# Sedimentological Influences of Detached Breakwaters

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# SEDIMENTOLOGICAL INFLUENCES OF DETACHED BREAKWATERS

by

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ABSTRACT

Wave diffraction and refraction in the surroundings of a new detached breakwater induce currents strong enough to cause substantial local sediment transport and consequently morphologic changes, the main feature of which are sand spits or tombolos.

As shown by field studies the morphologic changes cause an equilibrium state with some minor fluctuations due to changing wave climate. Model studies have also proved the existance of such an equilibrium state for any given geometry and sea state

The present paper treats mainly this equilibrium state, but also attempts to explain the mechanism of sand transport characterizing the initial and transitional states. According to observations by the authors in small scale models, the transporting mechanism in the transitional state involves sea bottom erosion, especially near the breakwater heads outside the protected area, and transport of sand towards the shore of the sheltered area in the form of small migrating sand bars, which finally join the shore line and widen it. Results of experimental investigations conducted by the authors, for the particular case of high impervious breakwaters attacked by waves of normal incidence, as well as results of field and model studies given by others, are used to define relationships among the factors determining the equilibrium state and to base a new hypothesis regarding the equilibrium state. This hypothesis states that a morphologic and sedimentologic equilibrium is reached behind a detached breakwater, when the shape of the contour lines becomes such, that along the sheltered beach the diffracted waves have components of momentum opposed to the gradients of the mean sea level induced by radiation stress due to non uniform wave heights along the wave fronts approaching from both sides of the breakwater. The significant parameters characterizing the dimensions of the spit or tombolo in the equilibrium state are shown to be the relative length of the breakwater (compared to its distance from the original shore line), the relative distance from the original shore line (compared to the position of the breakers' line) and the relative height of the breakwater crest (above M.S.L, compared to the incident wave height).

## INTRODUCTION

Offshore detached breakwaters are used worldwide for four engineering purposes; to shelter water bodies from waves, to protect beaches against erosion, to prevent silting of harbour entrances and to facilitate shore accretion for reclamation. The achievement of these goals

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can be accomplished by diminishing the wave heights inside the area protected by the breakwater, mainly due to wave diffraction, and by trapping sand inside this area in the shape of a spit, which in certain circumstances becomes attached to the breakwater and then it is called tombolo.

In the past the construction of these breakwaters was based on field experience and on empirical rules. Lately, there have been certain attempts to treat the complex hydraulic and sedimentologic phenomena and processes related to the presence of such an artificial obstacle in a wavy sea by theoretical methods and by laboratory investigations on reduced scale models.

The hydraulic and morphologic processes induced by the construction of a detached breakwater may be characterized by three stages of development as follows:

a - initial state
b - transitional state
c - equilibrium

Following the construction of a detached breakwater the current pattern in its surroundings changes immediately. In this initial state a circulatory current cell develops on each side of the axis of symmetry in the sheltered area as observed in the field by Johnson (1919), viewed in small scale model by Sauvage et al. (1954) and proved theoretically by Liu et al. (1974). These currents are directed near the shore towards the sheltered area and are generated by lateral gradients in the mean sea level in the zone of diffraction, due to the effect of radiation stresses in a non uniform wave field, as explained best by Gourlay (1974, 1976).

In the transitional state, the above mentioned currents transport sand and deposit it in the sheltered area, building a new morphological land shape named spit, or if this becomes attached to the breakwater, tombolo.

In the field this state has been studied by a number of researchers by different methods. Ingle (1966), used granulometric analysis to check the change of the mean sand grain size on the foreshore apex of the sheltered area of the Santa Monica breakwater with time (1940-1962). He found that the mean grain size at the spit apex became thinner as time passed. The explanation brought by him was that while the spit apex progressed towards the breakwater due to continuous sand deposit, regions with less and less wave energy were reached, where only small grains could be transported. U.S. Engineer Office (1939), Johnson (1940, 1949), Handing et al (1950), Wiegel (1966), Nir (1976) and Toyoshima (1976) have used differential bathymetric maps or control profiles to study the transitional state. These indicated accretion of the shore line and decrease of water depths in all sheltered area. No one succeeded to confirm whether the origin of sand deposited in the sheltered area was from the neighbouring shore or mainly from the area opposite the breakwater heads or else. However, Nir indicates (for breakwaters built inside the dominant surf zone) that the sand trapped in the whole sheltered area in the first year reached about 50 percent of the total sand trapped in the final state. In the second year the sand accretion rate regressed significantly but increased again in the following one to three years by the end of which it stopped and

and morphologic equilibrium was achieved. To Nir's opinion, the regression in the second year was due to the temporary diminution of sand sources in the area surrounding the breakwater. Furthermore, according to his opinion the main sand source was sand from the neighbouring beaches, which consequently suffered erosion in the first years.

