CHAPTER 311

NUMERICAL SIMULATION OF SHORELINE CHANGE WITH LONGSHORE SAND WAVES AT GROINS

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ABSTRACT: Longshore sand waves (LSWs) are macro-morphologic features that maintain form while migrating along the shore with speeds on the order of kilometers per year. LSWs can dominate shoreline evolution by causing both apparent long-term erosion and accretion seemingly unrelated to the calculated or estimated net and gross longshore sand transport rates. This paper explores three possible mechanisms, wave asymmetry, form advection, and surf-zone contraction, hypothesized to maintain and translate LSWs. The mechanisms are implemented within the framework of a shoreline change numerical model. Simulations implementing the LSW evolution mechanisms are tested with observations made of LSWs at Southampton, Long Island, New York. Consideration is also given to movement of LSWs at and through groins. It is concluded that fundamental questions remain on processes governing the behavior of LSWs.

INTRODUCTION

Shoreline change can be calculated by one-line numerical simulation models for a wide range of coastal structures, beach fills, waves, and boundary conditions. Such models are based on the continuity equation and a transport rate formula for the particulate movement of sand, such as the CERC formula (SPM 1984). It is well known that the one-line model, with a particulate transport rate formula dependent upon the incident wave angle, reduces to the diffusion equation. The result is that perturbations in

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shoreline position will tend to be smoothed, unless controlled or sustained by a boundary condition or another constraint. Particulate transport rate formulas pertain to micro-scale or meso-scale motion (minutes to hours or days) and are stepped through time, typically at 3- to 6-hr intervals, for calculation cell widths typically on the order of 50 to 500 m.

Engineers are becoming aware of morphologic features in the nearshore having much longer time and space scales that may impact project performance. Such features maintain their identities for months to years and move while preserving form. One such collective movement (Sonu 1968) of consequence is that of longshore sand waves (LSWs) (see Thevenot and Kraus (1995) for a literature review of LSWs), large wave-like features that migrate alongshore with a characteristic speed of kilometers per year. Verhagen (1989) examined a 100-year record of LSWs present along 20 km of Dutch coast and concluded that periodic accretion observed in a groin field coincided with the passage of LSWs and not to trapping of littoral (particulate) drift by the groins. LSWs have been associated with intermittency in sand supply, such as the discharge of river sediments, sediments discharged from inlets, artificial injection of a large quantity of sand, and welding of shoals on to the shore.

Recently, Thevenot and Kraus (1995) presented a one-line model that includes both particulate transport and representation of LSWs as a collective motion, and they successfully simulated LSW migration observed at Southampton Beach, Long Island, New York. The purpose of the present paper is to investigate possible mechanisms that maintain and translate LSWs and to extend the one-line model to examine LSW movement in groin fields. The model is tested with data from Southampton Beach.

THEORETICAL CONSIDERATIONS

Here, we discuss three mechanisms we hypothesize might act singly or jointly in the nearshore to preserve LSWs and translate them alongshore. First, basic concepts underlying longshore sand transport and shoreline change calculation are introduced.

General Relations

Shoreline change models have become a standard technique for calculating the long-term evolution of sandy beaches under impressed waves, boundary conditions, and coastal engineering activities (Hanson and Kraus 1989). In these models, the longshore sand transport rate is usually represented by an expression of the form

$$Q = Q_o \, sin2\theta_b = Q_o \sin\left[2\left(\theta_o - \arctan\left(\frac{\partial y}{\partial x}\right)\right)\right] \tag{1}$$

where Q_o = amplitude of longshore sand transport rate, θ_b = angle of breaking wave crests relative to the shoreline, θ_o = angle of breaking wave crests relative to an axis set parallel to the trend of the shoreline, y = shoreline position, x = distance alongshore, and $\partial y/\partial x$ = local shoreline orientation. For beaches with gentle offshore slopes, it can be assumed that the breaking wave angle, θ_b, relative to the shoreline and the shoreline orientation, $\partial y/\partial x$, are small. For such a situation, if the amplitude of the longshore sand transport rate and the incident breaking wave angle are constant (independent of x and time t), the equation for the change of shoreline position y reduces to the one-dimensional (1D) diffusion equation (Larson *et al.* (1997)

