CHAPTER 33

EXPERIMENTAL STUDY OF THE HYDRAULIC BEHAVIOUR OF GROYNE SYSTEMS

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SYNOPSIS

Results of an experimental study of the hydraulic behaviour of groyne systems, a very widespread coast erosion protection structure, are described. The characteristics of the evolution of beach stretches between groynes under the action of waves with different obliquity, heights and periods are defined. The results obtained are intended for design of systems of functional groynes which secure an adequate partition of the beach in satisfactory hydraulic conditions, and also meeting use requirements, notably from the architectural and recreation standpoints. Additionally the author briefly discusses longshore drift and presents some experimental conclusions on the relations between longshore drift and the characteristics of the waves.

1 - INTRODUCTION

Coast erosion and the creation of artificial beaches are two of the main problems which arise concerning the development of coastal areas. Both the problems can, in many instances, be solved using groyne systems, (see fig.1). This type of protection is also currently used to solve accretion problems in certain coastal zones or control shoal progression. Generally, hidraulic and architectural standpoints make the design of this type of works difficult, especially the determination of the length, spacing and crown elevation of the groynes, taking into account that the groyne structure itself is ruled by hydraulic characteristics and by its required utilization which, often, involves landscaping problems. The importance of designing efficient groyne which can be applied to a large number of extensive coastal areas (see fig.2) led to the present study, the purpose of which is to contribute towards the solution of the problems presented by such systems.

Systematical tests of fixed, high and impermeable groynes was carried out, (see figs.3 and 4). The groyne slopes had different structures and they were put perpendicularly to the shoreline, corresponding to rockfill prototypes with the purpose of studying the most usual type of groynes. The pattern beaches selected for study were those which can be classified as independent physiographical units, i.e stretches of beach located between groynes long enough to prevent the transposition of mobile material at their edge. The main purpose was the determination of the evolution characteristics

Fig.1 - Groyne. Cova do Vapor beach.

Fig.2 - Coast erosion. Caparica beach. February 1964.

Fig.3 - Laboratory test. Wave action. 1st series of tests.

Fig.4 - Laboratory test. Final situation (wave with maximum height).

Fig.5 - Tank.

of the beach stretches under the action of cycles of waves with different characteristics, setting the spacing and the length of the groynes in order to obtain stable beaches. Secondarily, taking advantage of the groynes as a way of measuring the littoral drift, it was tried to establish a relation of dependence between the littoral drift and the characteristics of the acting waves.

As fundamental parameters of the hydraulic behaviour of the groynes it was considered: the slope of the beach, the specific weight and the granulometrical characteristics of the mobile material; the height, period and obliquity of the acting waves; the length, spacing, crown elevation and slope structure of the groynes and also the orientation of groyne directrix.

The basis of this work were established as a contribute to the study of long groynes use at parcelling coastal areas, as it was referred in {1}.

2 - EXPERIMENTAL TECHNOLOGY

This study was carried out almost in its whole in a 20 m x 10 m tank (see figs. 5 and 6) equipped with a snake type wave generator and a tide reproducing system. This generator allowed the reproduction of single sinusoidal waves, the only ones which were taken into account in this study, although a generator able of reproducing wave trains is already available but not yet operative; tests under the action of wave trains will be soon carried out. The characteristics and limitations of the wave generator can be evaluated from figs. 7, 8 and 9. The graph in fig. 7 shows, as ordinates, the wave heights and, as abscissas, the eccentricities to be introduced into the generator. The wave range to be reproduced covers heights between 1.0 and 7.0 cm, periods of 1.0 to 1.8 sec and three obliquities: 20°, 10° and 5° (although the generator allows for obliquities in the 60° range). The thick lines in fig. 7 refer to situations where regular sinusoidal waves are generated while the interrupted lines correspond to irregular waves reproduced under deficient conditions. The histogram in fig. 8, plotted on the basis of 232 readings, shows the occurrences of certain deviations regarding a mean value of wave heights recorded by 12 resistance probes; the distribution of these deviations follows rather closely Gauss's normal law; it must be said that deviations from the mean values ranging from 15 to 18% have a rate of occurrence of 4%. Wave period was determined by chronometry with errors of 1%. The obliquities of the generated waves, obtained through calculated de-phasing of the paddles, were checked against photographic plans. The tidal records were made through limnographs.

Beach cross sections were considered and readings taken of the distances between the water line and a reference line; the error in the determination of such distances was of ± 0.5 cm. A complete survey of the bottoms was made at the end of each test through direct measurement of successive water lines obtained by lowering the level inside the tank. An automatic probe for direct recording of the bottom profiles was studied by LNEC's Instru-

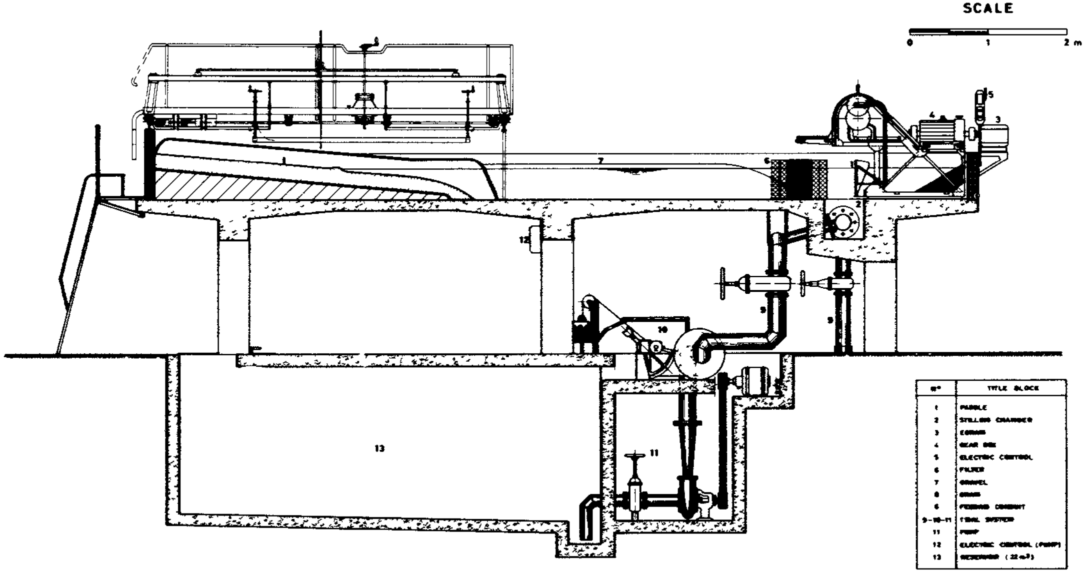


Fig.6 - Tank. Cross section.

