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Coupled Longshore and Cross-shore Models for Beach Nourishment Evolution at Laboratory Scale

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Abstract: A series of three-dimensional laboratory experiments on beach nourishment behavior are described and analyzed. The experiments were designed to isolate the influences of berm height, beachfill median grain size, wave height, and wave period. The results have not been scaled up to prototype conditions, but many features of the laboratory evolution have also been observed in previous field studies. Laboratory results indicate that beachfill half-life (time required for half of the added volume to leave the nourished footprint) is inversely correlated with wave height, and positively correlated with berm height. A weak positive correlation with grain size was found. The influence of wave period was inconclusive. A coupled model describing the effects of both longshore and cross-shore sediment transport was developed and applied. The model accounts for the rapid loss of nourishment material offshore via cross-shore sediment transport, followed by a more gradual redistribution up- and downcoast of the project via longshore sediment transport. The influence of cross-shore sediment transport decreases as the beach slope approaches that of the pre-nourishment beach. The new model has not been

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calibrated for application at field scales, but it does reproduce the salient features of the laboratory dataset, and previous field data sets, such as the flattening of the beach profile as the project evolves. By describing the position of three elevation contours (berm crest, waterline, and beachfill toe), it thus provides a more realistic alternative to the "one-line" models often applied to beach nourishment problems by accounting for cross-shore sediment transport.

CE Database subject headings: beach nourishment, physical modeling, numerical modeling, sediment transport

INTRODUCTION

Beach nourishment, sometimes referred to as artificial nourishment, beach replenishment, or beachfill, involves the placement of large quantities of sand along or near a shoreline, typically in response to long-term shoreline recession. The material is often pumped by dredge from offshore or from an area in need of deepening, or delivered by truck from an upland site (e.g. Kerchaert et al. 1986; Wang and Gerritsen 1995; Kana et al. 1997; Muñoz-Perez et al. 2001). Generally it is desired that the new material be slightly coarser than the native sediment, and of similar color and composition (Madalon et al. 1991; Schwartz et al. 1991; Kana and Mohan 1998; Creed et al. 2000; Benedet et al. 2004). Sediment quantities exceeding 1 million m^3 per project are not uncommon, and total costs can exceed US$10 million per project. In the United States, between 1950 and 1994, a total of 132 shore protection projects were authorized by the U.S. Congress (Committee on Beach Nourishment and Protection, National Research Council 1995), and the U.S. Army Corps of Engineers spent an average of US$25 million per year in 2001 dollars on beach nourishment during this period. Hamm et al. (2002) state that 597 sites have been nourished, with 348 million m^3 of sand, throughout Europe since the early 1950's. The annual rate of nourishment is quoted as 28 million m^3.

Nourishment projects are not a permanent solution to beach erosion problems, as they typically do not drastically or permanently alter the processes originally responsible for the erosion, but rather delay their consequences. In many locations, hard erosion control structures are prohibited and beach nourishment is the only viable option. As a result, many sites have been nourished multiple times. Simplified analytical or numerical models are often used to make predictions of project lifetime. These tools are often acknowledged to represent only some of the processes influencing project lifetime (e.g. Dette et al. 1994).

Previous investigations of beach nourishment performance and behavior have been conducted via analytical or numerical modeling (Larson and Kraus 1991; Dean and Yoo 1992; Walton 1994; Groenewoud et al. 1996; Work and Rogers 1997; Walton et al. 2005), laboratory experiments (Dean and Yoo 1994; Donohue 1998; Work and Rogers 1998; Dette et al. 2002) and prototype scale measurements (Bodge et al. 1993, Work and Dean 1995; Larson et al. 1997; Browder and Dean 2000; Matias et al. 2004; Seymour et al. 2005). A reliable numerical model that provides a detailed description of all of the relevant physical processes – wave transformation, interactions with mean flows in and near the surf zone, sediment transport near and above the seafloor, and the resulting morphological evolution at large time scales (years) – would be the most desirable predictive tool. This would allow predictions to be made for any site, under a wide range of incident conditions. Unfortunately, no widely accepted model exists yet that meets these requirements.

Field measurements of beach nourishment performance provide the ultimate dataset for model validation, but every site is different, and conditions are time-dependent. As a result, data describing project performance at one site cannot reliably be used to predict project performance at another site.