$$\frac{\partial y}{\partial t} = \epsilon \frac{\partial^2 y}{\partial x^2} \tag{2}$$

in which

$$\epsilon = \frac{2Q_o}{D} \tag{3}$$

where D = sum of depth of profile closure and elevation of the berm. Eq. (2) describes diffusion or spreading of perturbations that might be located along the shoreline, the diffusion acting to obliterate the distinct and persistent shoreline sand forms which are the subject of this study.

In this study, three possible mechanisms are postulated and investigated, by means of a one-line model, which may be responsible for the preservation of the form and translation of the center of mass of LSWs. These mechanisms are (1) wave asymmetry, (2) form advection, and (3) surf-zone contraction.

Wave Asymmetry Mechanism

There are a wide range of expressions for calculating the amplitude of longshore sand transport rate Q_o. For example, the SPM (1984) gives the relation

$$Q_o = \frac{\rho g}{16} H_b^2 \, C_{g_b} \, \frac{K}{(\rho_s - \rho)\lambda} \tag{4}$$

where H_b = significant breaking wave height, C_{gb} = wave group velocity at breaking, ρ (ρ_s)= density of water (sediment), g = acceleration due to gravity, K = non-dimensional empirical coefficient (approx. 0.5 - 0.8), and λ = porosity of sand (approx. 0.4). Eqs. (1) and (4) show that breaking wave height and direction are the dominant parameters determining the magnitude and direction of the longshore sand transport rate.

Thevenot and Kraus (1995) postulated that a LSW would refract waves toward it, similar to wave convergence at a headland, and this wave asymmetry would tend to “pack” the sand in place on the LSW. Their calculations with a simple 1D wave model showed this phenomenon to be potentially valid. To further evaluate the possible influence of wave asymmetry on LSW migration, breaking wave input for the shoreline change model was calculated with a full 2-dimensional (2D) wave transformation model (Larson and Hanson 1996) that was executed every time step.

The mild-slope equation (Berkhoff 1972) is often employed to describe the transformation of linear water waves. A simplified form of this equation was used in the present study, where diffraction was neglected, but energy dissipation due to depth-limited breaking was included. The dissipation was incorporated as a sink term in the equation for conservation of wave energy flux, and the magnitude of the dissipation was estimated according to the procedure of Dally et al. (1985). The mean water elevation was computed from the cross-shore momentum equation. The wave calculations involved in these simulations were, therefore, much more rigorous that what is normally done for shoreline-change model simulations. A practical limitation in accuracy is the finite grid size, as the breaking wave height and angle are calculated at discrete points across-shore.

Advective Form Mechanism

As shown by Inman (1987) and by Larson and Kraus (1991), the longshore migration of LSWs may be incorporated into Eq. (3) by including a morphologic form-advective term $V(\partial y/\partial x)$ to yield the advection-diffusion equation for a conservative substance

$$\frac{\partial y}{\partial t} + V\frac{\partial y}{\partial x} = \epsilon\frac{\partial^2 y}{\partial x^2} \tag{5}$$

where V = the migration speed of the LSW. Thevenot and Kraus (1995) related V to a longshore water discharge parameter R defined as (Kraus & Dean 1987)

$$R = \frac{1}{2}d_b y_b v_{ls} \tag{6}$$

in which d_b = depth at wave breaking, y_b = the distance from the shoreline to the break point, and v_{ls} = mean velocity of the longshore current. The discharge parameter was considered as an appropriate means to express the form speed because R is a macro-scale quantity, as is V.