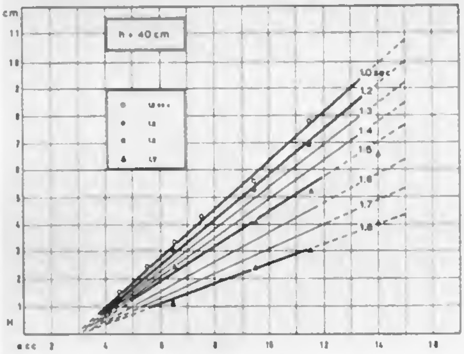


Fig.7 - Calibration curve of the wave-generator

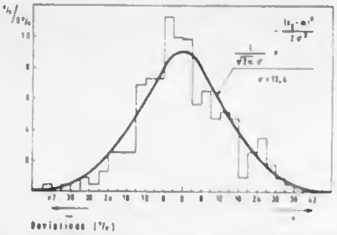


Fig.8 - Distribution of deviations of wave heights.

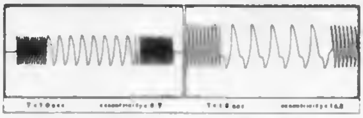


Fig.9 - Wave records (model).

Fig.10 - Servo-coordinograph. Experimental set-up.

Fig.11 - Servo-coordinograph. Detail of the probe.

Fig.12 - Servo-coordinograph. Detail of the record.

Fig.13 - Pumice-stone. γ_s = 1,67 gf/cm³.

Fig.14 - Bakelite. γ_s = 1,38 gf/cm³.

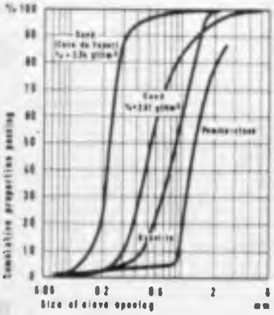


Fig.15 - Sand (model). γ_s = 2,61 gf/cm³.

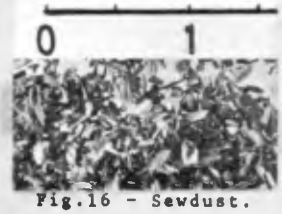


Fig.16 - Sawdust.

Fig.17-Mobile materials. Granulometric curves.

ment Design and Construction Division. This probe was studied and mounted at its experimental stage with excellent results (see figs. 10, 11 and 12); the need to make a few corrections and the difficulties of constructing the equipment in its final design made impossible the use of this recording method, which would have allowed a much more detailed study of the cross section evolution characteristics.

The technological characteristics of another tank where a few tests were made are identical to those described above.

The mobile materials used were pumice-stone, bakelite, sand and saw-dust. The specific weight of the satured grains and the granulometrical characteristics can be seen in figs. 13 to 17 (figs. 13, 14, 15 and 16 are photographs of microscope observations).

Fresh water was used for all the tests. The Reynolds' number has values over 3000, calculated according to Miche's formula, $R=\frac{L}{T}\,\frac{H}{2\nu}$ with $\nu=1.01\times10^{-6}\,m^2 s^{-1}$ thus justifying the classification of the movement as turbulent. As the testing set-up does not correspont to any specific case, but is only a schematic situation for systematic testing, there is no scale.

3 - EXPERIMENTAL RESULTS

A first series of tests was made by using the set-up described in fig.18. It was taken as a pattern a pumice-stone beach with an 8% slope in cross section and a depth of 40 cm at the base of the slope, (see fig.6). Groyne E1 was studied in different positions, in order to change the distances between groynes. E1 and E3 groynes were formed by loose rockfill with a 2/1 absorvent slope; E2 groyne, this non-absorvent, had a 1/5 slope. This set-up made possible the investigation of the differences of behaviour in groynes with different structures in the two stretches of beach. The initial water line is defined in fig.18 (t = 0).

The action of oblique waves on the stretches of the beach arises generally a longitudinal drift characterized by zigzag movements of the grains, which result from the combination of the oblique jet from the run-up of the wave after breaking, with the return flow following the highest slanting line of the beach (see fig. 3). A zone of erosion is thus created seaward while leeward, under the action of the groyne, there will be a zone of retention. The typical evolution can be observed in fig.18 and, after a period of time referred to as stabilization time, there will be a situation of equilibrium (see fig.19) with an adjustment between the water line and the acting wave, the incidence of which will become frontal along the whole stretch of beach. Littoral drift will consequently disappear. This situation is due to the evolution of the beach as well as to the refraction of the acting wave resulting from the alterations on the bottoms which happen during evolution. The wave action on stretch 1 is conditioned by the influence of the absorvent slopes of E1 groyne which, being a long groyne, originates, besides the wave difraction, an energy dissipation on the side slopes; thus, the final configuration of equilibrium (see fig.19) shows the point of highest

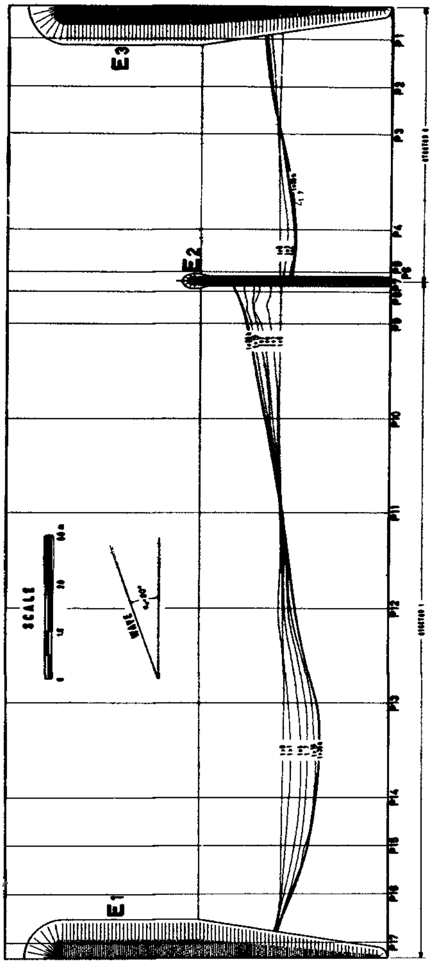


Fig.18 - Typical plan of evolution. 1st series of tests.

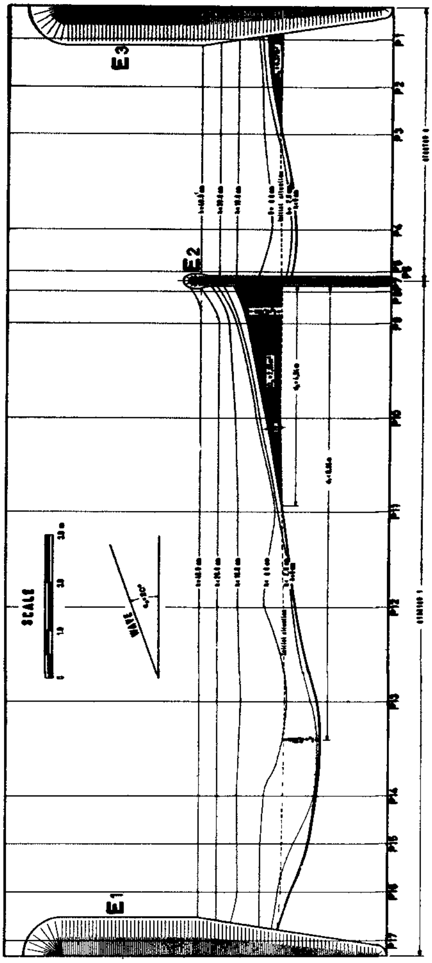
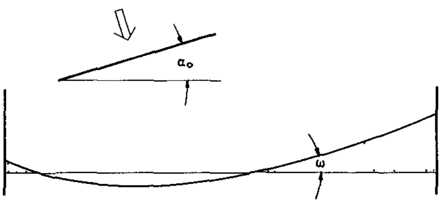


Fig.19 - Typical plan of final equilibrium situation. 1st series of tests.

erosion far away from the groyne E1, contrary to what happens in stretch 2 where that point is nearer to the groyne on account of the latter being non-absorvent.