The transitional state was studied also by means of small scale models. Sauvage et al. (1954) applied on a shore parallel detached breakwater normal waves and also waves of equal oblicity from both sides of the breakwater, while continuously supplying sand (artificial) in the surf zone outside the sheltered area. In both cases they found that the shore line progressed parallel to its original shape towards the breakwater with only a small spit formation until the distance from the breakwater reached a critical value beyond which a tombolo developed. According to their opinion, sediment deposit was best facilitated along the axis of symmetry in the sheltered area because of two reasons: a) collision of the two opposite currents developed, b) turbulence decrease due to diminished wave height on the center line. However, in certain cases they found that the main sand deposit occurred as two spits which developed opposite each breakwater head. This phenomenon was explained by wave diffraction. Their main conclusion was that the process of tombolo formation depends on the wave characteristics and on the breakwater geometry. Additional information was brought by Shinohara et al. (1966) who studied in a small scale model with natural sand the process of sand deposit behind shore parallel detached breakwaters under the action of waves of normal incidence. Two wave steepnesses representing summer waves ($H_0/L_0$ = 0.019) and winter waves ($H_0/L_0$ = 0.046) were applied on a breakwater model of fixed length but located alternately at different distances from the original shore line such that the relative distance $X_B/Y_B$ was 0.5; 1.0; 1.75; 2.5. They studied mainly the change of the water line with time, giving a few other contour lines only for the final state. Currents were not measured. Regarding the development process the main fact which may be observed from the data brought by these authors is that in almost all the tests the spit development started with the formation of two small spits each one opposite one of the breakwater heads. Furthermore, the transitional state ended with the formation of a spit of stable morphologic state but tombolo formation never occurred. for these testing conditions.

Finally, numerical models have been developed which forecast the shore (water) line in the sheltered area of a detached breakwater, all being based on the differential equations developed originally by Pelnard-Considère (1956). Results of numerical models developed by Hashimoto (1974), Sasaki (1976) and Perlin (1979) show considerable progress in the representation of the transitional state, forecasting shore line accretion with one or two spits. However, when compared with small scale model results, it comes out that the numerical results are mainly of a qualitative nature and differ considerably in forecasting the quantitative values. The accuracy of the numerical model results is limited because of problems related to accurate solution of combined refraction, diffraction and reflection in water of changing depths, non-linear wave-wave effects, correct solution of two phase (water-sediment) flow, problems related to numerical modelling methods, etc.

The equilibrium state was studied by a number of researchers by field observations and in small scale models.

Many field observations indicated that the new land formed by sand deposit behind a detached breakwater reaches finally a relatively stable shape, which fluctuates around an average state due to changing wave climate (Johnson (1952), Spataru (1963), Inman et al. (1966), Silvester (1972), Toyoshima (1974), Nir (1976) and Noble et al. (1978)). The conclusion reached by Inman et al. (1966) was that tombolo formation would take place if the ratio $X_B/Y_B$ is less than a third, but if this ratio is larger than six the size of the spit formed would be very small. Toyoshima (1974) observed that the final quantity of sand trapped by the detached breakwater is influenced by position of the breakwater relative to the position of the breakers line. (Nir (1976), found for detached breakwater built inside the predominant surf zone that the area of the new land reclaimed reached from 25 to 75 percent of the sheltered area ($X_B/Y_B$) and that the morphologic equilibrium state was achieved in three to five years from the construction. Dean (1978) found from field surveys of the shores of the Atlantic and those of the Gulf of Mexico that the shape of the shore line behind two headlands or two detached breakwaters (in equilibrium state of tombolo)could be approximated by an ellipse and that the change in the depths on the median between the two breakwaters is a function of the relative distance of the breakwaters from the initial shore line at the power 2/3. As one can see, the quantity of information gathered from field observations is quite limited.

Studies of the equilibrium state in small scale models brought further information regarding the equilibrium state. Sauvage et al. (1954) brought a most important evidence for the understanding of the equilibrium state. This is presented in a picture which showed the shape of the water line of a tombolo in equilibrium state. It may be observed that this shape is elliptical and not circular, as one might assume by analogy to the shape of diffracted wave fronts.

The results of a model study by Shinohara et al. (1966) proved again that a morphological equilibrium state is achieved behind a detached breakwater and from a limited number of tests in which the wave period and the breakwater length were kept equal and constant,concluded that the equilibrium state is influenced by the wave steepness and by the relative distance from the initial shore line. However, one could observe that the actual influence was due to the different wave heights and therefore the different relative positions of the breakwater with respect to the breakers' line. These results indicated that a maximum sand deposit occurs in the sheltered area for the case when $X_B/Y_B = 1$. Silvester (1970, 1974) studied the equilibrium state of the shore lines of tombolos formed between adjacent detached breakwaters or headlands. Using the findings of Yasso (1965) which showed that the natural water line between adjacent headlands is stable in nature and can be described by a section of a logarithmic spiral, Silvester described the equilibrium water line between two adjacent breakwaters as being formed by a section of a logarithmic spiral and a straight section tangent, to this spiral section. Furthermore, the hypothesis used by him to describe the equilibrium state was, that it occurs when no more sediment is moved in the sheltered area due to the development of contour lines parallel to the diffracted wave fronts. This, according to him would lead to zero oblicity of the wave fronts with the contour lines and hence to zero longshore sediment transport. Further information regarding the equilibrium state was brought by

Gourlay (1974, 1976). Though his study purpose was to prove other things, its results can be used to prove that the hypothesis brought by Silvester and generally accepted since then (Komar (1978)) is wrong. Gourlay (1976) measured the currents developing in the sheltered area of a detached breakwater model. The bottom's contourlines were casted in concrete so that outside the sheltered area they were straight and parallel to the breakwater but in the sheltered area they were made as concentric circular sections reproducing a tombolo shape and the breakwater was attacked by waves of normal incidence. Thus, the contour lines were parallel to the incident wave fronts both outside and inside the sheltered area. This however did not prevent the generation of currents in the surf zone of the sheltered area which had in this model speeds larger (0.4 m/sec) than the incipient natural sand transport velocity. The study showed that they were generated by a gradient in the mean sea level between the unsheltered area and the sheltered area due to non uniform wave heights (and hence different radiation stresses) in two regions. Therefore the general hypothesis used until now to describe the equilibrium state is erroneous.