The longshore current velocity may, in turn, be calculated using an accepted empirical relation (Komar & Inman 1970)

$$v_{ls} = \frac{1.35}{2}\gamma\sqrt{gd_b}\sin(2\theta_b) \tag{7}$$

in which γ = ratio of wave height to water depth at breaking. Based on these parameters, the volume rate of transport Q_{LSW} may be calculated as (Thevenot and Kraus 1995)

$$(Q_{LSW})_{calc} = \alpha(R - R_{crit}) \tag{8}$$

where α = empirical proportionality coefficient, and R_{crit} = threshold value of R. Both of these values must be determined from field measurements or from inferences made through modeling of shoreline change. On the other hand, based on geometric properties, the volume rate of transport may be estimated as

$$(Q_{LSW})_{est} = \eta D V \tag{9}$$

where η = amplitude of the LSW measured from the ambient shoreline. Elimination of Q_{LSW} between Eqs. (8) and (9) gives an expression for the migration speed of the LSW to be substituted in Eq. (5) as:

$$V = \frac{\alpha (R - R_{crit})}{\eta D} \tag{10}$$

Contracted Surf Zone Mechanism

This analysis is based on the assumption that the presence of a LSW does not alter the alongshore location of depth contours beyond the depth of closure. Under this assumption, because the LSW protrudes seaward from the ambient shoreline, the slope of the profile on the LSW must be steeper than that of the adjacent beach.

The beach profile is assumed to follow a Bruun - Dean equilibrium ($y^{2/3}$) shape. Along the ambient shoreline (unaffected by the LSW), the horizontal distance from the shoreline to D_c is the active width of the surf zone y_c. The equilibrium shape relation for y_c may be expressed as

$$y_c = (D_c/A)^{3/2} \tag{11}$$

where A = empirical scale parameter. Along sections of shore occupied by a LSW, the active width of the surf zone will decrease. If an equilibrium profile is assumed to exist along these sections as well, the steeper profile will be characterized by a modified scale parameter A^* given by

$$A^* = D_c/(y_c^*)^{2/3} \tag{12}$$

where y_c^* is the modified active width, $y_c - \eta$ (Fig. 1). Similarly, the surf-zone width, defined as the distance y_b from the shoreline to the breaker line at depth D_b, may be written as

$$y_b = (D_b/A)^{3/2} \tag{13}$$

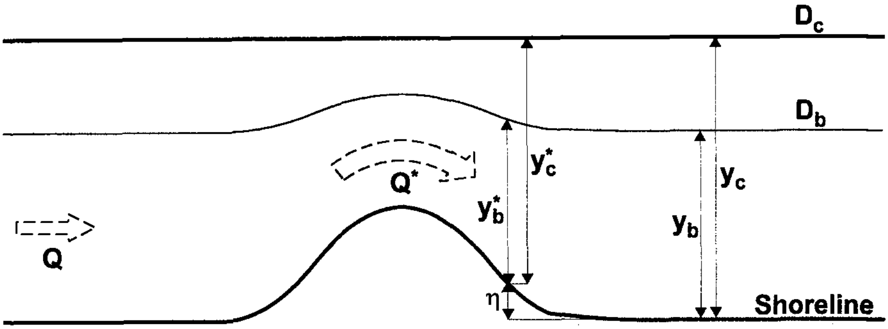

Fig 1. Definition sketch for the contracted surf zone approach.

along ambient beach sections, whereas along the beach at the LSW, the corresponding relation reads:

$$y_b^* = (D_b/A^*)^{3/2} \tag{14}$$

By expressing the longshore sand transport rate Q as an Inman-Bagnold-type relation and applying the continuity equation for the longshore transport of water yields

$$\begin{aligned} &Q \sim v_{ls}\, H_b^2, \quad Q^* \sim v_{ls}^*\, H_b^{*\,2} \\ &v_{ls}\, Area_b = v_{ls}^*\, Area_b^* \end{aligned} \tag{15}$$

where $Area_b$ = cross-sectional water area between the shoreline and breaker depth, and the superscript * denotes values in the region of the LSW. Based on the unmodified longshore sand transport rate distant from the LSW, the corresponding rate along the LSW is given by

$$\frac{Q^*}{Q} = \frac{A}{A^*}\left(\frac{y_c}{y_c^*}\right)^{5/3} \tag{16}$$

CALCULATION RESULTS

In the following, predictions of the three approaches for maintaining and translating LSW are evaluated through numerical simulation.

