CHAPTER 154

SHORELINE RESPONSE TO A SINGLE TRANSMISSIVE DETACHED BREAKWATER

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ABSTRACT

Criteria are presented for predicting the long-term shoreline response to a single detached breakwater. The criteria, expressed as two algebraic equations, distinguish tombolo formation, salient formation, and limited shoreline response, and were developed by calculation-intensive application of the shoreline change numerical model GENESIS for a large number of wave conditions and structure configurations. A unique feature of the modeling effort is explicit incorporation of wave transmission at the structure. The two other major non-dimensional parameters in the criteria are the length of the structure divided by the average wavelength at the structure and the average deep-water significant wave height divided by the depth at the structure. Prediction of the generalized criteria agree with available field data.

INTRODUCTION

The response of the shoreline and beach to detached breakwaters is difficult to predict. For example, Seiji, Uda, and Tanaka (1987) in a survey of 1552 breakwaters constructed in Japan found that 60 percent produced accretionary developments and 35 percent did not. A frequency diagram for the data set shows shoreline advance ranging from zero to 140 m. Although some empirical guidance is available to design the basic configuration of detached breakwaters, the criteria are crude and based on a few, typically two to four, out of as many as 14 governing variables. A major variable missing in previous work is wave transmission through the breakwater. The objective of the present study is to perform a generalized calibration of the shoreline change numerical model GENESIS against observed field response to a single shore-

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parallel and transmissive detached breakwater for a wide range of structure configurations and wave characteristics.

PROCEDURE

Governing Parameters

By inspection, at least 14 parameters can be identified which control the response of a sandy beach to a single or multiple detached breakwater system (Fig. 1):

$$\text{Beach Resp.} = F[(X,\ Y,\ K_T,\ G),\ (D,\ \Delta D,\ S),\ (H,\ T,\ \theta,\ \theta_S,\ \sigma_H,\ \sigma_\theta,\ \sigma_T)]$$

or (1)

$$\text{Beach Resp.} = F[(\text{breakwater properties}),\ (\text{beach properties}),\ (\text{wave properties})]$$

where X = length of structure segment; Y = distance of segment from original shoreline; K_T = structure segment transmissivity; G = gap distance between segments; D = depth at structure segment; ΔD = variation in depth at the structure, as from the tide; S = sediment availability; H = wave height; T = wave period; θ = predominant wave angle to trend of coast; θ_S = orientation of structure to trend of coast; σ_H = standard deviation (SD) of wave height; σ_θ = SD of wave angle; and σ_T = SD of wave period. In a practical situation, the engineer has control over the first group of parameters only.

In GENESIS, the equilibrium beach profile shape is calculated as $D = A(d_{50})\ Y^{2/3}$, where A is an empirical scaling parameter depending on the beach median grain size d_{50}. Once the beach grain size is

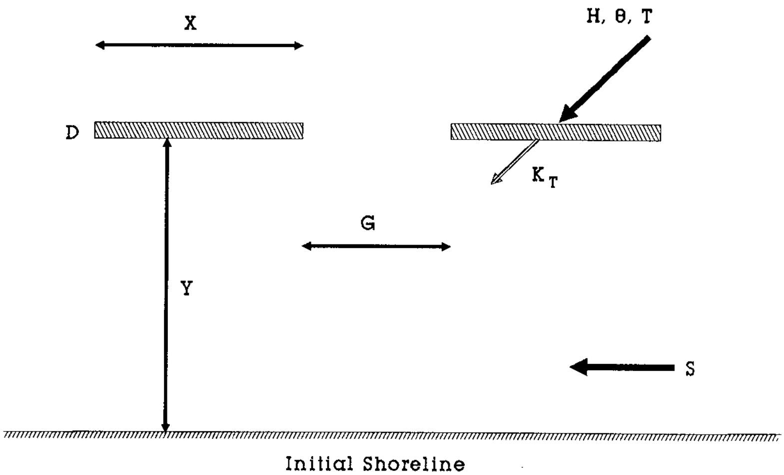

Figure 1. Segmented detached breakwater parameters

specified, D is a function of Y and is not an independent variable. The functioning of all 14 parameters governing long-term shoreline change can be represented in GENESIS.