Several studies have focused on numerical modeling approaches or a combination of field measurements and numerical modeling to investigate beach nourishment performance. Work and Dean (1995) analyzed field data from Perdido Key, Florida, describing the response of an evolving 7 million m^3 beach nourishment project and the causative forces. They applied separate numerical models for planform and profile evolution and tested against the field data. A "one-line" (defined below) numerical model was used to describe the longshore gradient of longshore sediment transport and remaining volume of new material in the nourished region. Two dominant time scales were observed defining the beach evolution: an initial adjustment of the steep as-built beach profile, which took place on a time scale of months, followed by planform adjustments as the nourishment material spread to areas up- and downcoast of the project over a longer time scale. Browder and Dean (2000) modeled this same project at a later time with additional monitoring data. As noted by Elko and Wang (2007), the shorter time scale for the cross-shore evolution can in some cases be controlled by the timing of a post-nourishment storm event.

Hanson and Kraus (1993) analyzed the function of beachfill transitions by incorporating both longshore transport processes and economic considerations. Their approaches ranged from a simple analytical method to a fully time-dependent numerical simulation with a shoreline response model. The Ocean City, Maryland beachfill project (10 km by 50 m; 5 million m^3) served as a case study. The analytical calculation method was judged to be too crude to apply in final design, but considerable cost reduction was concluded to be feasible by applying numerical simulation models of shoreline evolution.

Dean and Yoo (1992) presented two numerical methods for calculating shoreline evolution subsequent to a beach nourishment project. Both are one-line models that are capable of representing shore-perpendicular structures and background erosion. The interaction of nourishment retention structures with background transport was examined, and the effects of different nourishment sands were investigated. For nourishment materials less and more transportable than the native sediment, the centroids of the planform anomalies introduced by beach nourishment migrated updrift and downdrift, respectively, with time.

Work and Rogers (1997) described several governing equations and analytical solutions for beachfill evolution, including effects of project-induced wave transformation. They investigated four alternatives for description of wave transformation for one-line modeling applications, together with three descriptions of bulk longshore sediment transport rate, and presented a new governing equation and analytical solution which accounts for project-induced wave refraction using a two-line approach. The analytical solution may be used as a design aid to indicate the influence of beachfill parameters (depth to toe, taper length) on beachfill lifetime.

Laboratory experiments can be influenced by scaling effects, but allow for precise control of variables and can be replicated. The new data described in this paper are derived from scale models of beach nourishment projects observed in a laboratory. For reference, prototype projects are often up to 10 km and 100 m in longshore and cross-shore extent, respectively, with predicted lifetimes of years. Most model studies of coastal sediment transport take place in basins or flumes that have a maximum horizontal dimension of less than 100 m, implying a model scale of 1:100 or more. It is not possible to satisfy both Reynolds and Froude Number similarity with any scale other than unity, if water is to be used in the model, so scaling effects are introduced. The sediment is typically scaled down only slightly, resulting in further distortion. As a result, time scales differ in the model and prototype, and processes can also differ. For example, suspended load is typically much less significant in the laboratory, where the velocities are much smaller and the sediment overly large. This issue is discussed by Work and Rogers (1998) for the case of a beach nourishment scale model.

A relatively small number of 3-D laboratory investigations of beach nourishment behavior are described in the literature. Dean and Yoo (1994) employed analytical, numerical and experimental approaches to demonstrate the behavior of a beach nourishment project in front of a seawall. They conducted four wave basin experiments with monochromatic waves. Experimental conditions included sandy and seawalled shorelines and normal and oblique wave incidence. With a beach composed of compatible sand, the centroid of the nourishment planform remained nearly fixed and the planform symmetric about its centroid. With a seawall present, the project centroid migrated with increasing speed in the downcoast direction. Wave direction had greater significance on the performance of beach nourishment projects on seawalled coasts relative to sandy shorelines. Similar results were found both experimentally and via numerical modeling.