In view of the importance of wave refraction on groyne behaviour it might be assumed that beach evolution would only be dependent on the wave obliquity and period and that the wave height would be a less important parameter. Actually, the influence of height is very much important, seeing that it restrains the location of the breaking line and the run-up. Thus, two waves with the same obliquity α_0 the same period but different heights will present different incidences on breaking for the highest wave will break at greater depths and its slope base obliquity will thus suffer a minor variation through refraction. One can actually obtain bigger accretion with higher waves provided the material will not go into suspension. It was found that for the same obliquity at the slope base and the same period, the value of the ω angle for lower waves was about $\alpha_0/2$ while for higher waves the ω angle increased until it reached values around α_0. The accretion zone located next to the groyne generally presents certain singularities due to the action of the jet formed under the action of the oblique wave on the groyne slope (see fig.22). As significant data on beach evolution it was presented the graph on fig.20 referring to P9 and P5 profiles defined in fig.18. A rather accentuated beach evolution was recorded during the first few hours of tests. This evolution decreases progressively until it reaches, for each wave, a final situation of equilibrium. Advances on profile P9 increase, for the same obliquity and period, whenever wave height increases but after a certain value is reached, which for pumice-stone may be set at 6.0 cm, mobile material goes openly into suspension and beach behaviour acquires different characteristics as in the case of the 7.0 cm high wave; the diagram in fig.20 shows a backward movement of the beach at the starting near the centre groyne and final values lower than those obtained with waves 5.0 cm high. As the other hand when the material is carried in suspension it goes through the end of the groynes and there is a recovery of the initially eroded beach in profile P5. Beach evolution is very regular for major obliquities; for 5° obliquity its behaviour is more irregular and there are some cases where transversal movements predominate over the longitudinal ones. It can be seen from profile P5 that for 5° obliquity waves with greater wave-steepness led to erosions while those with lesser wave-steepness originated accretion.



The pumice-stone used for testing is a heterogeneous material. As it can be seen from fig.4 there are two distinctive zones in the final situation of equilibrium: one of dark coloured material and the other of light coloured one which correspond, respectively,

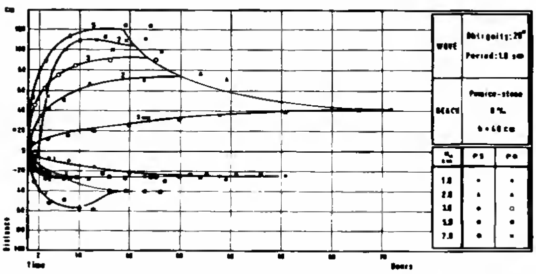


Fig.20 - Typical curve of profile evolution. 1st series of tests.

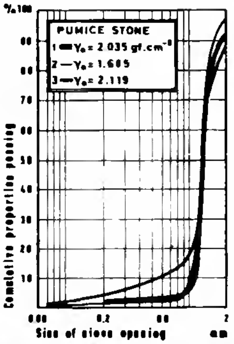


Fig.21 - Pumice-stone. Granulometric curves.

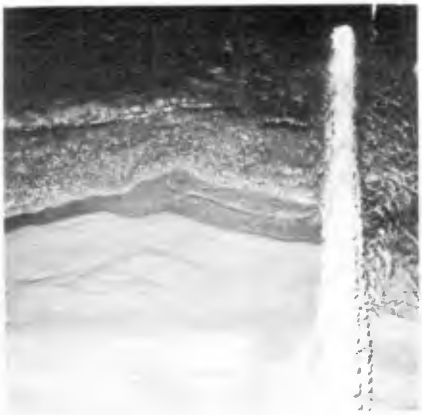


Fig.22 - Wave action near the groyne.

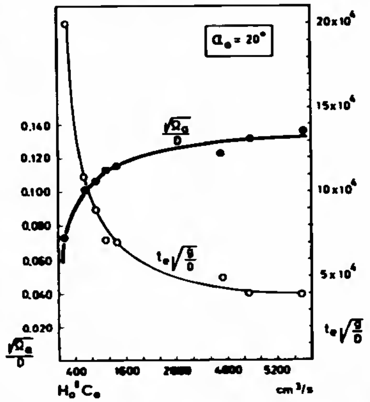
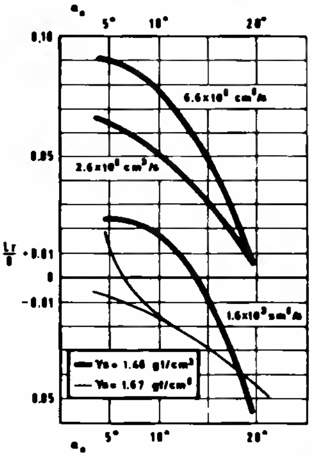


Fig.23 - Typical curve of dimensionless parameters variation.



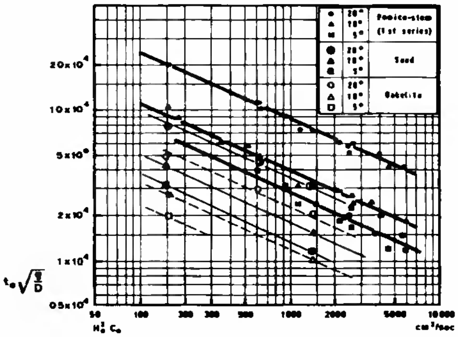


Fig.24 - Curve of L_r/D variation. Fig.25 - Curve of $t_a\sqrt{g/D}$ variation.
Leeward

to higher specific weights and a larger percentage of fine components, and lower specific weights with larger diameters. The material initially found on the beach is a mixture of both (see fig. 21). The zone of retention is formed by the lighter material, while the heavier material remained on the eroded zone. However, the tests carried out with sand, a more homogeneous material, showed that behaviour characteristics were identical to those obtained with pumice-stone. It should be noted that although the darker pumice-stone, with higher specific weight, has a large percentage of fine components, its mean diameter is the same as that of the lighter pumice-stone.

To define the evolution characteristics of the beach stretches it was considered values expressing quantitatively the forward and backward movements, accretion areas, stabilization times, length of groynes and the distances defining the area of erosion. These values, whenever no indication on the contrary is to be given, refer to the final situation of equilibrium. Thus, designating as D the distance between the groynes which limit a stretch of beach, it is to be consider the following dimensionaless parameters:

l_a/D - defining the maximum advance, l_a, of the water line near the groyne (on a cross section close to the groyne not affected by the singularities described).

l_r/D - defining the maximum erosion, l_r, found on the beach stretch.