Wave Asymmetry Calculation Approach

Starting with a representative single LSW with a length of 5.5 km and an amplitude of 34.2 m (Fig. 2), a standard shoreline change model (particulate transport rate only) was run for 2,000 hr with constant offshore (20-m depth) wave climate of H = 1.0 m, wave period T = 6 sec, and θ = 10 deg. Other parameters in the simulation were time step Δt = 4 hr, cell spacing Δx = 50 m, and K = 0.7. As has been shown previously

(Hanson and Larson 1987), wave transformation modules run on assumed locally plane and parallel contours that are typically included in shoreline change models produce wave properties alongshore that results in a high degree of symmetrical transport patterns around a protruding symmetric feature such as a LSW. As a result, the LSW experiences little advection, although the diffusion is significant (Fig 2).

In the 2D wave modeling simulations, the number and size of alongshore calculation cells were the same as in the 1D simulation. The calculation area was divided into 50 sections, each of 20-m spacing across shore. Time step and duration of the simulation were the same as in the 1D case. As seen in Fig. 2, the LSW evolution produced by the 2D wave modeling displays a much greater degree of asymmetry, but there was no significant advective LSW motion, although diffusion was significant.

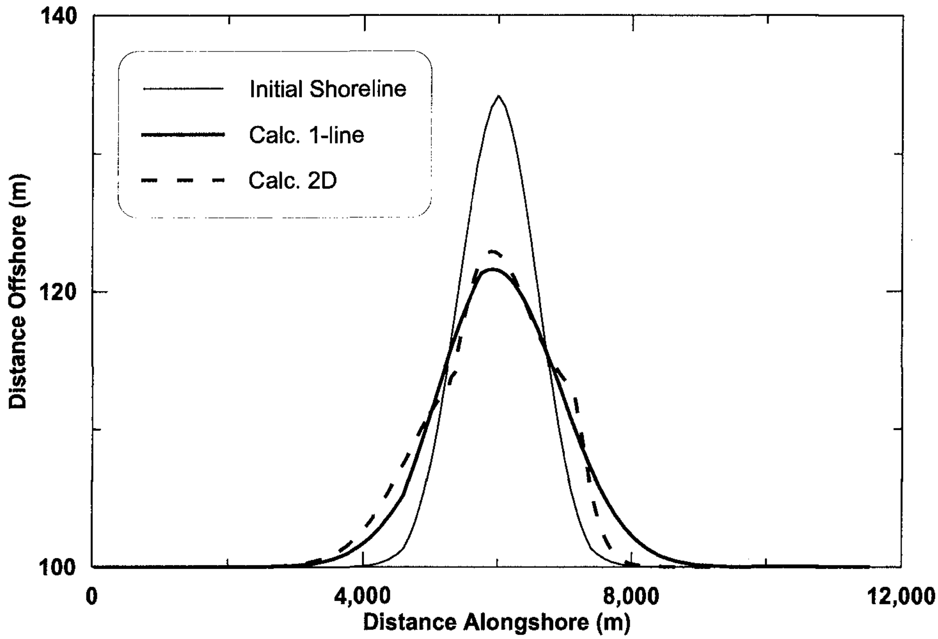

Fig 2. Shoreline change calculated using 1D and 2D wave transformation modeling.

Based on this and other calculations, it is concluded that a 2D wave calculation scheme as run in typical engineering studies will not create enough wave- and associated sand-transport asymmetry around a LSW to cause the LSW to migrate.

Advective Form Calculation Approach

As seen from Eq. (10), the advective speed of any section of a LSW is inversely proportional to its displacement from the baseline. Thus, the center of the initially symmetric LSW in Fig. 3 moves faster than the flanks, resulting in a flatter up-drift plan shape of the LSW and a steeper down-drift flank, in agreement with field observations. From a modeling point of view, the advective speed concept offers significant flexibility. The migration speed is controlled by α and R_{crit} in Eq. (10), whereas the diffusion is controlled by K in Eq. (4).