## PARAMETRIC DESCRIPTION OF THE EQUILIBRIUM STATE

The significant physical parameters influencing the morphologic equilibrium resulting by the implantation of a detached breakwater are as follows:

- $Y_B$ - the length of the breakwater
- $X_B$ - the breakwater's distance from the initial shoreline
- $S$ - the elevation of the breakwater's crest above MSL.
- $K$ - the porosity of the breakwater
- $D_B$ - depth at centerline of the breakwater
- $\beta(x)$- local bottom slope
- $H_o$ - deep water wave height
- $T$ - wave period
- $\alpha$ - wave approach angle

In addition some parameters pertaining to the local sediment may be mentioned , like:

- $\rho_s$ - the specific density of the sediment
- $d_{50}$ - median grain diameter
- $\theta_r$ - repose angle
- $\sigma_\phi$ - skewness factor of grain size distribution
- S.F.- shape factor of the grains

However, all this features may be summarized by the most significant property of the sediment from the point of view of the transport process, it is the characteristic fall velocity ($V_f$).

In the particular case of tombolo or spit formation induced by a shore parallel, impermeable and high breakwater (not overtopped by waves) the following dimensionless relationships can be deduced from the list of the relevant significant physical parameters:

- When only a spit is formed then

$$(1) \quad \frac{X_A}{X_B} = \phi \left(\frac{Y_B}{X_B}, \frac{X_{br}}{X_B}, \frac{H_o}{V_f . T}, \frac{H_o}{L_o}\right)$$

where the parameter $X_A$ represents the distance from the land spit at its apex measured from the original (equilibrium) shore line,

- In the case of a complete tombolo, the characteristic dependent variables are $Y_T$, $A_T$ and $V_T$. Consequently the dimensionless relationships may be written as:

$$(2) \quad \frac{Y_B - Y_T}{2X_B} = \phi_2 \left(\frac{Y_B}{X_B}, \frac{H_o}{V_f T}, \frac{H_o}{L_o}\right)$$

$$(3) \quad \frac{A_T}{X_B Y_B} = \phi_3 \left(\frac{Y_B}{X_B}, \frac{H_o}{V_f \cdot T}, \frac{H_o}{L_o}\right)$$

$$(4) \quad \frac{V_T}{Y_B X_B^2 \tan\beta} = \phi_4 \quad \frac{Y_B}{X_B}, \frac{H_o}{V_f \cdot T}, \frac{H_o}{L_o}$$

where:

$Y_T$ - the attachment width at the breakwater

$A_T$ - the accreted sand area

$V_T$ - the total volume of sand trapped in this protected area

The expressions indicate the dependence of the geometric parameters characterizing the sedimentologic development caused by a detached breakwater on the parameters of the waves, of the sediments and of the beach profile.

SMALL SCALE MODEL STUDY

A series of tests were carried out in a small scale moveable bed model with a high impervious detached breakwater parallel to the shore line attacked by waves of normal incidence. The model study was conducted in a wave tank. A beach was built of artificial sand (coarse bakelite, $\rho_s$ = 1.42 gr/cm$^3$, $d_{50}$ = 0.64 mm, $V_f$ = 2.9 cm/sec)see slopes in fig. 1. The beach was 7 m long, the depth near the wave generator was 40 cm and the water line was located at about 9 m from the wave generator.

Three groups of tests were performed for three deepwater wave steepnesses ($H_o/L_o$) of 0.015, 0.025 and 0.040. For each wave steepness only one wave height H and one wave period were used. For each group of tests the breakwater length $Y_B$ and its distance from the original shore line ($X_B$) varied (see table 1) to cover different conditions.

For each group of wave steepness the beach was initially brought to a natural equilibrium state, taking care that the equilibrium state would not be influenced by the initial beach slope using Dalrymple et al. (1976) conclusions. Then for such an equilibrium beach a detached breakwater with the smallest length ($Y_B$ = 0.5 m) was implanted at a distance $X_B$ from the new equilibrium water line and attacked by the same waves.

When morphological equilibrium state was attained, the breakwater was lengthened to $Y_B$ = 1.0 m attacked further with the same waves until a new equilibrium was attained and then the process was repeated with $Y_B$ = 2.0 m. At the end of these tests the initial beach slope was rebuilt, brough again to equilibrium by the same waves and the small breakwater was then built at a new distance $X_B$ from the natural(equilibrium) water line. Then the process of breakwater lengthening was carried out as explained above.

During each test the transitional state was monitored by eye observation, by pictures, by marking with small sticks the progressing water line and by measuring control profiles by means of a point gauge installed on a carriage moving above the model area.

Morphological equilibrium was indicated by the stability of the water line, and by the practical identity of three consequitive outcomes of control profile measurements which also served as a basis for the contour charts.