Work and Rogers (1998) used laboratory models of beach nourishment projects to investigate the influence of breaking wave height, wave period, beach slope and beachfill length on project lifetime. They performed nine experiments with monochromatic, nominally shore-normal waves. The experimental results were compared with analytical and numerical shoreline evolution models that simulated planform evolution in the absence of cross-shore sediment transport. They found that beachfill longevity positively correlated with project length and wave period, and negatively correlated with breaking wave height and beach slope.

Donohue and Dean (1999) conducted experiments in a three-dimensional wave basin to determine the longshore sediment transport rate in the vicinity of a nourished beach. Two different fill sand placement configurations and three different fill sand sizes were used in the experiments. Monochromatic waves were generated with a 5 degree breaking wave angle. The results from the experiments showed that the tests with larger fill sand size on a nourishment template that placed the sand high on the initial profile had the least transportability.

Yamashita et al. (2004) conducted two-dimensional laboratory experiments to investigate the movement of coarse nourishment material subjected to large waves. It was observed in the experiments that the coarse fill material moved into the surf zone within 30 minutes, and then was gradually buried within the seabed. The migration was also simulated using the SBEACH numerical model for cross-shore sediment transport (Larson and Kraus, 1989).

Karasu (2004) investigated the effects of wave height, berm height, beach slope, wave period and grain size on the performance of beach nourishment projects via laboratory experiments in a three-dimensional wave basin. Percentage of material remaining within the nourishment template was used to quantify project performance (Karasu et al. 2005). Percentage of remaining material was positively correlated with berm height and grain size, and inversely correlated with wave height and beach slope. Additional analysis of this dataset formed the basis of this paper.

In the following pages, a series of laboratory scale model experiments related to beach nourishment are described and interpreted. A new modeling approach is then described and compared to the measurements. The model, applied in finite-difference form, includes two simple, coupled models addressing longshore and cross-shore sediment transport, respectively, and is referred to as a “three-line” model. Although the results are not scaled up to prototype scale, it is shown that several features of the laboratory-scale projects are consistent with previous field observations, and that the inclusion of cross-shore sediment transport provides a more realistic depiction of project evolution.

LABORATORY EXPERIMENTS

A series of laboratory experiments was performed to investigate the performance of beach nourishment under different scenarios. Three different fill sand sizes and two different wave heights, berm heights and wave periods were used in the experiments. Table 1 provides a list of the parameters used for the experiments.

Model Basin

The experiments were conducted in a three-dimensional wave basin in the Hydraulics Laboratory, Civil Engineering Department, Karadeniz Technical University, Trabzon, Turkey.

The wave basin is 30 m long, by 12 m wide, by 1.2 m deep. The still water depth was fixed at 0.75 m for all experiments. The wave basin was equipped with a flap-type, impermeable, monochromatic, wavemaker (Figure 1), placed parallel to one wall, with a sand beach (0.18 mm median diameter) on the opposite side. Thus all experiments featured normally incident waves.

The initial planform of the nourished beach, shown in Figure 1, was the same for each experiment. Wave height was adjusted by changing wavemaker paddle stroke, and wave period was changed by adjusting the speed control on the drive motor. A resistance-type wave gauge, 5 m from the wave paddle, was used to record water level traces which were then analyzed to determine mean wave heights in the flat portion of the basin. The standard deviation of wave height was less than 10% of the mean wave height in each case.

Measured wave heights include the influence of any reflected waves. Reflection coefficients were estimated as a function of the surf similarity parameter, which includes the influence of wave height, period, and beach slope (US Army Corps of Engineers, 2002). In each case, reflection coefficients in the experiments were estimated to be less than 3%. Thus the measured wave heights were assumed to be equivalent to the incident wave heights.

Many previous researchers have noted that simulated beaches evolve differently when subjected to random wave fields as opposed to monochromatic waves with the same basic statistics. With monochromatic waves, the breakpoint location varies less, often leading to a more pronounced sandbar. Details of the shape of the beach profile, such as the location of the bar, are not of particular importance in the study discussed here, which emphasizes volumetric changes and the overall slope of the beach profile.

Experimental Methodology

For each experiment, the native beach was first subjected to waves until the beach profile appeared to equilibrate. The beach was then surveyed on the grid shown in Figure 1 before adding nourishment material. Saturated fill sand was added to create a trapezoidal beach nourishment planform, using a steel template frame to quickly build all model projects to the same footprint.