The initial LSW in Fig. 3 is the same as in the previous figure. In this case, the wave conditions were H = 1.0 m, T = 8 sec, and θ = 20 deg, and the simulation duration 720 days. The LSW migrates with an average speed of 3 km/yr with a decrease in amplitude of about 50%. Variation of input wave characteristics in several similar simulations (not shown) indicated that the LSW would move in either direction, always migrating in the direction of net sand transport, in agreement with field observations. At the same time,

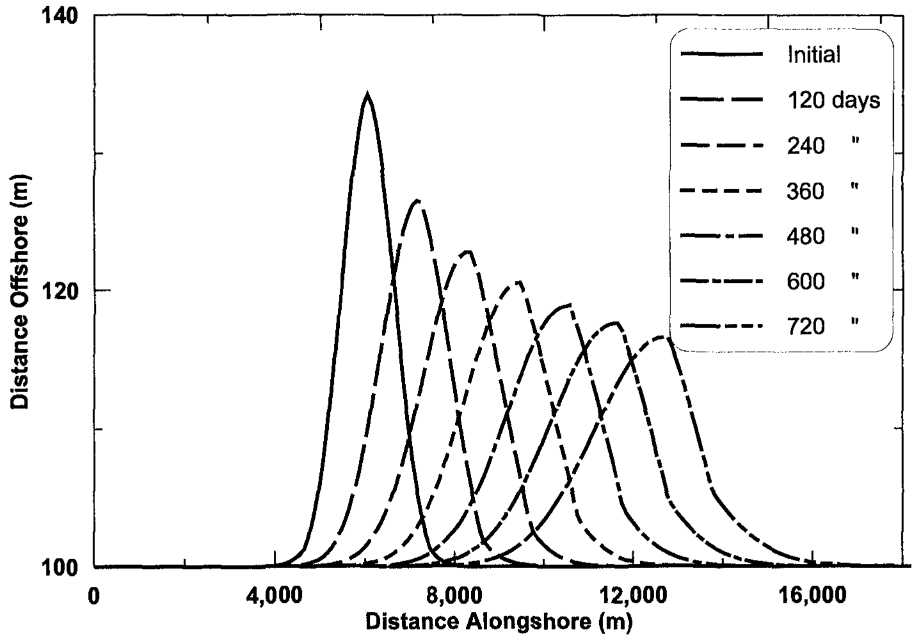

Fig 3. Calculated LSW migration using the advective form approach.

there was always an increase in length of the calculated LSW with time, while its amplitude decreased due to diffusion. Available field observations seem to indicate that LSWs have a more stable amplitude and do not increase in length.

Contracted Surf Zone Calculation Approach

A simulation was performed with the contracted surf zone approach implemented and with identical conditions as in the previous cases. As seen from Fig. 4, the calculated LSW does indeed move downdrift, but with considerably less speed and diffusion than in the previous case. During the simulated 2 years, the LSW moves with an average speed of 0.6 km/yr while maintaining 82% of its amplitude. At this stage, it is not possible to determine which of the two very different results is correct, because both are reasonable.

Distinguishing Advection and Diffusion

One problem both approaches have in common is, however, that any kind of perturbation in the shoreline will move downdrift, which is not reasonable. For example, the local erosion and accretion associated with the presence of a groin are expected to remain in the vicinity of the groin and not to move alongshore as a coherent form.