$\sqrt{\Omega_a}/D$ - defining the emersed area of accretion, Ω_a, near the groyne.

c/D - defining the effective length, c, of the groyne.

$t_e\sqrt{g/D}$ - defining the stabilization time, t_e, for the beach stretch.

d_A/D - defining the distance, d_A, measured from the retention groyne, to the point where evolution is null, (intersection of the final situation of equilibrium with the initial situation).

d_r/D - defining the distance, d_r, measured from the retention groyne to the point of highest erosion.

Values l_a, l_r and Ω_a were measured between the water lines corresponding to the initial and final situations. Value Ω_a was considered to be representative of the groyne capacity of retention instead of the volume of the material retained, owing to the difficulty of measuring accurately the volumes retained (these calculations were only made in connection with the volumes retained during the 1st hour of the tests with a view to the determination of littoral drift). Value c was measured between the line corresponding to the initial situation and the limit of the underwater deposits at the final situation, next to the retention groyne. The c value defined in this way takes only into account the beach evolution seaward, since the consideration of possible erosions leeward close to the groyne, would make necessary to determine, for each case, the length of the rooting portion which will be added to c value. t_e represents the number of test hours until the stretch of beach reaches the equilibrium.

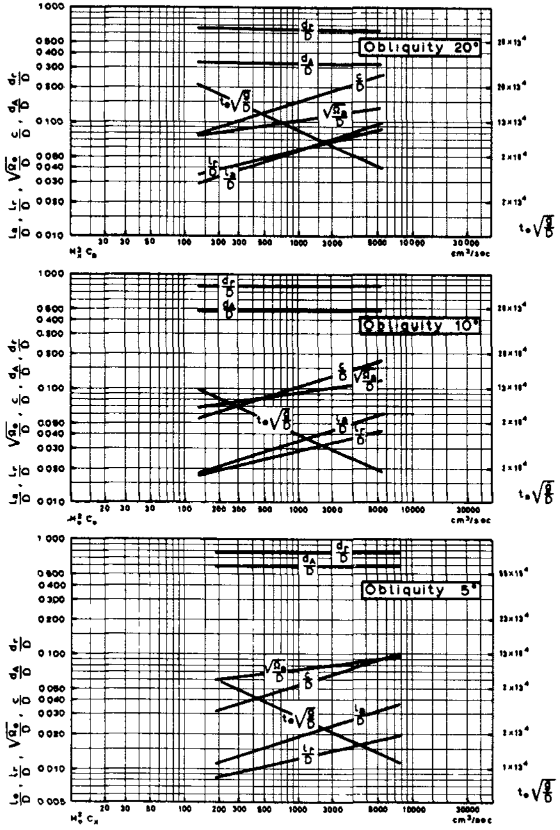


Fig.26 - Results of 1st series of tests.

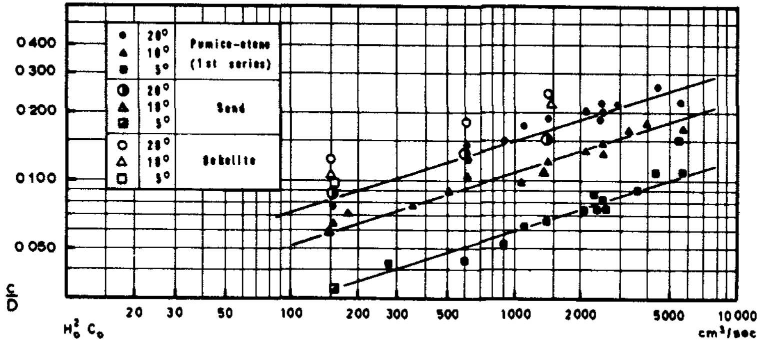


Fig.27 - Curve of results obtained with different mobile materials.

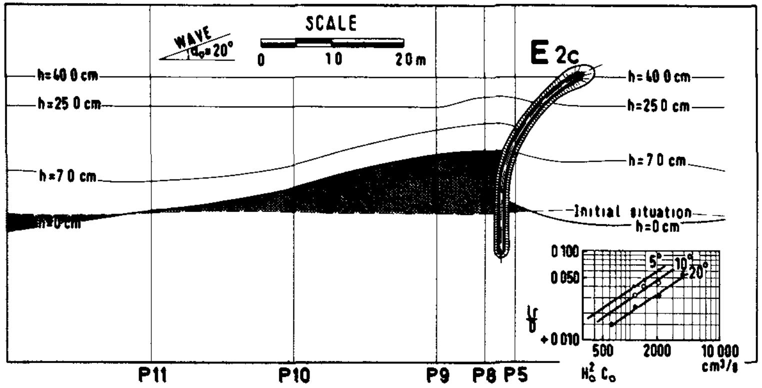


Fig.28 - Partial plan of curved groyne. Curve of the evolution leaward of the groyne.

The value $H_o^2C_o$ was considered as typical parameter of the acting wave, proportional to the power transmitted by the wave, conjugated with a function of α_o angle, obliquity at the base of the beach slope. Values H_o and C_o are, respectively, the deep water wave height and celerity. The results now presented refer to the evolution of beaches where bed-load transport is predominant. The extrapolation to $H_o^2C_o$ values higher or lower than these tested is not valid, as the conditions of evolution where transport by suspension is predominant and the critical conditions at the starting of transport will have to be the object of detailed studies.

The results obtained in stretch 1 of the set-up for the 1st series of tests are represented on the diagrams in fig.26. It was found that the dependence of the parameters characterizing the evolution of the beach stretch as related to the power transmitted by the wave is represented, for each obliquity and within the limit values tested, by straight lines in logarithmic graphs. There is a minimum dispersion of the experimental points as it can be seen from the typical diagram, in linear scale, in fig.23. The values of l_a/D, l_r/D, $\sqrt{\Omega_a}/D$ and c/D increase, for the same obliquity, whenever the $H_o^2C_o$ value increases and present maximum values resulting from the mobile material going into suspension. The value of $t_e\sqrt{g/D}$ decreases as $H_o^2C_o$ increases for the same obliquity. d_A/D and d_r/D values remain constant for the same obliquity when $H_o^2C_o$ increases. For the same amount of power transmitted, the values of l_a/D, l_r/D, $\sqrt{\Omega_a}/D$, c/D and $t_e\sqrt{g/D}$ increase whenever the wave obliquity increases, while the values of d_A/D and d_r/D increase with decreased obliquity, i.e. the accretion area covers a larger part of the beach for lower obliquities, although the accretion surface is smaller, while the erosion area gets closer to the seaward groyne (E1). As an example, and in order of importance to the values of these parameters, admitting an extrapolation into nature, there will be, for a distance between groynes D = 200 m and an obliquity of 20°, the following maximum values. l_a = 20 m, l_r = 18 m, Ω_a = 730 m², d_A = = 68 m, d_r = 134 m, c = 52 m and t_e = 250 h. One should take notice that an actual length of the groyne including the rooting portion, which depends upon the characteristics and possible erosions of stretch 2, must correspond to c value. On the other hand, c length was determined from the initial water line, corresponding to the mean level at rest which was constant during testing; however as due to tides there are actually variations of the level at rest, it becomes necessary, for practical purposes, to set a level wherefrom to measure the c length which presents, for each case, particular conditions either due to the dimensions rize of tides, or to wave breaking conditions and intensity of littoral drift. As regards t_e value, it must be put in evidence that it corresponds to a period of constant action of a certain wave which, in the case under consideration, would correspond to a wave of minimum power from a transport capacity standpoint, and would equal, in an extrapolation into reality, to a continuous action over a period of approximately 10 days. However, in the case of t_e the minimum value, correspond ing to the more powerful wave, might be of interest from a point of view of the movement into suspension of the material which would result, for 20° obliquity and D = 200 m, a value t_e = 50 h, approximately 2 days of continuous wave action.