The median diameter of the native sand was 0.18 mm, while beachfill material featured median grain sizes of 0.18 mm, 0.40 mm or 0.80 mm. Sorting indices for the three sediments were 0.02, 0.14 and 0.17, respectively. When sand coarser than the native material was used as nourishment material, the mixed layer that resulted at the end of the experiment (up to 5 cm thick) was scraped off of the beach and replaced with the finer native sand before the next experiment commenced.

The initial beach nourishment length for all experiments was 2.15 m, including the tapered ends that extended 0.22 m on either side (Figure 1). The total surveyed area was 4.85 m in length. All profiles were measured to a distance of 3.3 m from the survey baseline. The measurement grid was 10 x 20 cm within the nourishment footprint, and 20 x 20 cm outside of this area. At each point and time of interest, sand elevations above the basin floor were simply measured using a thin rod to which a tape measure had been affixed. Each experiment was continued for a total of ninety minutes, with a survey of the entire measurement grid being done before and after the experiment, and measurements within the nourished footprint at intermediate times. Visual observations suggested that no nourishment material left the survey grid.

Any dimensionless measure of the size of the sand in the laboratory (wave height over diameter, H / d_{50}, for example) reveals that it is significantly larger than that in the prototype, implying that the sediment transport processes will differ in the two scenarios. In the lab, suspended sediment transport will be much less pronounced, and the rate of evolution will also differ. Despite these issues, as will be shown, several trends observed in the laboratory dataset match prior field observations.

Laboratory Data Interpretation

There are a number of ways in which the experimental data may be analyzed. The first-order analysis focuses on sediment volumes within various portions of the experimental domain and how they change over time. Three domains were specified (Figure 2): Region A, the nourished footprint (the 2.15 x 1.70 x 0.40 m trapezoidal planform in each experiment), Region B (2.15 x 3.3 m), of which Region A is a subset, and Region C (4.85 x 3.3 m), which is the entire surveyed grid. Regions B and C are large enough that cross-shore sediment transport beyond their offshore boundary was negligible in each experimental case.

Conservation of sand mass (volume) within Region C was considered to investigate the significance of survey errors. Differences in volume between the beginning and end of an experiment ranged from +1 to -15 percent, a negative value suggesting a net loss of sediment over the course of the experiment. The bias toward negative values is probably a byproduct of limited survey resolution.

Material leaving the nourished footprint can either move offshore, remaining in Region B, or move updrift or downdrift. A volumetric analysis was also used to quantify the amount of material moving in either direction. The volume of material lost from Region B was taken to represent lateral losses due to longshore sediment transport, whereas the difference between the volumes remaining in Regions B and A was taken to represent losses from the nourished template due to cross-shore sediment transport. At the conclusion of Experiment 1, for example, 59% of the nourished volume was found to be remaining within Region B, and 33% within Region A. Thus 26% of the material moved out of the nourished area in the cross-shore direction, and 41% moved updrift or downdrift, out of Region B. The volumetric analysis for each experimental case is summarized in Table 2.

The rate of loss of material from the nourished footprint to areas up- and down-coast of the project controls what is often referred to as the project lifetime. Project half-life (time required to lose 50% of the nourishment project volume from the nourishment footprint) was found to be negatively correlated with wave height, and positively correlated with berm height. A weak positive correlation between grain size and half-life was also found. Influence of wave period was indeterminate. The correlation of half-life with berm height is really a correlation with project volume – for the same footprint, a larger berm height implies a larger volume of sediment to be redistributed along the coast.

Figures 3 and 4 show the surveyed initial and final conditions for Experiment 9 (median grainsize d_{50} = 0.18 mm), which was qualitatively similar to many results, even those with much coarser nourishment sediments. There is a reduction in beach width within the nourished region, and accretion immediately adjacent to the nourished region, due to longshore gradients of longshore sediment transport. There is also a net loss of subaerial sediment, due to net positive (offshore) cross-shore sediment transport. This is a common observation in field projects; see Elko and Wang (2007) for a recent example.

The beach profile evolution at the center of the nourished region for Experiment 9 is shown in Figure 5. The profile shows a net loss of sediment and recession of the waterline. Figure 6 shows profiles located 28 cm away (x = 378 cm) from the nourished region for this same case, where a net gain of sediment is observed, and the waterline moves slightly seaward.