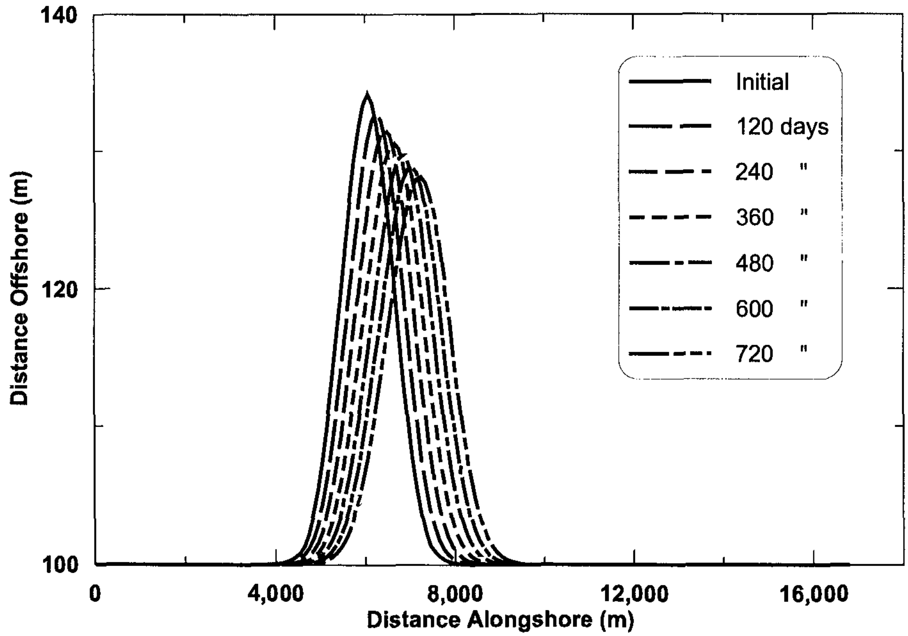

Fig 4. Calculated LSW migration using the contracted surf zone approach.

Fig. 5 shows the situation of an initial LSW identical to that in Fig. 3, calculated with the advective-form approach. The simulation was driven with a Corps of Engineers hindcast wave time series for Southampton Beach, Long Island, New York, that covers the period 1956-75. The simulation started on Jan. 1, 1958, and continued for 1,600 days, chosen to represent a period of unusually strong longshore transport wave conditions and a persistent sediment transport to the west (right). With a groin blocking the sediment transport, impoundment or accretion are expected on its updrift side and corresponding erosion on the opposite side of the structure. However, as these features start to develop, they, too, begin to migrate, resulting in the wavy shoreline shape downdrift of the groin. This behavior is unrealistic.

One *ad-hoc* means of eliminating advection of all perturbations is to *a-priori* identify and specify which features are to migrate. These features will subsequcntly evolve by advection as well as diffusion. Other features that appear spontaneously in response to constraints or placement of beach fills, such as shoreline displacements near groins, will not be subject to the advective mechanisms and not migrate alongshore. Such an *ad-hoc* specification might be implemented in an engineering application if the results are monitored with caution, but it is not satisfactory because it does not address why some