## SEDIMENT TRANSPORT IN THE TRANSITIONAL STATE

The process of sand deposit in the sheltered area was continously observed during the development stage. Current patterns were visualized using fluorescent dye. The observed phenomena are described below:

a) After the implantation of the detached breakwater, two circulatory currents as described theoretically by Liu et al. (1971) were observed. In some cases the dye indicated currents returning to the unprotected side of the breakwater around the heads (kind of fluctuating rip current).

b) Sand was observed to be transported from area outside the sheltered zone towards the sheltered zone and towards the shore line. Inside the sheltered area the sand accumulated around the axis of symmetry (perpendicular to the shore line) in such a way, that the resulting bathymetry was saddle - like due to concentration of sand deposit near the original shore line and near the breakwater.

c) From time to time, the formation of submerged sand bars was observed in the inshore area, opposite each one of the breakwater heads.

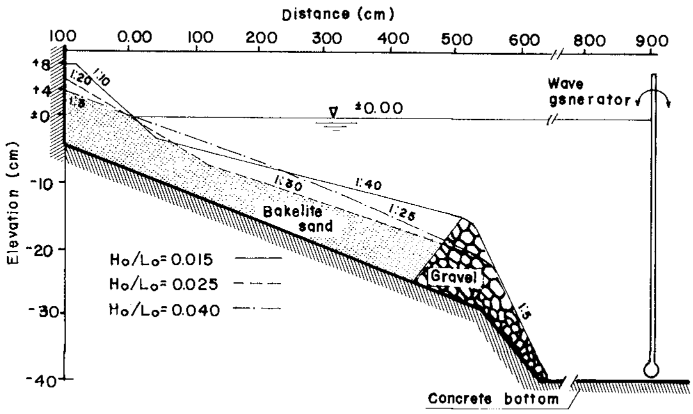


Fig.1-INITIAL BEACH SLOPES FOR THE THREE SERIES OF TESTS PERFORMED

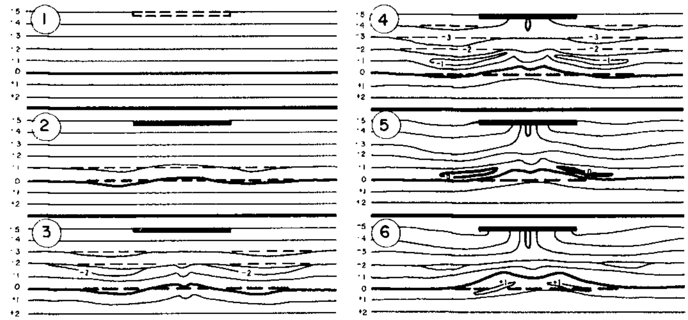

Fig. 2- TRANSITION STATE

DEVELOPMENT OF THE SAND SPIT BEHIND A DETACHED BREAKWATER

On these bars the sand moved with the waves and also with the circulatory current.

The slope of the bar was relatively moderate in the direction of wave progress but terminated with a steep slope (almost vertical) on its shoreward end (see fig. 2). The typical height of the sand bars was about 5 mm. The sand bars migrated towards the shore from both sides of the breakwater and towards each other. When they were close to the foreshore, they created with the shore line a kind of troughs. On the symmetry axis the two troughs joined and formed a channel near the water line. In the two troughs relatively high velocities were observed, but the sand was transported mainly near the edges of the troughs. The transporting speed was also high in the channel formed on the axis of symmetry of the sheltered area, but sand was transported mainly as bed load towards the ridge of the "saddle" area described previously, were most of the sand settled. The rest moved further towards the breakwater heads, parallel to the breakwater.

d) After some time, the migrating bars joined the shore creating two small spits. With time other sand bars joined them and also the area between the two spits filled with sand so finally in most cases a single spit was formed.

ANALYSIS OF THE TESTING RESULTS

The beach morphology in the equilibrium state was analyzed by comparing the change in the beach profile at control sections (fig.3), and by comparison of the final water lines obtained in each test (see figs. 4,5 and 6).

It was considered that the sand deposit in the sheltered area can be well represented by the value of $X_A$, i.e. the size of the sand spit at its apex measured from the initial (equilibrium) water line. Using the beach profiles the influence of the breakwater length ($Y_B$), its distance from the shore line ($X_B$), and of the wave steepness ($H_o/L_o$) on the size of the spit were studied. The main results of these analyses are presented in the following lines:

Influence of the breakwater length ($Y_B$)

The lengthening of the breakwater in a given wave regime lead usually to sand deposit in the sheltered area. The amount of sand deposited decreases from the axis of symmetry towards the unsheltered area.

Near the breakwater in the sheltered area a channel parallel to the breakwater is formed. Its dimensions grow with increasing breakwater length, especially when the breakwater was relatively far from the original water.

In the front of the breakwater, a series of sand bars develop with their length of the same approximate size like that of the breakwater. This is clearly due to wave reflection.

Influence of the distance of the breakwater from the shore line($X_B$)

The closer the breakwater is placed to the shore line, the larger the sand deposit in the sheltered area and the bigger the chance that the spit would become a tombolo.