Numerical Model

GENESIS is a numerical modeling system which calculates wave transformation (refraction, shoaling, diffraction from multiple coastal structures, transmission, and breaking), longshore sand transport rate, and associated shoreline change (Hanson 1989, Hanson and Kraus 1989, 1991). The system is generalized in that it allows representation of a wide variety of user-specified offshore wave inputs, initial beach configuration, boundary conditions, coastal structures (groins, jetties, seawalls, and detached breakwaters), and beach fills.

Several numerical and physical model studies have investigated the response of the shoreline to detached breakwaters. However, these studies did not include wave transmission, referring to wave energy passing through and over a structure, which is present in most projects. This capability is included in Version 2.0 of GENESIS (Hanson and Kraus 1989) and has been tested with excellent results for Holly Beach, Louisiana, with six breakwaters of different construction and transmission (Hanson, Kraus, and Nakashima 1989), as well as for Lorain, Ohio, with three detached breakwaters (Hanson and Kraus 1991).

SENSITIVITY TO GOVERNING PARAMETERS

Prior to the generalized calibration of the modeling system, an investigation of the sensitivity of the shoreline response to variations in the main governing parameters was performed. In all the following simulations, the median sand grain size is 0.2 mm. The empirical predictive formula for the longshore sand transport rate used in GENESIS is:

$$Q = (H^2 C_g)_b \left(a_1 \sin 2\theta_{bs} - a_2 \cos\theta_{bs} \frac{\partial H}{\partial x}\right)_b \tag{2}$$

in which C_g = wave group speed, b = subscript denoting wave breaking condition, θ_{bs} = angle of breaking waves to the local shoreline. The nondimensional parameters a_1 and a_2 are given by

$$a_1 = \frac{K_1}{16(S - 1)(1 - p)W}$$

and (3)

$$a_2 = \frac{K_2}{8(S - 1)(1 - p)W\tan\beta}$$

in which K_1 and K_2 = empirical coefficients, treated as a calibration parameters, $S = \rho_s/\rho$, ρ_s = density of sand (2.65 10^3 kg/m^3), ρ = density of water (1.03 10^3 kg/m^3), p = porosity of sand (0.4), $\tan\beta$ = average nearshore bottom slope), W = a numerical factor ($1.416^{5/2}$) used to convert from significant wave height to root-mean-square height.

Effect of variation in wave input mean values

An illustration of the effect of changing wave height is given in Fig. 2. The wave climate was held constant during the simulations with a period of 4 sec and a total simulation time of 100 hrs. The breakwater was 300 m long and placed 300 m offshore in 3 m depth. As expected, shoreline advances with increase in wave height. The maximum shoreline progression varies approximately linearly with wave height, whereas accumulated volume for the greater wave height is an order of magnitude bigger than that for the smaller wave height. This is in part explained by the difference in breaking wave height, but also because the bigger waves are less refracted before breaking, they will break under a bigger angle to the shoreline.

An example of the variation in shoreline response behind a detached breakwater due to changing wave period is given in Fig. 3. The wave climate was otherwise held constant during the simulations with a wave height of 1 m, normally incident wave crests, and a total simulation time of 100 hr. The breakwater configuration was the same as in the previous figure.