In stretch 2 of the set-up for the 1st series of tests identical results were obtained, with the exception of the erosion areas characteristics, defined by l_r and d_r values. The area of greatest erosion is located nearer to the seaward groyne (E2), due to the structural characteristics of its slopes (lesser degree of wave power dissipation). It can be said, in practical terms, that the ratio d_r/D becomes equal to 1.00. Relatively to the l_r/D value it can be seen from the diagram in fig.24 that with a 20° obliquity a practically constant value in the order of 0.044 can be obtained when $H_o^2C_o$ varies. For this obliquity and for D = 200 m there would be a backward movement of about 9.0 m near the seaward groyne. It is found that for lesser obliquities erosion is smaller and that for a 5° obliquity there is a reduced erosion for greater wave steepness and accretion along the whole stretch for smaller wave steepness.

The tests made with sand on stretch 1 of the set-up for the 1st series of tests produced results identical to those obtained with pumice-stone. The diagrams in fig.26 remain unaltered to the exception of the one corresponding to $t_e\sqrt{g/D}$, as these values are lower to those obtained with pumice-stone (see fig.25). As this material goes easily into suspension due to the low diameter values of the particles, the straight lines in fig.26 are limited as it regards the value of $H_o^2C_o$ = 1000 cm^3/s. The only few significant differences were obtained with 5° obliquities where the prevailing influence of the transversal movements is reinforced by the facility with which the material goes into suspension.

With bakelite and a similar set-up, identical results were also obtained. Bakelite, with low mean diameter value and a specific weight lower than the former, goes into suspension even more easily and the limit value of $H_o^2C_o$ is approximately equal to 600 cm^3/s. There was consequently a tendency to higher accretion as compared to pumice-stone. However, although the parameters defining the accretion areas, advancement and effective length of the groyne are higher the maximum values remain the same taking into account that the limit $H_o^2C_o$ is lower than for pumice-stone (see fig.27). The $t_e\sqrt{g/D}$ values are even lower than those obtained with sand (see fig.25).

When using sawdust with the same set-up of the previous tests no satisfactory results were obtained regarding the extreme facility which made sawdust go into suspension together with the very high heterogeneousness of the particles (see fig.16) which present an exceedingly irregular shape. This causes the material look like a paste when submerged.

All the previous tests were carried out with an 8% slope for the initial cross section of the beach. The tests made with 5% and 11% slopes did not show any significant changes in comparison with the previous tests. Actually the cross section of the beach varies according to the acting wave, and for the range of slopes tested, the initial slope of the beach lead to no alterations in the characteristics of the equilibrium situation.

As a variant of the set-up used for the 1st series of tests a central and curved groyne was adopted and its positioning oriented in order to avoid the erosions which take place leeward of the groyne. (see fig.28). For the range of values tested there was an advancement near the groyne slope leeward, the value of which increases, for the same obliquity, as the $H_0^2C_0$ values increases. For the same $H_0^2C_0$ value the rate of advancement is higher when the wave obliquity decreases as the diffraction originated by the groyne forms a shadowed area where the decrease in power is greater for waves of higher obliquity. For the range of values tested, reduced advancement values are obtained (maximum 12 m for D = 200 m), but the roots are no longer subject to erosions. The hydraulic behaviour of the curved groyne tested presents on stretch 1 characteristics identical to those of straight groynes. There is only a slight increase in the c length of the groyne for the higher obliquities tested.

Tests with tide reproduction were also made using the 1st series set-up and pumice-stone. The water level was made to alter gradually, without the reproduction of tidal currents. This is a very interesting aspect in certain cases (see {2}). Tests of tides with amplitudes equalling 4.30 to 6.40 cm and cycle periods equivalent to 20 and 30 minutes were made. In all the cases the mean level corresponded to a depth of 40 cm and the maximum level variations were calculated not to introduce significant changes in the generated waves. It is found that the characteristics of groyne behaviour are maintained without significant differences; there was only a slight increase - maximum 30% - in the values for the accretion area, due to the retention effects which are originated by the underwater deposit. This is higher along its whole length owing to the depositions occuring in the low tide. There were, however, for the values tested, no alterations concerning the values of the c length of the groynes.

A 2nd series of tests was made using the set-up shown in figs.29 and 31 with pumice-stone and an 8% slope for the initial beach cross section. The pumice-stone used for this series had a specific weight of 1.46 gf/cm^3 (lower than that of the pumice-stone of the 1st series) and mean diameter approximately equal to that of the pumice-stone weighing 1.67 gf/cm^3. The groynes, shorter than those previously used, are of the non-absorvent type. The results obtained can be seen in fig.30. Regarding the 1st series results, there were the following changes:

- In a general way, there was an accretion along the whole stretch of beach between groynes due to the influence of the transversal movements which became easier by the granulometrical characteristics of the mobile material as well as by the wave action which, in this case, have not the retarding and dissipation action of the absorvent slopes of the groynes. Bigger areas of accretion were achieved on the beach stretch due to the combined effects of the transversal and longitudinal movements, the latter being also more

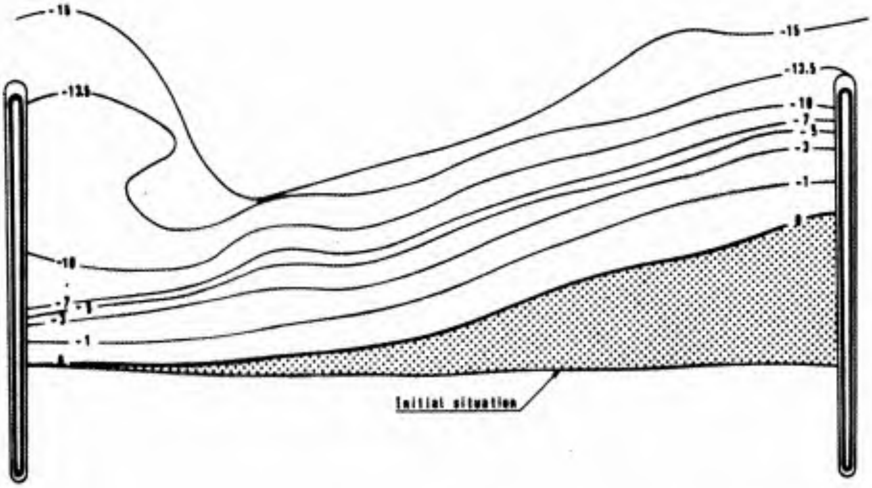


Fig.29 - Plan of test setting for 2nd series of tests.