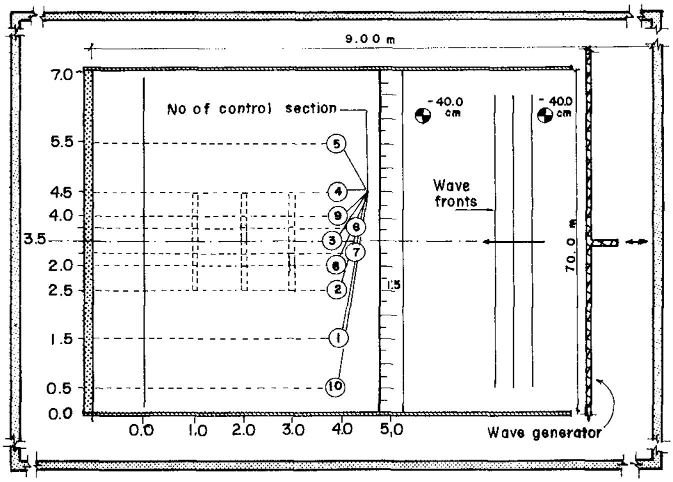


Fig. 3 - LAY OUT OF THE MODEL IN THE WAVE TANK AND LOCATION OF THE BREAKWATERS AND OF THE CONTROL PROFILES.

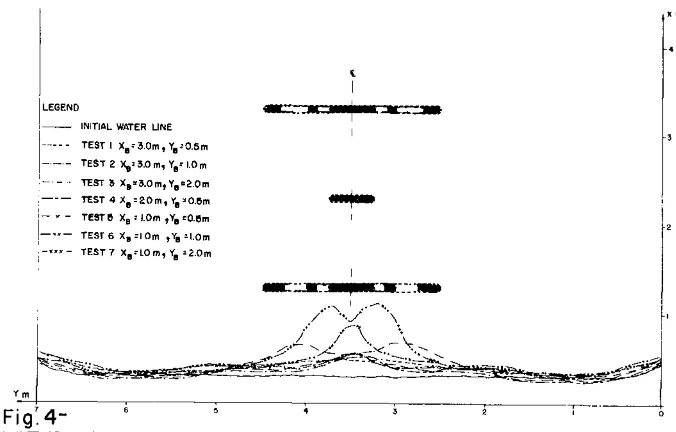


Fig. 4 -
WATER LINES IN EQUILIBRIUM STATE FOR TESTS SERIES $H_o/L_o = 0.015$

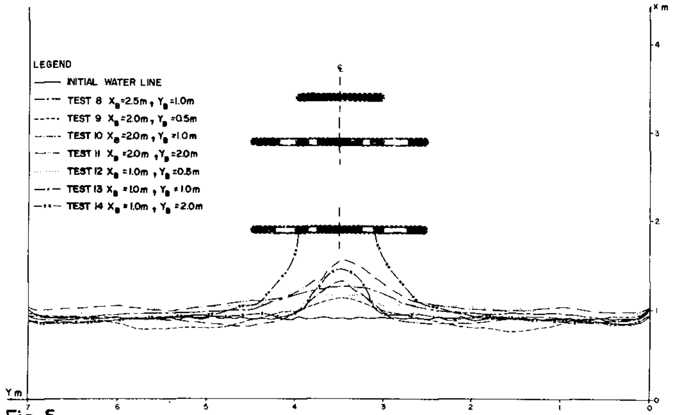


Fig. 5-
WATER LINES IN EQUILIBRIUM STATE FOR TESTS SERIES $H_o/L_o$=0.025

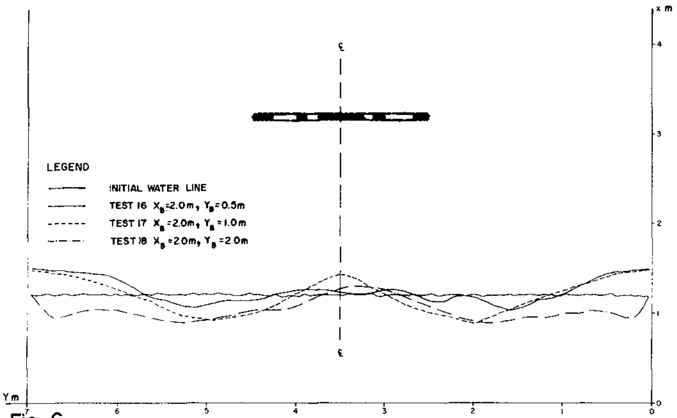


Fig. 6-
WATER LINES IN EQUILIBRIUM STATE FOR TESTS SERIES $H_o/L_o$=0.040

When the breakwater is placed close to the shore line the channel which develops near the breakwater, when it is far from the shore line, disappears.

Influence of the non dimensional parameter $Y_B/X_B$

Regarding the influence of both $Y_B$ and $X_B$, and considering the outcome of the dimensional analysis it was concluded that the actual independent variable on which the geometry of the sand spit depends is the relative length of the breakwater $Y_B/X_B$. This served, as a matter of fact for the preparation of fig. 7, in which the dependence of the spit geometry on this factor is clearly demonstrated.

This analysis included also results from nature and from other model studies which are summarized in tables 2 and 3.

Further, for the cases when a tombolo was formed ($X_A/X_B$=1.0) another analysis was made and the outcome is presented in fig. 8.