Increasing wave period results in greater salient growth behind the structure. The explanation for this is illustrated in Fig. 4, displaying the associated wave height distributions behind the detached breakwater for the three simulations in Fig. 3. The wave height distributions associated with waves entering on either side of the breakwater are shown separately. Longer waves results in a higher

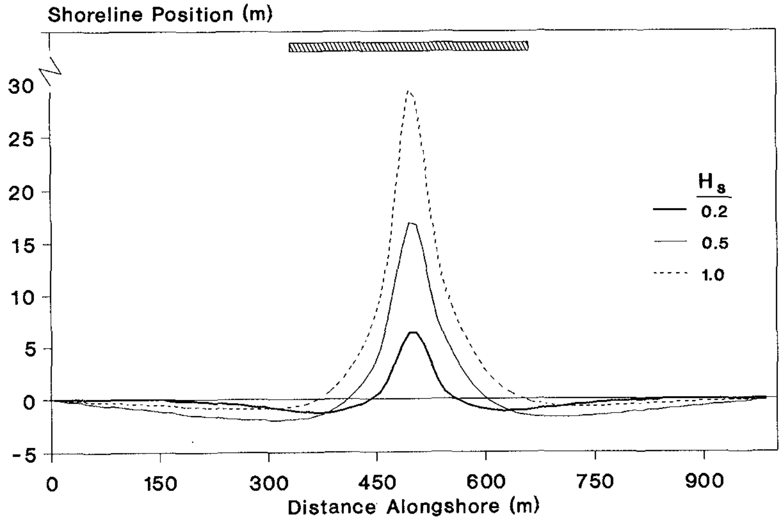

Fig. 2. Influence of varying wave height on shoreline change behind a detached breakwater

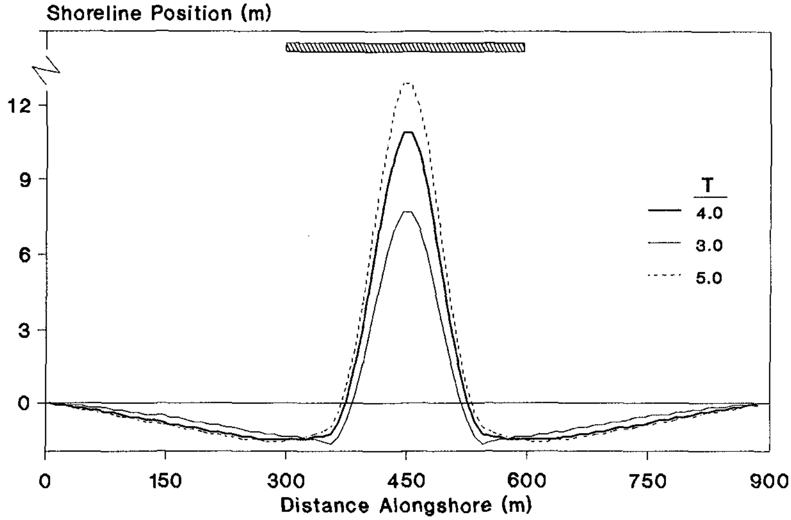

Fig. 3. Influence of varying wave period on shoreline change behind a detached breakwater

shoaling coefficient, causing these waves to break further offshore, resulting in a greater breaking wave height, the offshore wave height being the same.

This means, for the longer waves, that the first term in Eq. 1 (K_1 - term), with a larger H-value, will transport more sand into the area behind the breakwater. Also, the wave height for longer period waves decreases more steeply alongshore behind the structure. This means that the second term in the transport Eq. 1, (K_2 - term), with a higher $\partial H/\partial x$-value, will also transport more sand into the area behind the breakwater for the longer waves.

Effect of wave variability

In use of the model in a predictive mode, the factors responsible for beach change are not known in detail. The time series of wave height, period, and direction forecast for use in the shoreline change prediction and can be considered as only one of many possible wave climates that might occur. For shoreline response prediction, it is necessary to incorporate wave variability to calculate a probable range of expected shoreline change. The standard deviation is conveniently used as a realistic measure of wave variability and determines the likelihood and magnitude of extreme events (Kraus, Hanson, and Harikai 1984).