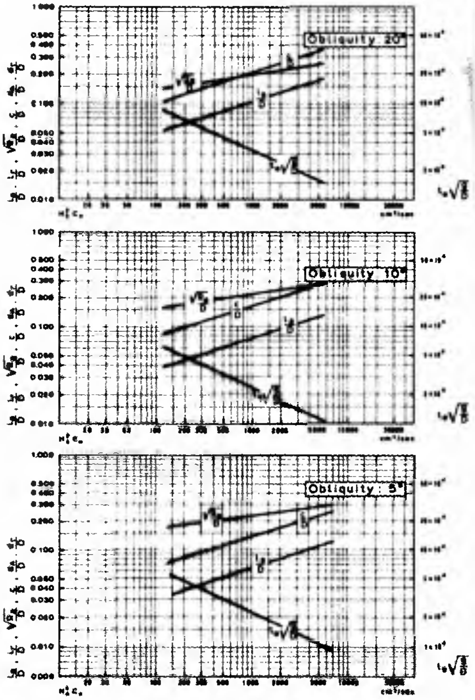


Fig.30 - Results of 2nd series of tests.

Fig.31 - Test setting for 2nd series of tests.

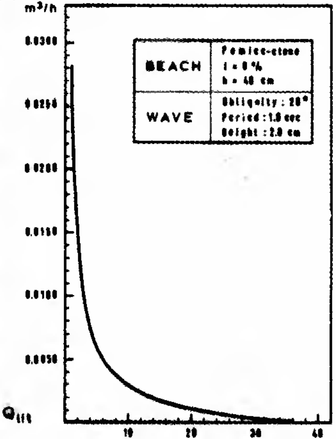


Fig.32 - Curve of $Q_{lit.}$ variation. 1st series of tests.

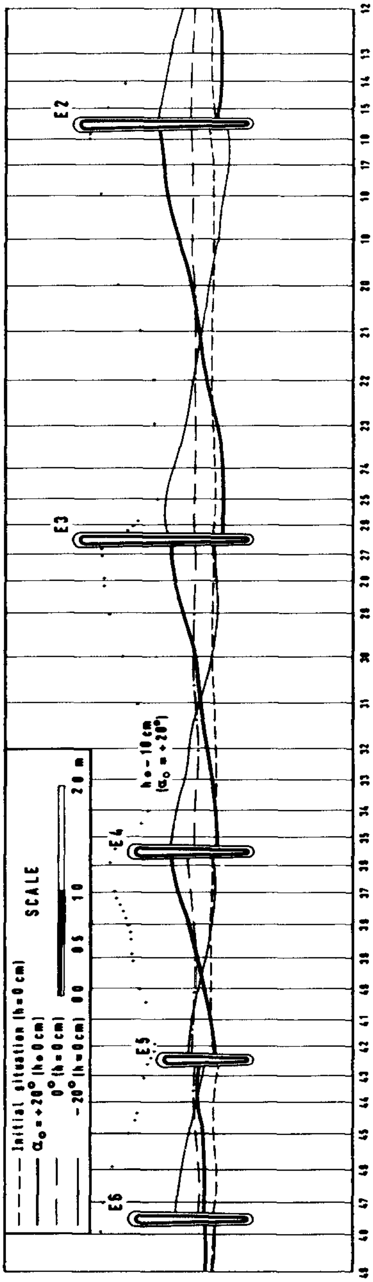


Fig.33 - Plan of groyne system. 3rd series of tests.

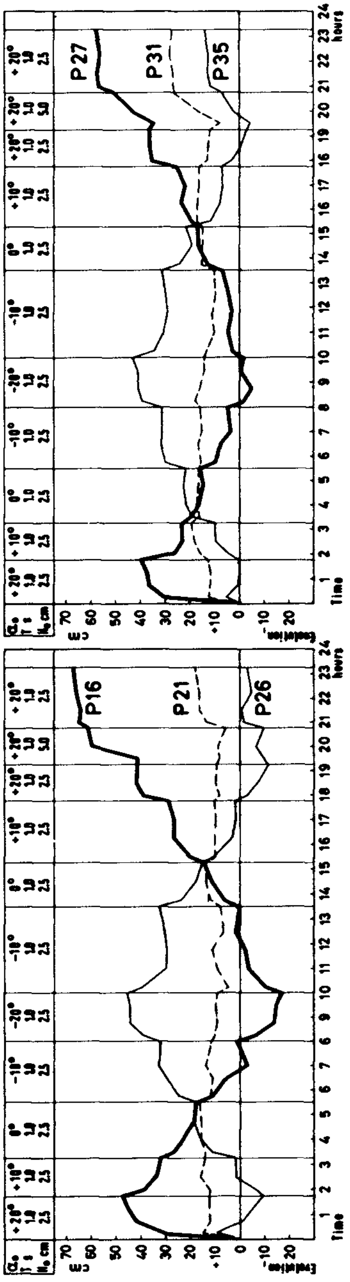


Fig.34 - Curves of profile evolution. 3rd series of tests.

intensive as the wave action took place with higher obliquities in the seaward area. As it can be seen on fig.24 there was one erosion near the leeward slope of the groyne only for the lowest value of transmitted power, this erosion being of the same importance as the one which occurred in stretch 2 of the 1st series set-up. In all the other cases it was found that the higher the transmitted power was, the higher were the accretion values for the 10° and 5° obliquities leeward of the groyne. For the same $H_o^2 C_o$ value, the accretion value increases when obliquity diminishes due to transversal movement influence.

- An increase of $\sqrt{\Omega_a}/D$, l_a/D and c/D values was observed due to the reasons set forth in the previous paragraph. The d_A/D value is close or equal to the unit. The $t_e\sqrt{g/D}$ values are near those obtained with bakelite in stretch 1 of the 1st series set-up. The operating conditions of this set-up are the most unfavourable from the point of view of establishing the c length. For this reason the c/D values of this series will be the ones proposed for the design of groyne systems.

At last a 3rd series of tests was made with wave cycles acting on the groyne system defined in fig.33. Pumice-stone, similar to the one used for the 1st series, and an 8% slope for the initial beach cross section were adopted. Obliquties of +20°,+10°,0°,-10° and -20°, a period of 1.0 sec, a mean height of 2.5 cm and a maximum height of 5.0 cm were tested. Results are shown in fig. 34. The evolution is not perfectly symmetrical as the underwater deposits formed for the +20° obliquity are kept during the action of the wave with a -20° obliquty. It was however observed the reversibility of the equilibrium situation for the extreme symmetrical obliquities of the acting wave. With the frontal attack, $\alpha_o = 0°$, the stretch of beach goes forward in a practically uniform way owing to the transversal movements, the cross section being dependent upon the characteristics of the acting wave. Beach oscillations were noticed around the line corresponding to the frontal wave action. The action of very high waves, after an equilibrium situation corresponding to a wave of average height had been reached, led to a new evolution, by increasing the accretion area. With short groynes, allowing for transposition, final equilibrium situations are also obtained for each obliquity. After the action of waves with great obliquity a shoal is formed around the transposed groyne. This shoal facilitates the reversibility of movements for the extreme symmetrical obliquty. On the stretch of beach lying next to the transposed groyne it was formed during the frontal attack an accretion bigger that the one found in stretches where no transposition was observed. With short groynes it was found that for the highest wave there was an erosion concerning the average wave equilibrium situation due to the greater intensity of movements. That erosion was only compensated after the average wave had acted again with the same obliquty.