For points in fig. 7, indicating tombolos formed in nature, the distance of the breakwater relative to the breaker line ($X_B/X_{br}$) is not specified because it is variable, usually including cases with $X_B/X_{br}<1$.

Influence of the wave steepness ($H_o/L_o$)

It was found that the general equilibrium beach profile differred considerably for wave steepness 0.015 which was of a "summer" type, relative to the general beach profile obtained for the other two steepnesses(0.025 and 0.040), which were of similar "winter" type. This result corresponds well to the ones obtained by Johnson (1952), but also to the ones of Dean (1973) which concluded that the fall velocity parameter $H_o/V_{f}.T$ determines the type of beach profile, the critical value for transition from summer profile to winter profile being 0.85 (see table 1).

ANALYSIS OF THE EQUILIBRIUM STATE

The existence of a morphologic equilibrium in the surroundings of a detached breakwater under the influence of a certain incoming wave was proved by the present study. Additional information obtained from actual observations in the nature shows, that this statement can be extended for the average morphology developing under the influence of a certain wave climate.

There are various hypothesis how this equilibrium state is reached and how can the stability of the new configuration be physically explained or characterized by the relevant mechanism of sediment transport.

The attempts to find such an explanation led to the following assumptions:

a) Due to bathymetric changes the longshore current in the sheltered area fades completely or becomes so weak that the longshore sediment transport stops.

b) The longshore transport does not stop in the sheltered zone (along the tombolo beach) but continuity is maintained by recirculation of sand.

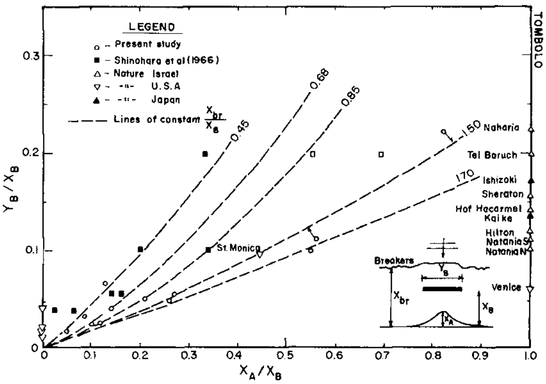


Fig. 7 -
RELATIONSHIPS AMONG PARAMETERS DETERMINING THE SPIT SIZE IN THE EQUILIBRIUM STATE

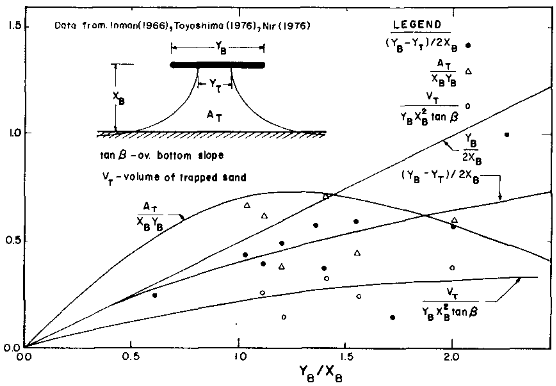


Fig. 8 -
RELATIONSHIPS AMONG PARAMETERS DETERMINING THE TOMBOLO SIZE IN THE EQUILIBRIUM STATE

| $\frac{H_o}{L_o}$ | Test No. | $H_o$ (cm) | T (sec) | $L_o$ (m) | $X_B$ (m) | $Y_B$ (m) | $X_A$ (m) | $X_{br}$ (m) | $\frac{Y_B}{X_B}$ | $\frac{X_A}{X_B}$ | $Y_T$ (m) | $\frac{Y_B-Y_T}{2X_BY_B}$ | $\frac{H_o}{V_f.T}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | | | 3.0 | 0.5 | 0.16 | 1.36 | 0.167 | 0.053 | | | |
| | 2 | | | | 3.0 | 1.0 | 0.26 | 1.36 | 0.333 | 0.087 | | | |
| | 3 | | | | 3.0 | 2.0 | 0.38 | 1.36 | 0.667 | 0.127 | | | |
| 0.015 | 4 | 1.5 | 0.8 | 1.0 | 2.0 | 0.5 | 0.21 | 1.36 | 0.25 | 1.105 | | | 0.65 |
| | 5 | | | | 1.0 | 0.5 | 0.24 | 1.36 | 0.56 | 0.24 | | | |
| | 6 | | | | 1.0 | 1.0 | 0.56 | 1.36 | 1.11 | 0.56 | | | |
| | 7 | | | | 1.0 | 2.0 | 0.82 | 1.36 | 2.22 | 0.82 | | | |
| | 8 | | | | 2.5 | 1.0 | 0.35 | 1.70 | 0.40 | 0.14 | | | |
| | 9 | | | | 2.0 | 0.5 | 0.23 | 1.70 | 0.25 | 0.115 | | | |
| | 10 | | | | 2.0 | 1.0 | 0.42 | 1.70 | 0.50 | 0.21 | | | |
| 0.025 | 11 | 3.9 | 1.0 | 1.56 | 2.0 | 2.0 | 0.66 | 1.70 | 1.0 | 0.33 | | | 1.34 |
| | 12 | | | | 1.0 | 0.5 | 0.26 | 1.70 | 0.50 | 0.26 | | | |
| | 13 | | | | 1.0 | 1.0 | 0.55 | 1.70 | 1.0 | 0.55 | | | |
| | 14 | | | | 1.0 | 2.0 | 1.0 | 1.70 | 2.0 | 1.0 | 0.86 | 0.57 | |
| | 15 | | | | 1.0 | 0.5 | 0.25 | 1.70 | 0.5 | 0.25 | | | |
| | 16 | | | | 2.0 | 0.5 | 0.05 | 1.0 | 0.25 | 0.025 | | | |
| 0.040 | 17 | 8.0 | 1.15 | 2.06 | 2.0 | 1.0 | 0.24 | 1.0 | 0.50 | 0.12 | | | 2.40 |
| | 18 | | | | 2.0 | 2.0 | 0.23 | 1.0 | 1.0 | 0.115 | | | |