Fig. 5 illustrates an example showing accretion behind a 200-m long detached breakwater located in 2 m depth 200 m from the initial straight shoreline. The mean values in deep water characterizing the wave climate are: $T = 4$ sec, $H_s = 1$ m, and $\theta = 0$ deg. The thin solid

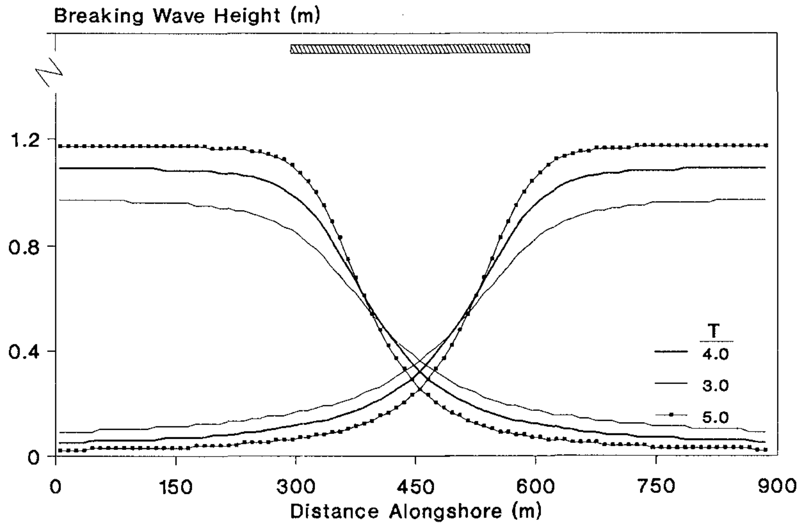

Fig. 4. Influence of varying wave period on wave height distribution behind a detached breakwater

line represents a wave climate with T, H, and θ held constant at their mean values. In the other three simulations, two of the three parameters were held constant while the third was normally distributed with its standard deviation given in the figure as a percentage of the respective mean value.

As seen from the figure, allowing T and H to vary has very little effect on the shoreline response. In contrast, increased variability in the wave direction dramatically increases accumulation behind the structure. The major reason for this is that variation in T and H around their respective mean values merely redistributes the incoming wave energy in time but does not significantly change the total longshore wave energy flux. A deviation in wave direction from normal in any direction, however, increases the longshore component of wave energy flux, which in turn causes more sand to move alongshore. Because of shadowing from the structure, more sand will be transported into than out of the shadow region behind the structure, accounting for the large growth of the salient.

Breakwater Transmissivity

In most cases, detached breakwaters designed for shore protection allow some portion of the incident wave energy to pass through or over the structure because it is economical and often advantageous from the perspective of beach change control to build low or porous structures to allow wave energy to penetrate behind them. Wave transmissivity is difficult to quantify. In order to describe wave transmission in GENESIS, a value of a transmission coefficient K_T must be provided for each detached breakwater (Hanson and Kraus 1989). The transmis-

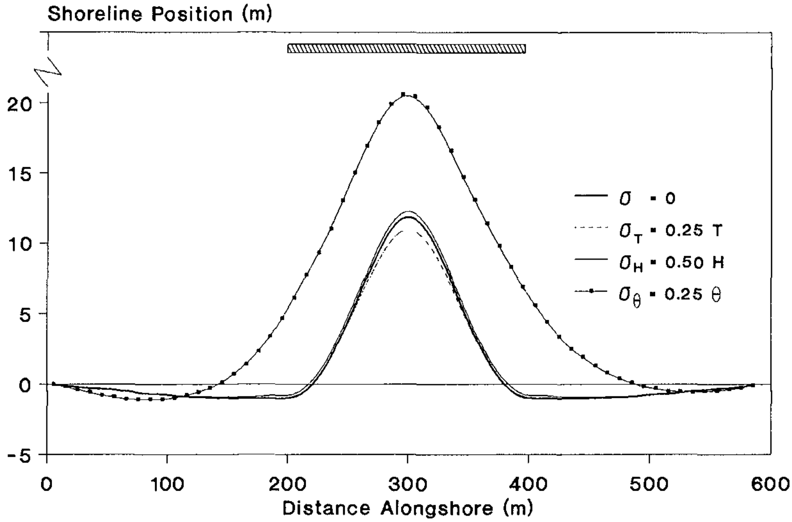

Fig. 5. Influence of wave variability on shoreline change behind a detached breakwater