4 - CONSIDERATIONS ON LITTORAL DRIFT

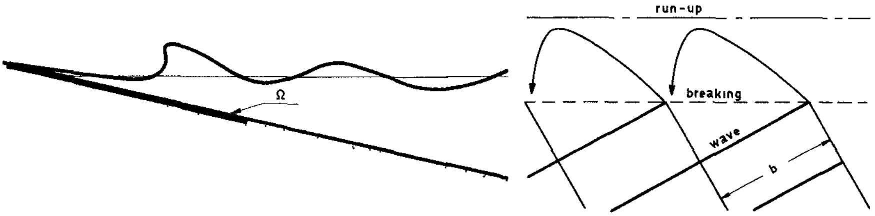
The movement of mobile materials on sandy beaches is fundamentally characterized by longitudinal transport due to the oblique action of the waves. Quantitatively it may be considered as an amount of sands carried through one section in one period of time. This value is known as littoral drift. Groynes being elements of retention of mobile materials, make possible to establish the accumulated volume in a certain section and for a certain period of time, and consequently estimate the littoral drift.

It is considered in this study that, owing to transport by bed load, the littoral drift is directly related to the power transmitted by the wave. Assuming that $(\gamma s-\gamma)$ is the specific weight of the submerged solid matter, β the friction coefficient of movement by dragging of the grains, and $d\omega$ an element of volume, with a v velocity, the power needed to carry such a volume at such a velocity will be $\beta.(\gamma s-\gamma).d\omega.v$. Assuming further that the power used for the transport of the grains is a η fraction of the power transmitted by the wave, P_{tr}, it will be found that $\int_V \beta.(\gamma s-\gamma).d\omega.v=\eta P_{tr}$, where V is the volume of material crossing a given section for the time unit. If $d\Omega$ were the cross section of the grains, perpendicular to the course, and dl the dimension in the movement direction, there will be then, for a Ω cross section:

$$\int_V \beta.(\gamma s-\gamma).d\omega.v=\int_\Omega\{\beta(\gamma s-\gamma).dl.v\}d\Omega=\beta.(\gamma s-\gamma).dl.\int_\Omega v.d\Omega=$$

$$=\beta.(\gamma s-\gamma).dl.Q_{lit}$$

The Ω cross section will be directly related to the wave and beach characteristics, namely the location of the wave breaking line, wave



run-up and beach slope. It could then be said that $\beta.(\gamma s-\gamma).dl.Q_{lit}=$ $=\eta.P_{tr}=\eta.\frac{1}{8}.\rho g.H^2.\frac{L}{T}.b$ in which b is the wave crest width occurring to the zigzag movement seen on the diagram and which, since a beggining, will depend both upon the wave characteristics, especially upon its obliquity, and the beach characteristics. It will then be $Q_{lit}=\frac{\eta.\frac{1}{8}.\gamma.H^2C.b}{\beta.(\gamma s-\gamma).dl}$, i.e. $Q_{lit}=kH^2C$, in which k is related to the characteristics of the mobile material and to wave obliquities. So it can be seen that, at a first approach, the littoral drift for a certain obliquity and a certain beach is proportional to the power transmitted by the wave and that the coefficient k depends on the characteristics of the mobile material, as far as its specific weight, dimensions and friction coefficient are concerned, as well as to the fraction of transmitted power that originates transport. This fraction will depend fundamentally upon the obliquity of the wave action. On the other hand, the application of dimensional analysis, consider

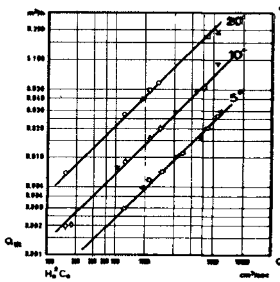


Fig.35-Log curve of the $Q_{lit.}$ variation.

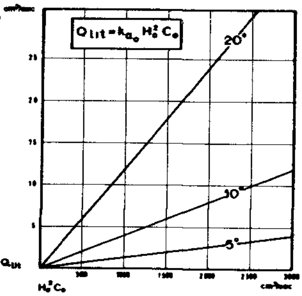


Fig.36-Linear curve of the $Q_{lit.}$ variation.

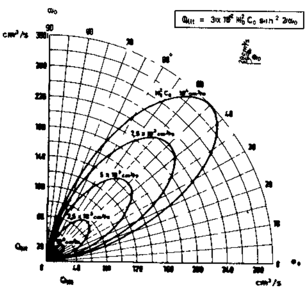


Fig.37-Polar curve of the $Q_{lit.}$ variation.

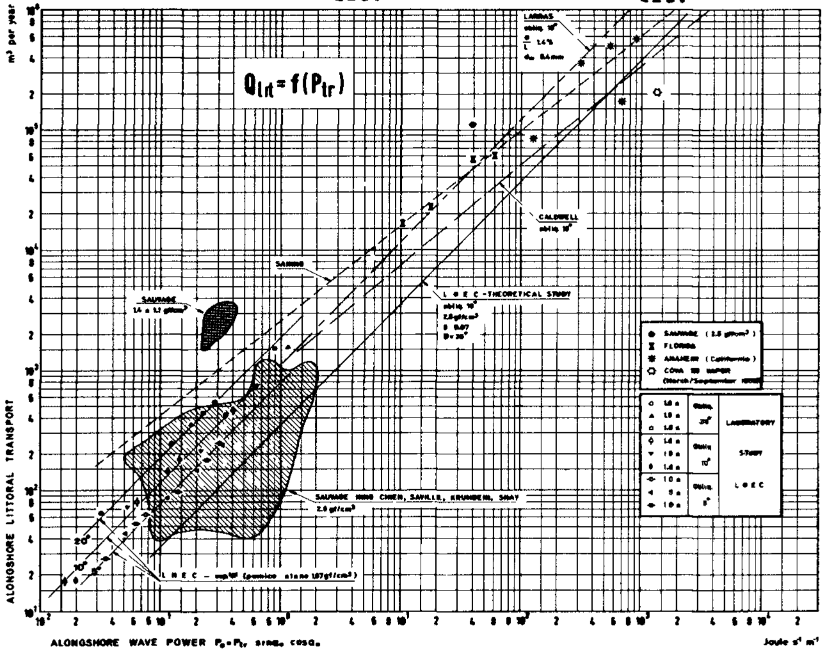


Fig.38 - Log curve of the $Q_{lit.}$ variation with wave power.

