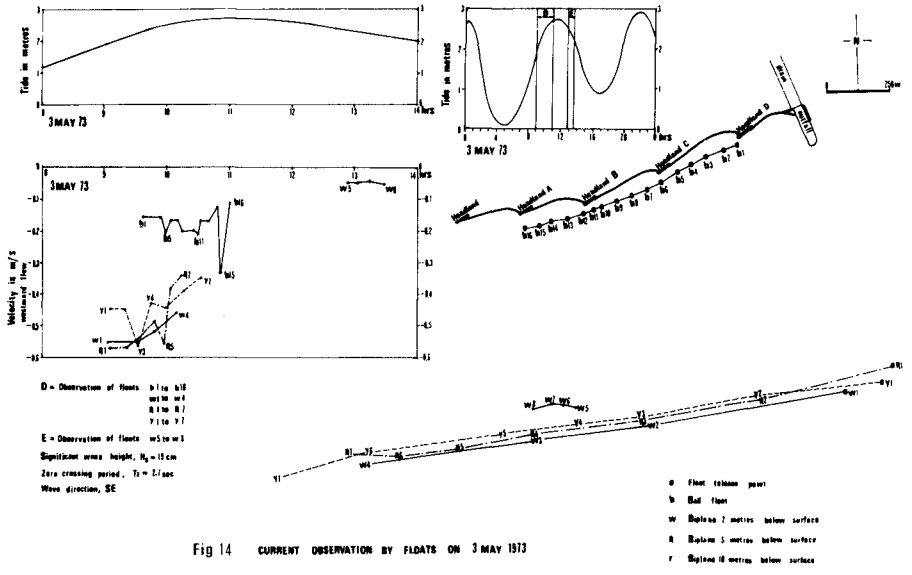


Fig 14 CURRENT OBSERVATION BY FLOATS ON 3 MAY 1973

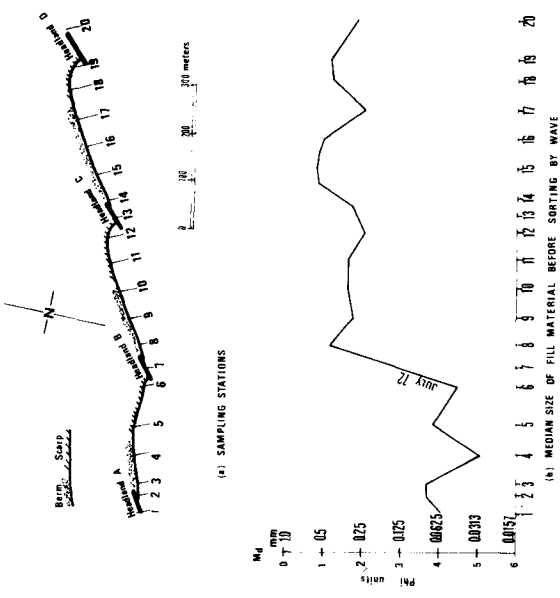


Fig 16. Grain size characteristics of fill material.

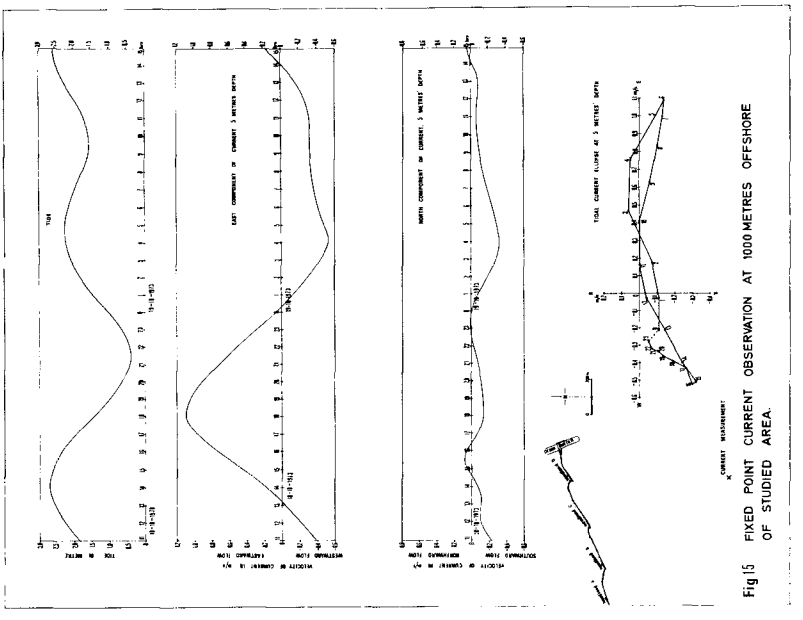


Fig 15 FIXED POINT CURRENT OBSERVATION AT 1000 METRES OFFSHORE OF STUDIED AREA.