sion coefficient, defined as the ratio of the height of the incident waves directly shoreward of the breakwater to the height directly seaward of the breakwater, has the range $0 \leq K_T \leq 1$, for which a value of 0 implies no transmission and 1 implies complete transmission.

To investigate the sensitivity of the calculated shoreline response to variations in wave transmission, a series of simulations was made to investigate predicted sand accumulation in the lee of a shore-parallel breakwater, as illustrated in Fig. 6. The breakwater is 200 m long and located 250 m offshore. Incident waves with $T = 6$ sec and $H_s = 1.5$ m propagate with wave crests parallel to the initially straight shoreline. The simulation time was 180 hr.

As expected, the seaward extent of the induced large salient decreases as wave transmission increases, showing that shoreline response is sensitive to breakwater transmissivity. For example, a 20 percent transmissivity reduces the maximum shoreline advance by 36 percent and the accumulated volume by 25 percent. Because of the difficulty of determining the transmissivity for real structures, the value of the parameter is, at present, determined in the shoreline change calibration procedure.

The capability to simulate wave transmission at detached breakwaters and its impact on shoreline change was first tested with excellent results for Holly Beach, Louisiana, a site containing six breakwaters of different construction and transmission characteristics (Hanson, Kraus, and Nakashima 1989). This application also showed that it would

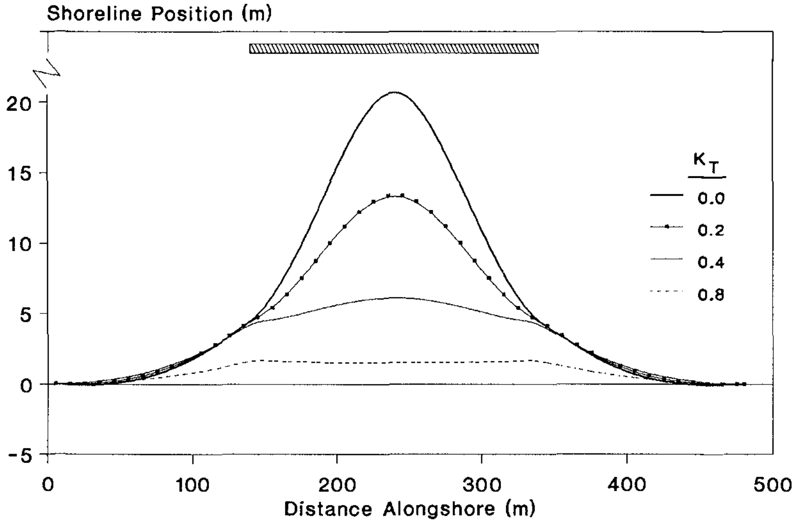

Fig. 6. Shoreline change as a function of transmission (from Hanson et al. 1989)

not be possible to obtain good agreement between field measurements and model predictions if wave transmission were not taken into account.

RESULTS

With an understanding of model capabilities established in the preceding text, we now turn to the problem of developing design curves to predict shoreline response to single, transmissive detached breakwaters. There are two general problems to be addressed. The first is to determine appropriate parameters for distinguishing tombolo development, salient development, or no effective shoreline change (limited or transitory response). The second problem is to develop design curves relating shoreline response to these governing parameters. Here, we present design curves for shoreline response to a single detached breakwater, based on three nondimensional parameters.

Based on field observations and simulation results, shoreline response was classified into three categories as illustrated in Fig. 7:

* Limited response - maximum accumulation is less than 4 m.