TABLE - 1: Experimental data conditions and results

| Author | $\frac{H_o}{L_o}$ | $H_o$ (cm) | T (sec) | $L_o$ (m) | $X_B$ (m) | $Y_B$ (m) | $X_A$ (m) | $X_{br}$ (m) | $\frac{Y_B}{X_B}$ | $\frac{X_A}{X_B}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *0.75* | *1.50* | *0.25* | | *2.00* | *0.333* |
| | | | | | *1.50* | *1.50* | *0.30* | | *1.00* | *0.20* |
| *Shinohara* | *0.0192* | *2.55* | *0.922* | *1.33* | *2.625* | *1.50* | *0.375* | | *0.57* | *0.14* |
| *and* | | | | | *3.75* | *1.50* | *0.25* | | *0.40* | *0.067* |
| | | | | | *0.75* | *1.50* | *0.52* | | *2.00* | *0.693* |
| *Tsubaki* | | *6.12* | *0.922* | *1.33* | *1.50* | *1.50* | *0.50* | | *1.00* | *0.333* |
| *(1966)* | *0.0461* | | | | *2.625* | *1.50* | *0.425* | | *0.57* | *0.16* |
| | | | | | *3.75* | *1.50* | *0.10* | | *0.40* | *0.027* |
| *Horikawa and Koizumi (1974)* | *0.020* | *8.7** | *1.15* | *2.06* | *2.0* | *4.0* | *1.1* | | *2.00* | *0.55* |
| *Sasaki (1976)* | *0.02** | *8.7** | *1.15* | *2.06* | *2.0* | *4.0* | *0.70* | | *2.00* | *0.33* |
| | | | | | *100.* | *200.* | *26* | | *2* | *0.26* |
| | | | | | *100.* | *300.* | *48* | | *3* | *0.48* |
| *Perlin* | *0.0086** | *86.0** | *8.0* | *100.0* | *100.* | *400.* | *35* | | *4* | *0.35* |
| *(1979)* | | | | | *100.* | *600.* | *28* | | *6* | *0.28* |
| | | | | | *400.* | *800.* | *50* | | *2* | *0.125* |
| | | | | | *200.* | *400.* | *96* | | *2* | *0.24* |
| | | | | | *50.* | *100.* | *18* | | *2* | *0.18* |
| | *0.0217* | *217.0** | *8.0* | *100.0* | *100.* | *200.* | *50* | | *2* | *0.50* |
| | *0.030* | *30** | *8.0* | *100.0* | *100.* | *200.* | *11* | | *2* | *0.11* |
| *Sauvage et al (1956)* | | | *0.80* | *1.00* | *1.00* | *0.80* | *1.00* | | *0.80* | *1.0* |

*Estimated by present authors from other data given by the author

TABLE 2: - Results obtained by other researchers by numerical and physical small scale models

| Author | Location | Name of structure | $h_B$ (m) | $X_B$ (m) | $Y_B$ (m) | $X_A$ (m) | $Y_T$ (m) | $\frac{Y_B}{X_B}$ | $\frac{X_A}{X_B}$ | $\frac{Y_B-Y_T}{2\,X_B}$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Inman et al (1966)* | *Venice* | *Venice breakwater* | 5.0 | 300 | 180 | 300 | 36 | 0.60 | 1.0 | 0.24 | *Groyne not removed* |
| *Noble* | *St. Monica* | *St. Monica brwtr.* | 7.2 | 555 | 540 | ∿250 | - | 0.97 | 0.45 | - | |
| *(1978)* | *Thum's Island* | *Island B* | 9.0 | 780 | 325 | ∿ 0 | - | 0.42 | 0 | | |
| | - " - | - " - C | 9.0 | 1666 | 325 | ∿10 | - | 0.20 | 0.006 | - | |
| | - " - | - " - D | 12.0 | 1985 | 260 | ∿ 0 | - | 0.13 | 0 | - | |
| | *Rincon Island* | *Rincon Island* | 12.5 | 1650 | 160 | ∿ 0 | - | 0.10 | 0 | - | |
| *Bruno et al (1979)* | *California* | *Channel Island Harbour brwtr* | 9.0 | 600 | 700 | 260 | - | 1.167 | 0.433 | - | |
| *Toyoshima* | *Ishizaki* | | - | 35 | 60 | 35 | 50 | 1.714 | 1.0 | 0.143 | |
| *(1974,1976)* | *Kaike* | | 5.0 | 110 | 150 | 110 | 25 | 1.364 | 1.0 | 0.568 | |
| *Nir (1976)* | *Naharia* | *Naharia brwtr.* | - | 80 | 180 | 80 | 20 | 2.25 | 1.0 | 1.0* | *Groynes in its neighbourhood* |
| | *Haifa* | *Hof Hacarmel* | 3.0 | 200 | 280 | 200 | 130 | 1.40 | 1.0 | 0.375 | |
| | *Netanya* | *North brwtr.* | - | 200 | 207 | 200 | 35 | 1.035 | 1.0 | 0.43 | |
| | | *South brwtr.* | - | 215 | 240 | 215 | 70 | 1.116 | 1.0 | 0.395 | |
| | *Tel Aviv* | *Tel Baruch* | 3.0 | 100 | 200 | 100 | 105 | 2.00 | 1.0 | 0.475 | |
| | | *Sheraton* | 4.0 | 200 | 310 | 200 | 75 | 1.55 | 1.0 | 0.588 | |
| | | *Hilton* | 4.0 | 200 | 240 | 200 | 45 | 1.20 | 1.0 | 0.488 | |