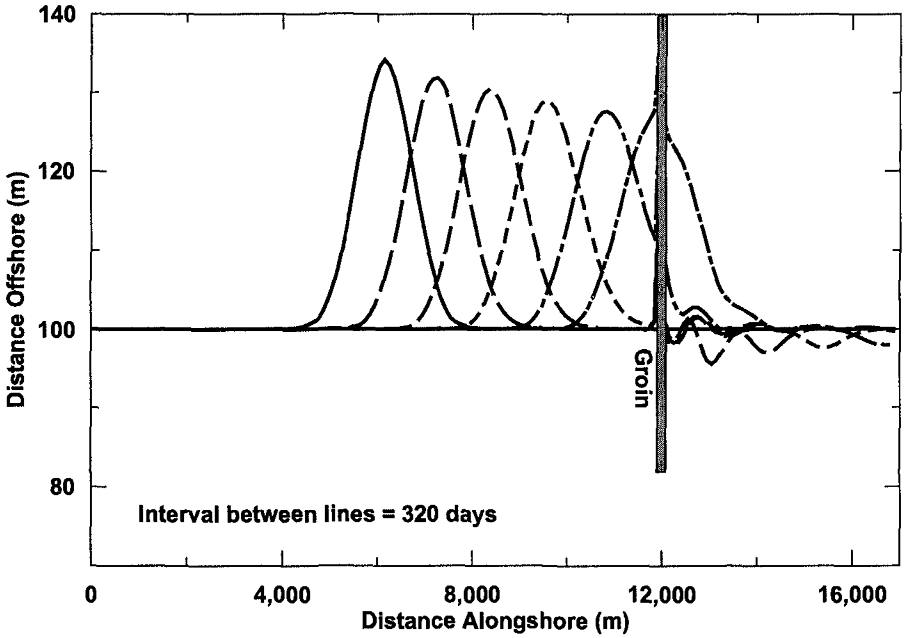

Fig 5. Calculated LSW interaction with a groin using the advective form approach.

shoreline features move and others do not, that is, the physical processes associated with cause and effect of the LSW migration are omitted.

A result of a simulation with such a distinction between advection and diffusion in the advective-form approach is displayed in Fig. 6, representing the same wave conditions as in the previous case, but now only run for 1,200 days. With the LSW distinguishing capability active, accretion as well as erosion adjacent to the groin develop, as expected. With elapsed time, the LSW passes the groin, initially deformed by the presence of the groin, but later resumes its shape as it moves away from the structure.

Application to Southampton Beach

To validate qualitatively the preliminary approach described here to modeling LSW migration, the advective form calculation was applied to the situation at Southampton Beach, Long Island, New York. Here, eleven LSWs present in the early 1990s were identified from aerial photos (Thevenot and Kraus 1995). The LSWs had an average length of 0.75 km, an average amplitude of about 40 m, and an estimated average annual migration speed of 0.35 km/yr. Their speed was found to vary seasonally with the strength of the inferred longshore discharge parameter calculated from the wave hindcast.

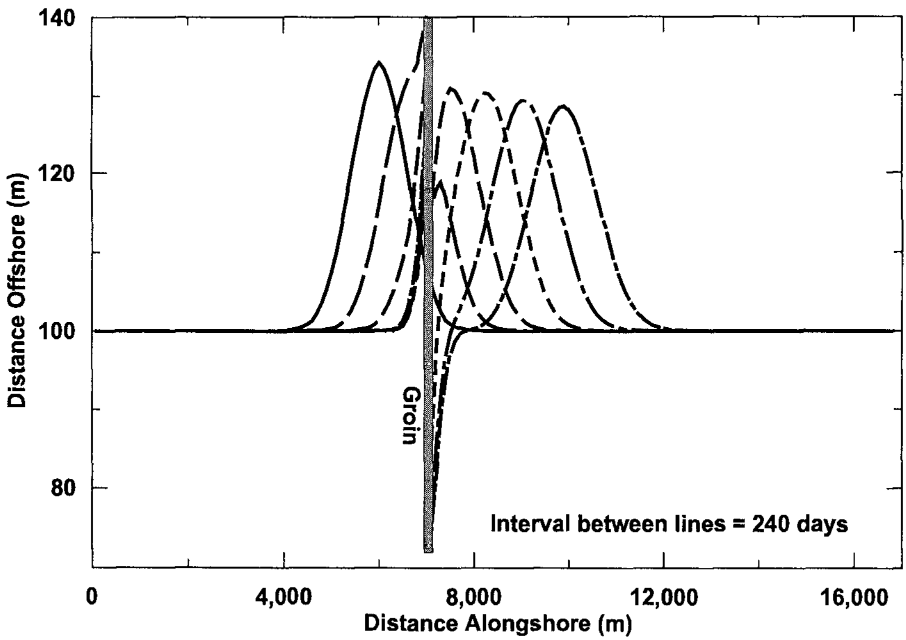

Fig 6. Calculated LSW interaction with a groin using decoupled advection and diffusion.

Available aerial photos dated Sep. 4, 1991, Dec. 20, 1991, and Jan. 2, 1993, served as references for the simulations. The simulated shoreline covers 16.9 km, with a spatial resolution of 100 m and a time step of 3 hr. Results of the simulation are shown in Fig. 7. The same wave hindcast time series as in the above was specified, but now starting on Sep. 4, 1956, and ending Jan. 2, 1958, representing the time period Sep. 4, 1991, to Jan. 2, 1993, because the actual time period of the LSW observation is not covered by the hindcast. The hindcast time period was selected to represent typical conditions at the site.