* Salient development - maximum accumulation is greater than 4 m, but the salient does not reach the breakwater.

* Tombolo development - salient reaches (touches) the breakwater.

The wave height distribution behind a structure produced by diffraction to a large extent depends on the wavelength L, where the energy of longer waves penetrates further into the shadow region behind the structure. Also, the length of the structure X controls the amount of wave energy reaching the beach. It is therefore likely that

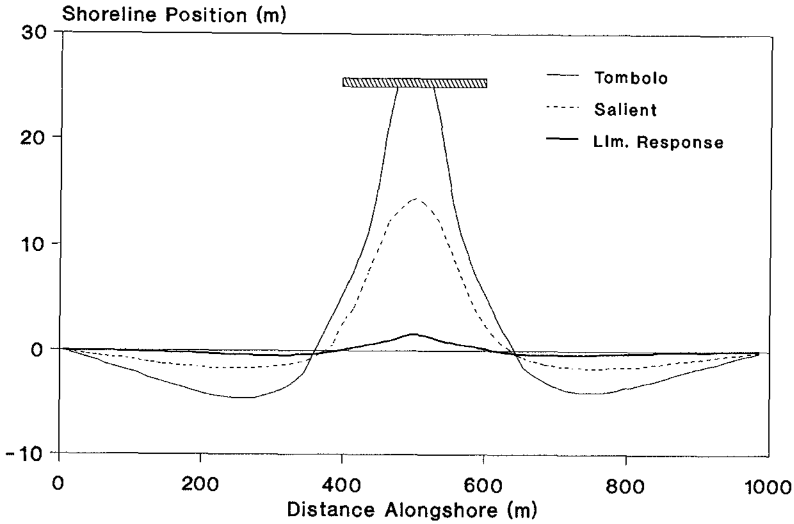

Fig. 7. Possible shoreline response to detached breakwaters

the shoreline response behind a detached breakwater is a function of the ratio X/L. Waves breaking seaward of a detached breakwater have a greater tendency to develop salients and tombolos than waves breaking on the landward side since there is a greater width of longshore transport. The location of the breakwater relative to the breaker line is conveniently expressed through the ratio H_0/D, where H_0 and D are the significant deep-water wave height and the water depth at the location of the breakwater. Thus, these two dimensionless parameters were taken as primary variables for examining prototype data and developing design curves. Other parameters were tested and rejected in favor of X/L and H_0/D, based on their performance in distinguishing shoreline response.

Field Data

Most empirical and modeling analyses of shoreline response to detached breakwaters have relied heavily on physical model results, including combined segmented as well as single detached breakwater cases. There are only a few well-documented field examples in the literature for single detached breakwaters, and Table 1 presents conditions at all such sites known to the authors. The values for the transmission coefficient K_T were subjectively estimated on the basis of descriptive classifications ("poor condition," "high and impermeable," etc.) in the project reports.

In the present study, the numerical shoreline change model GENESIS was used to determine the equilibrium shoreline response behind a single shore-parallel detached breakwater. As mentioned previously, the persistence of shoreline response is closely related to the variability in incident wave height, period, and direction. More realistic

Table 1

Project site	Struct. length X	Wave height H_o	Water depth D	Wave-length L	Estim. trans-mission K_T	Obser. beach resp.
Nahariyya	180	1.0	3.2	29	0.2	Sal.
Carmel	280	1.0	3.0	29	0.2	Sal.
Tel Baruk	200	1.0	3.0	29	0.2	Sal.
Venice, New	183	1.0	1.8	48	0.1	Tom.
Redington	100	0.8	2.4	20	0.4	Sal.
Santa Monica	610	1.2	7.6	91	0.5	Lim.

simulations of shoreline change are expected by including variability in wave parameters. Seven "standard" yearly wave climates were developed including different means and standard deviations of the wave climate for the simulations, based on review of conditions related to the data in Table 1.