TABLE 3: - Data regarding spits and tombolos in nature

Silvester (1970, 1974) explained hypothesis a) by assuming that the bottom contour lines become parallel to the diffracted wave fronts. Model tests carried out by Gourlay (1976) indicate, that this may not be the case, because such a morphology involves strong currents capable of causing intensive sediment transport along the sheltered beach. Consequently, hypothesis a) should be discarded. The condition for hypothesis b) clearly must be the existence of a circulatory current strong enough to maintain longshore transport along the equilibrium spit or tombolo beach. However, continuity considerations show, that such a strong current may not exist in the vicinity of a detached breakwater because the current at the breakwater heads would be much weaker than that at the shore, facilitating there sediment deposit which would mean that equilibrium was not reached. This was also indicated by the model tests of Gourlay (1976). Therefore, this conclusion leads back to hypothesis a) which had to be given another physical explanation.

## DISCUSSION OF A NEW EQUILIBRIUM HYPOTHESIS

The authors observed in the model and then in nature that the morphological equilibrium was reached when the shape of the contour lines was not completely parallel to the diffracted and refracted wave fronts (see fig. 9 and 10). The present hypothesis states that a morphologic and sedimentologic equilibrium is reached when the shape of the contour lines is such that along the sheltered beach the diffracted waves have a component of momentum opposed to the gradient of the mean sea level induced by radiation stress due to non uniform wave height along the wave fronts. This explains the fading of the currents which caused sediment transport during the earlier stages of development.

Fading of the currents does not mean a complete absence of them, but rather indicates a state of lack of longshore sediment transport, due either to the weakness of the remaining currents, or to the combined influence of diffracted waves and weak currents, which cause only local oscillation of sediments.

As a matter of fact, weak currents may be observed along tombolo beaches in spite of their apparent state of equilibrium.

In model tests carried out in our laboratory involving detached breakwaters the weakening of the circulatory currents towards the end of the development process of tombolos was clearly observed.

In the same state sand movement along the tombolo beach could not be detected. This also confirms our hypothesis concerning the dynamic conditions required for the establishment of equilibrium in the process of tombolo development.

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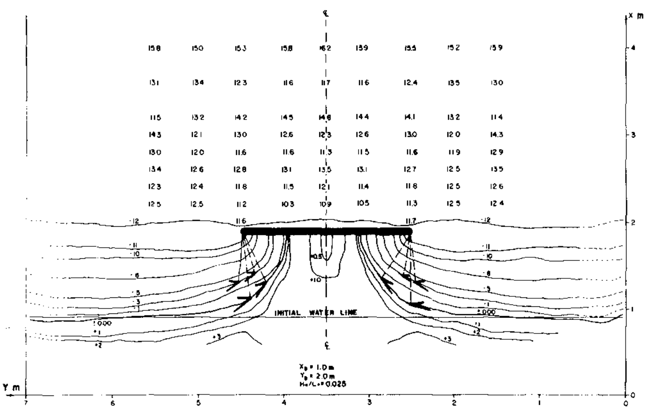


Fig. 9- TOMBOLO DEVELOPMENT-MODEL
(CONTOUR LINES NOT PARALLEL WITH DIFFRACTED WAVE FRONTS)

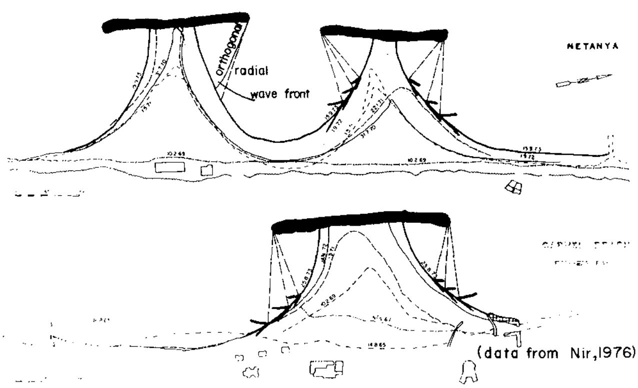


Fig. 10- TOMBOLO DEVELOPMENT-NATURE
(SHORE LINE NOT PARALLEL WITH DIFFRACTED WAVE FRONTS)

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