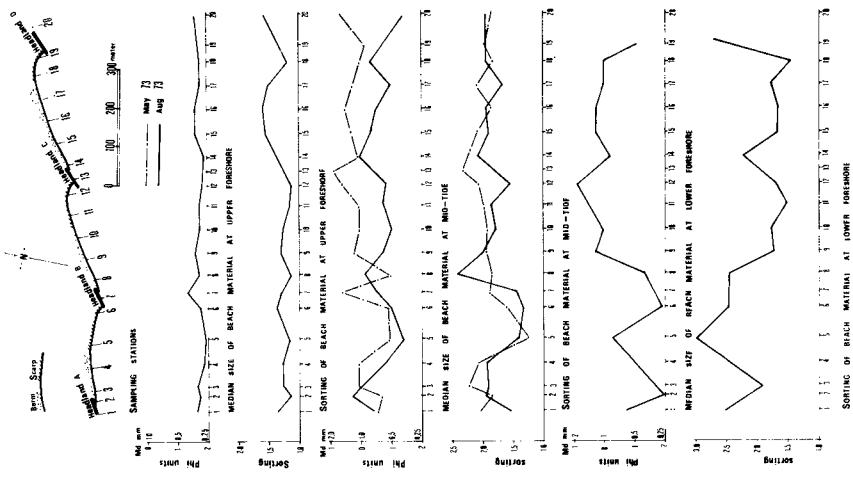


Fig 17. Characteristics of beach material.

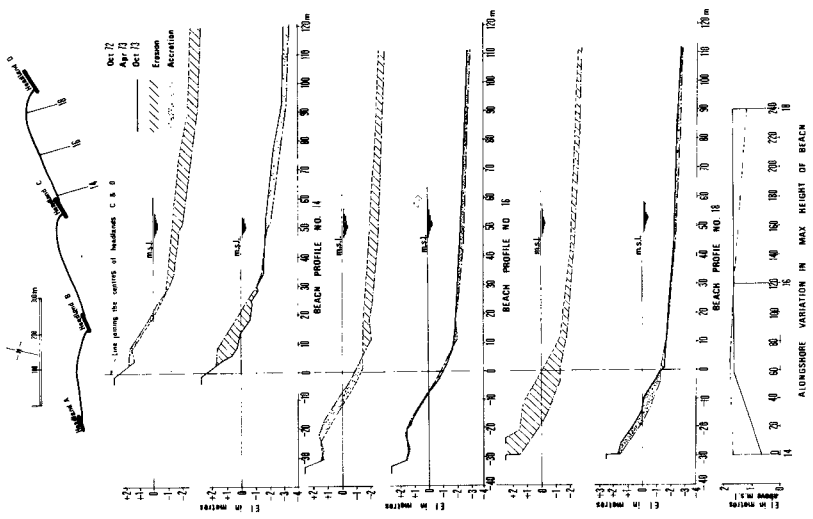


Fig 18. Beach profiles 14, 16 and 18.

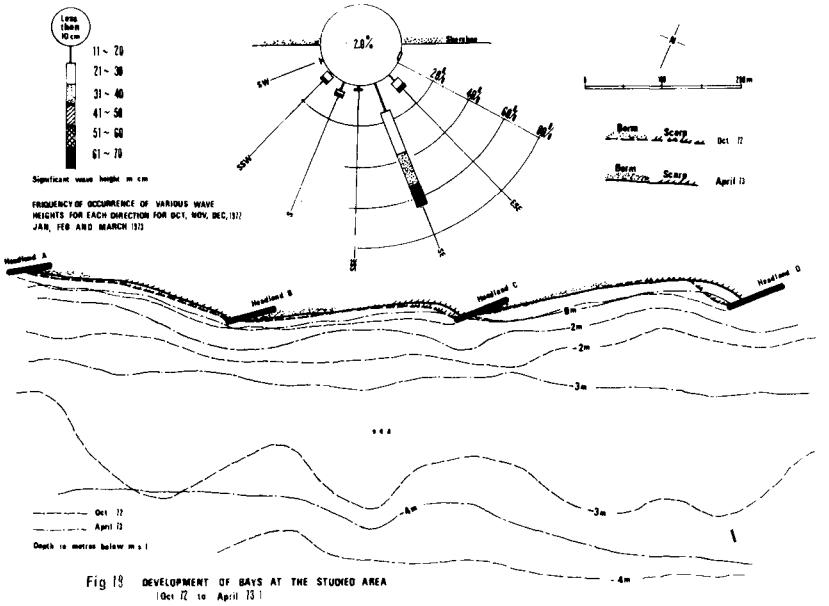


Fig 19 DEVELOPMENT OF BAYS AT THE STUDIED AREA (Oct 72 to April 73)