For each of the wave climates a Monte-Carlo simulation technique was applied to input the wave data, with random wave heights generated from a Rayleigh distribution and wave angles and periods specified from normal distributions, resulting in a 1-year wave data set discretized at 12-hr intervals. In these simulations, the mean wave period T = 2.5, 7, and 12 sec with a standard deviation of $T/4$; the significant wave height H = 0.2, 0.5, and 1.0 m; and the mean wave direction was normal to the straight, initial shoreline with a standard deviation of 5 deg. The chosen values encompass conditions along U.S. Atlantic Ocean and Great Lakes beaches. The length of the structure X was varied between 40 and 100 m, with the distance from the initial shoreline Y varying from 16 to 300 m, and with a transmission coefficient of 0.00, 0.20, 0.50, and 0.75, respectively. The beach median grain size was 0.2 mm in all simulations.

Fig. 8 shows the results of simulations for a single detached breakwater oriented parallel to an initially straight shoreline, for different X/L and H_o/D values. This figure is the main result of this study. Each of the 166 combinations of wave and structure configuration and transmissivity parameter values was run for two years or until a tombolo formed. The different symbols indicate the response type. Situations with short structures in shallow water exposed to high, long-period waves are more likely to produce salients, whereas long structures in deep water exposed to small, short-period waves more often results in a limited shoreline response.

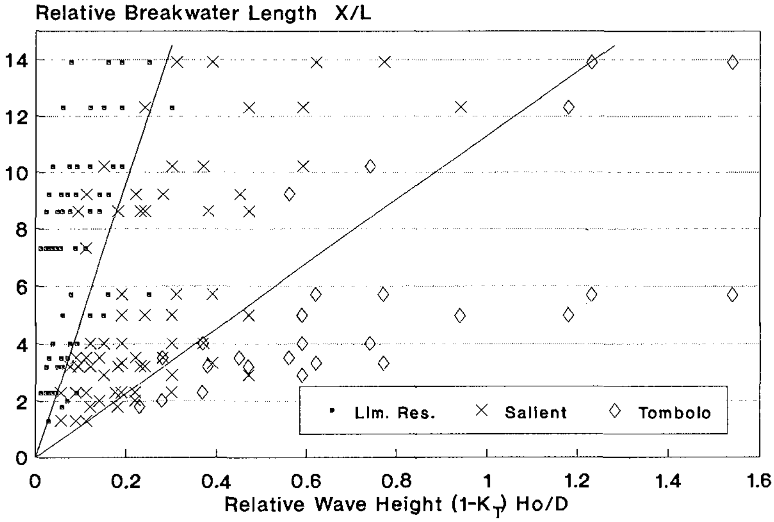

Fig. 8. Calculated shoreline response to a single detached breakwater

Straight lines were drawn to separate the different response types as a function of wave transmissivity. It was found that as breakwater transmissivity increases, shoreline response decreases. Based on these results, the criterion for a salient to form was found to be:

$$\frac{X}{L} \le 48\ (1 - K_T)\ \frac{H_o}{D} \tag{4}$$

which separates regions of limited shoreline response and clear salient development. Similarly, the criteria for a tombolo to form was found to be:

$$\frac{X}{L} \le 11\ (1 - K_T)\ \frac{H_o}{D} \tag{5}$$

which separates regions of salient and tombolo formation.

As evidence for the validity of the proposed relationships, the prototype measurements as presented in Table 1 are plotted in Fig. 9. The prototype measurements fit well within the domains of the proposed criteria and provide at least limited validation of the calculated results.