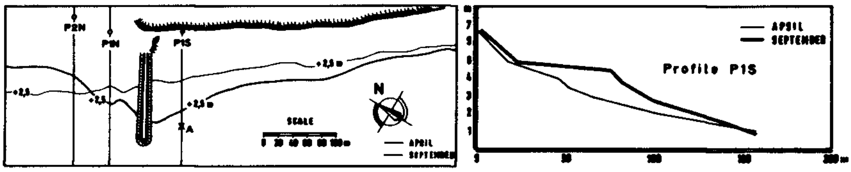


Fig.39 - Cove do Vapor groyne. Plan and cross-section.

ing the littoral drift which is depending on the wave height and its celerity, makes possible the conclusion that the ratio of dependence, for a certain beach and a certain obliquity, will be of the type $Q_{lit}= kH^2C$, i.e. the littoral drift will be proportional to the power transmitted by the wave.

The determination of littoral drift values, for the various waves tested, was made by measuring the areas of accretion near E2 groyne in the 1st series set-up, during the 1st hour of each test. This value, multiplied by the mean height of accretion in cross section, allowed to the calculation of an hour mean volume of accretion. In the tested set-up, the Q_{lit} value decreases during testing until it becomes null (see fig.32). The readings taken at test starting may thus be considered approximately equal to the wave carrying capacity, which value has to be determined. It was found that it is possible to establish a ratio of dependence of the type theoretically deduced, in which Q_{lit} is proportional to the power transmitted by the wave as well as to a trigonometrical function of α_o obliquity. The tests with 20°, 10° and 5° obliquities, the results of which are shown on the diagram in fig.35, allows the deduction of the following ratio:

$$Q_{lit}=0.03.H_o^2C_o.\sin^2 2\alpha_o \quad cm^3/s$$

These results are represented on the diagrams in fig.36 and 37. In reference to the first one it must be said that although the straight lines concur to the origin, which means that littoral drift is annulled whenever the power transmitted by the wave is annuled too, actually the conditions of annulment of littoral drift will be a function of the critical conditions under which the material is dragged which were not included in this study. The diagram in fig.38 shows the experimental results obtained, as they were compared to the results obtained through other studies (see {3}). It was found that the values referring to readings taken with the pumice-stone model fit in pretty well with those obtained in other studies with different materials and that the extrapolation of results from actual cases leads to acceptable values. The diagram shows a point referring to readings taken at an experimental groyne built at Cova do Vapor, a beach situated near the mouth of Lisbon harbour (see figs. 39 and 40); the value which was given, 200 000 m³/year for the period which goes from April till September 1959, in which T = 9 sec, α_o = 10° and H_o = 1.0 m may be considered, is very low but its determination offers several difficulties. On the one hand, the groyne is too short (see fig.40) and its efficiency very much reduced. A correction had to be made to the values obtained through previous calculations due to the fact that, for low tidal levels, there was no retention of sand by the groyne. On the other hand, there was no accurate data available on the wave regimen which could make possible calculation with accuracy the mean value of the transmitted power susceptible of association with the value considered as littoral drift. A sand spit formed by the sands which passed over the above mentioned groyne, can be seen in fig.40.

Fig.40 - Aerial view of Cova do Vapor beach.

5 - CONCLUSIONS

- The hydraulic behaviour of groynes in the case of phisiographically independent units, subject to the obligue action of sinusoidal waves of constant characteristics, is marked by an evolution of the beach stretches which are in process until they reach a final equilibrium situation conditioned by the obliquity and the power transmitted by the acting wave. That evolution is fundamentally due to the littoral drift originated by the longitudinal currents which are caused by the oblique breaking of waves. In the case of reduced obliquities there is also a significative influence from the transversal movements. The groyne accretion areas increase, for the same obliquity, whenever there is an increase of the power transmitted by the wave, but they present a maximum which is determined by the suspension transport of the mobile material. The stabilization times become smaller, for the same obliquity, as the value of transmitted power grows higher, which leads to very swift evolution during the storms acting upon the beach. There is, generally, a possibility of erosions in the seaward area of the beach stretch near the groyne slopes but its characteristics are mainly governed by the transversal movements on the beach. The design of the groyne infrastructure is also depending upon the erosion characteristics which occur in the leeward of the groyne. For the same value of power transmitted by the wave, the accretion areas and the stabilization times increase as much as the wave obliquity increases.
- Groyne efficiency is conditioned by the suspension transport. Even for wave regimes with very variable directions, a groyne systems can be efficient provided that it has been dimensioned taking into account the above principles, since there is no intensive transport in suspension. This conclusion is of particular interest in the case of groyne systems where the artificial accretion of sands has to be done. When applying the results of this study to real cases, the maximum values of the dimensionaless parameters present, for the 1st series of tests, the same values for pumice-stone and for bakelite, although corresponding to different amounts of transmitted power; it is assumed that the maximum values taken into consideration will be kept in the prototype, corresponding to extreme power values conditioned by the prevalent transport in suspension. The results of the tests using sand (see fig.27) show that there will be no correct reproduction of the phenomena, from a similarity standpoint, as the final maximum values obtained with this material would be lower than the former. It is evident that only a thorough knowledge of similarity ratios, allied to the observation take into account the behaviour of a prototype with an identical set-up to the one used for tests, would make correctly possible to estimate the extrapolation which had been considered.
- The evolution characteristics of the beach stretches depend on the structure, implantation and length of the groynes. It might be interesting, in certain cases, to adopte an asymmetrical structure for the cross section of the groynes with softer absorvent slopes in the leeward. In the case of non-absorvent groynes

the use of curved groynes, creating a difraction area in the leeward, is recommended.

- The D/c ratio (the reverse of the dimensionaless parameter previously considered), the relation of the distance between groynes and their effective length presents, for the obliquities tested, maximum values conditioned by the entering into suspension of mobile material, which are, for the most unfavourable case: 2.5 for $\alpha_0 = 20°$; 3.5 for $\alpha_0 = 10°$ and 4.0 for $\alpha_0 = 5°$. To apply these values it must be taken into account the tide level in each case, depending on the characteristics of the tide itself, the intensity of transport during the several tidal stages, and the transversal limits of the beach stretch under consideration. The total length of the groyne will have to include its rooting portion, conditioned by wave run-up and by eventual erosions near the leeward slope.

- The reversibility of equlibrium situations for extreme symmetrical obliquities is found in groyne systems acted upon wave cycles with variable directions.

- Short groynes, adopted in emergency works of temporary nature due to the very high costs of maritime works and the lack of knowledge of the coastal physiographic regimes, have been found to be of extremely reduced efficiency. Nowadays techniques, taking advantage of an increasingly through knowledge of coastal phenomena, especially as it regards wave regimes, allow for the designing of efficient groyne systems. Amongst these, long groynes - for the design of which this study will have contributed - occupy an outstanding position concerning the interest they offer in solving many coastal engineering problems.

- The consideration of a dependence ratio between littoral drift and wave characteristics, based on the proportionality between the littoral drift and the transmitted power, was accepted in view of the experimental results of several studies and the readings taken from actual cases.

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