As expected, the LSWs moved to west (to the right in the simulations). However, it was noted that during the last two weeks of the simulation period, i.e., the end of 1957 (representing the end of 1992), the LSWs moved significantly in the opposite direction, ending on the incorrect side of the intermediate LSW positions. This reversal is an artifact of the wave time series in the hindcast for 1957. The calculations were therefore halted 2 weeks before the end of the simulation period.

The locations of the calculated LSW are in reasonable agreement with most of the LSWs in the photographs. However, representation of the amplitudes is poor. The reason for this is, as indicated previously, that the model cannot produce growth in LSW amplitude,

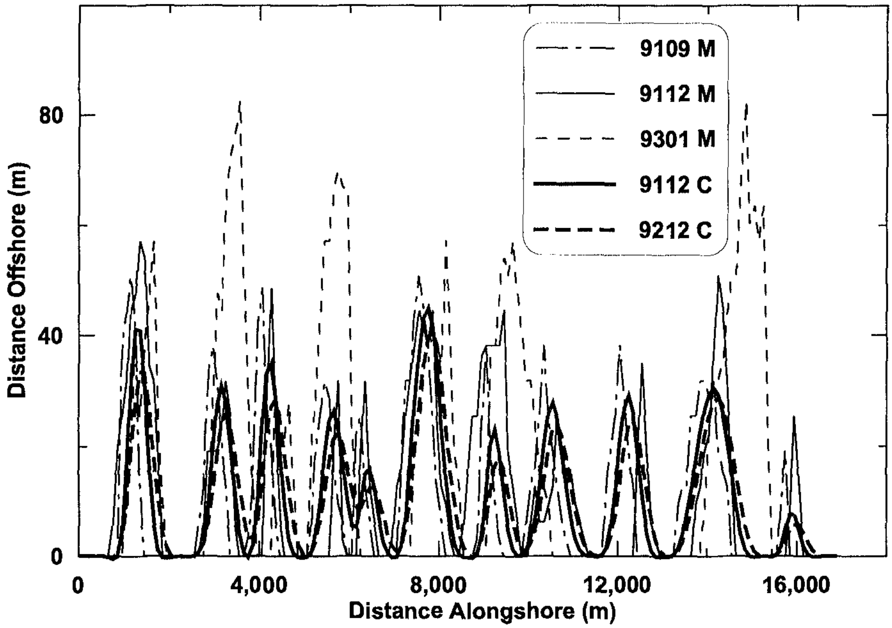

Fig 7. Measured and calculated LSW movement at Southampton Beach, LI, New York.

which appears to be a significant process in the field. It is not known at this point what phenomena are acting to produce a substantial increase in amplitude of the LSWs. It is possible that varying tide level may have contaminated the dimensions of the LSWs measured in the aerial photographs.

CONCLUDING DISCUSSION

Longshore sand waves (LSWs) are a large-scale phenomenon of major significance in coastal engineering and science. The physical processes governing preservation and migration of LSWs have not been firmly identified, no less understood. Predictive models describing LSWs are only at the formative stage, and the present paper has explored three approaches for describing the evolution of LSWs. The interaction between LSWs with groins was also explored.

Comparisons of calculations with measurements of LSWs at Southampton Beach, Long Island, New York, shows that the migration of LSWs may be described by shoreline-change model modified to include a form advection term. However, the temporal and spatial variation in permanence of form and amplitude of the LSWs were not satisfactorily reproduced in the model. Presented results indicate that the advective form calculation approach reproduces the LSW migration better than other methods, whereas the contracted surf zone calculation approach seem. to be superior in preserving LSW amplitude. Further model developments will depend on improved understanding, characterization, and conceptualization of the mechanisms controlling the behavior of LSWs.

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