CONCLUSIONS

This paper described a generalized calibration against field measurements of the numerical model GENESIS for simulating shoreline response to detached breakwaters. Three dimensionless parameters, the length of the structure relative to the local wavelength, the deep-water wave

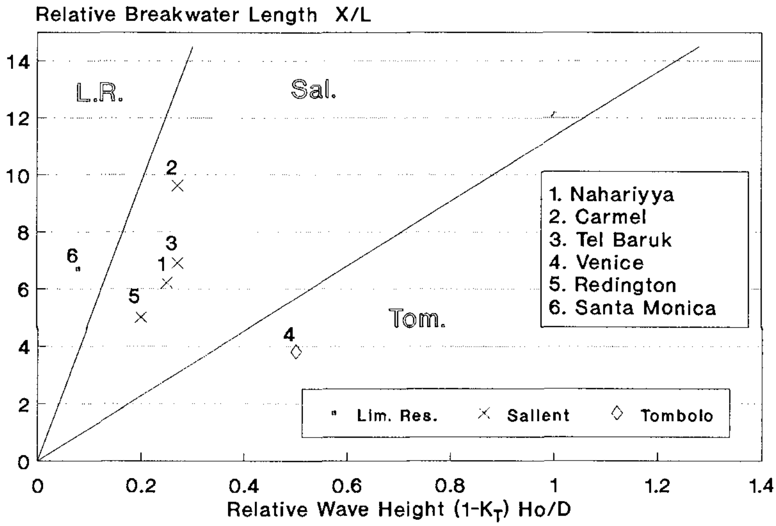

Figure 9. Field measurements and proposed criteria

height relative to the water depth at the structure, and wave transmission through the structure were taken as primary variables in study.

Field measurements and model simulations showed a systematic trend in shoreline response as a function of the three dimensionless variables. In summary, the results indicate that:

* Holding all other variables constant, as the wavelength (period) increases, shoreline response goes from limited, to salient, to tombolo, because more sand is transported into the shadow zone.

* Holding all other variables constant, as the length of the structure increases, shoreline response goes from tombolo, to salient, to limited response, because the amount of sand transported into the area behind the structure is distributed over a longer portion of beach.

* Holding all other variables constant, as the wave height increases, shoreline response goes from limited, to salient, to tombolo, because more sand is transported into the shadow zone.

* Holding all other variables constant, as the depth at the structure increases, shoreline response goes from tombolo, to salient, to limited response, because a smaller portion of the area behind the structure is located inside the surf zone.

* Holding all other variables constant, as wave transmissivity increases, shoreline response goes from tombolo, to salient, to limited response because of direct incidence of the transmitted waves, which suppresses protruding features.

* The independent parameters selected (X/L, H_o/D, and K_T) provide effective but preliminary design criteria for distinguishing shoreline response to a single, transmissive detached breakwater.

Although the criteria presented here are based on a most advanced and thorough numerical model study, the results are not intended to replace the judgement of an experienced engineer familiar with a project coast.

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REFERENCES

Hanson, H. 1989. CENESIS - A generalized shoreline change numerical model. J. of Coastal Research, Vol. 5(1), 1-27.

Hanson, H. and Kraus, N. C. 1989. GENESIS: Generalized model for simulating shoreline change. Report 1: Technical Reference, Tech. Rep. CERC-89-19, US Army Engr. Waterways Exp. Station, Coastal Engrg. Research Center, Vicksburg, MS.

Hanson, H. and Kraus, N. C. 1991. Numerical simulation of shoreline change at Lorain, Ohio. J. of Waterways, Port, Coastal and Ocean Engrg. (in press).

Hanson, H., Kraus, N. C., and Nakashima, L. D. 1989. Shoreline change behind transmissive detached breakwaters. Proc. Coastal Zone '89, ASCE, 568-582.

Kraus, N. C., Hanson, H., and Harikai, S. 1984. Shoreline Change at Oarai Beach - Past Present and Future, Proc. 19th Coastal Engrg. Conf., ASCE, 2107-2123.

Seiji, M., Uda, T., and Tanaka, S. 1987. Statistical study on the effect and stability of detached breakwaters. Coastal Engrg. in Japan, Vol. 30(1), 131-141.