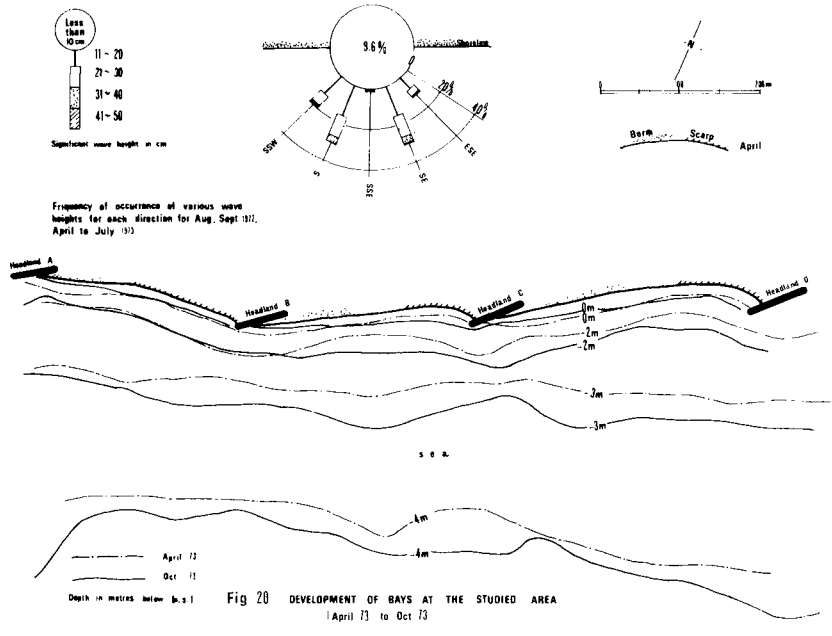
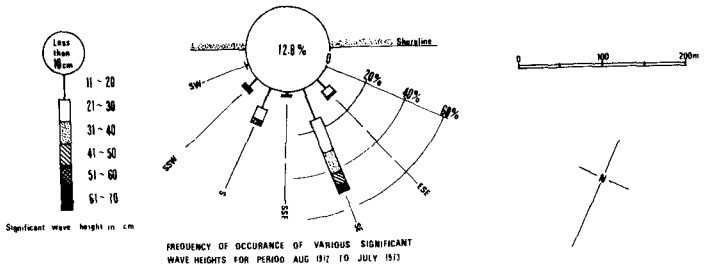


Fig 20 DEVELOPMENT OF BAYS AT THE STUDIED AREA (April 73 to Oct 73)



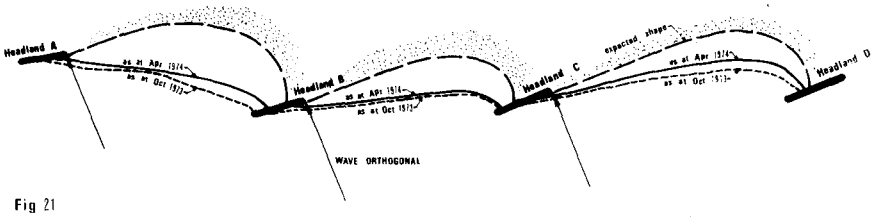


Fig 21
EXPECTED SHAPE OF BAY BETWEEN HEADLAND BREAKWATERS WHEN NETT WESTWARD DRIFT IS REDUCED/CUT OFF

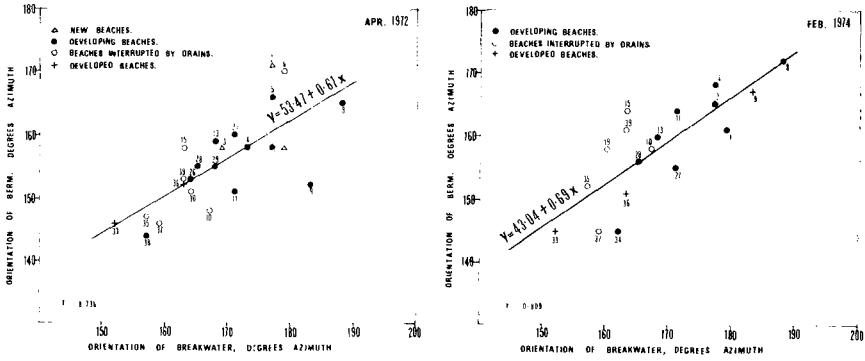


FIG. 22 RELATIONSHIP BETWEEN ORIENTATION OF BERMS AND ORIENTATION OF BREAKWATERS.