The survey data were also used to estimate longshore gradients of longshore sediment transport, $\partial Q / \partial x$, where Q is the longshore sediment transport rate, integrated across the surf zone, and x is the longshore coordinate. The longshore gradient of longshore sediment transport can be estimated from the rate of change of beach profile area, $\partial A / \partial t$, which in turn can be computed from the survey data:

$$\frac{\overline{\partial Q}}{\partial x} = -\frac{\overline{\partial A}}{\partial t} \approx -\frac{\Delta A}{\Delta t} \tag{1}$$

Here the overbar denotes time averaging, ΔA is the change in cross-sectional area of the beach profile, and Δt is the time interval between surveys. A positive longshore sediment transport gradient implies a loss of sand from a cross-section, and a negative change in area, ΔA.

The computed longshore gradient of longshore sediment transport, evaluated using Equation (1), for four different experiments is presented in Figure 7. The positive local maxima indicate erosion from the two ends of the nourished footprint, with negative values indicating accretion on either side of the nourished area. Similar observations were made regarding prototype scale projects (e.g. Work and Dean 1995).

The laboratory data thus reveal the longshore and cross-shore movements of sediment away from the nourished footprint, consistent with field observations. The following section describes a simple approach to modeling this behavior.

MODELING OF BEACH NOURISHMENT EVOLUTION

Ideally, one would use a detailed description of nearshore hydrodynamics and sediment transport to predict beach nourishment evolution. Unfortunately, an accepted and practical model of this type that is reliable at larger time scales (months to years in prototype) is not yet available. Also, in some circumstances, such as investigating project feasibility, it is desired to have a less cumbersome predictive tool. The model discussed here was designed with this philosophy in mind.

Many longer-term predictions of coastal behavior have been made with one-line models, which address only the effects of longshore sediment transport and assume that the beach profile shape remains constant as the shoreline moves (e.g. Hanson and Kraus 1989). This is often a poor assumption for a beach nourishment project, which typically features as-built slopes that are substantially steeper than the natural slope of the beach. The nourishment project typically displays two time scales: one associated with the cross-shore profile evolution, and one with the evolution of the planform. The profile evolution typically occurs over a shorter time scale (weeks to months; e.g. Work and Dean 1995, Elko and Wang 2007). Laypersons often see this (with justification) as a rapid loss of new beach, since the dry beach area is reduced. Note that the focus here is not on day-to-day, often periodic, changes in the beach profile, but rather on how its overall shape or slope changes as it evolves over months.

So the goal of the modeling effort described below was to develop a relatively simple model for beach nourishment evolution that accounts for 1) the cross-shore evolution of the beach profile and 2) the planform evolution due to longshore gradients of longshore sediment transport. The model includes two components to account for these processes. The cross-shore model is developed analytically, and then applied via a numerical solution that allows coupling with the longshore model, as described below. The resulting model is then compared to the laboratory data discussed above.

Cross-Shore Evolution of Nourishment Project

Most beach nourishment projects are constructed such that their cross-shore slopes are steeper than found on the pre-existing beach. One of the first responses is for material to move offshore, as the profile approaches a more natural slope and configuration, similar to the pre-nourishment beach profile.

Many models have been proposed to describe the cross-shore evolution of beach profiles under conditions of variable waves and water levels. Many of these models describe only short-term (hours to days) storm effects and are not well-suited to longer-term applications (e.g. Kömürcü et al. 2007). The approaches that have been more successfully applied at longer time scales often involve the assumption that an equilibrium beach profile shape will result if a beach is subjected to constant forcing (e.g. Kriebel and Dean 1985).

What is desired here is a simple model that results in an improved description of long-term (duration of the laboratory experiment, or months to years at prototype scale) beach planform evolution, compared to a simple one-line model that does not account for cross-shore sediment transport at all. A simplified description of cross-shore sediment transport is proposed, with particular emphasis on describing what was observed in the laboratory. The experiments described above feature nearly planar pre-nourishment profiles, with the majority of the nourishment material originally above the waterline.

At this stage, the following assumptions will be invoked regarding the cross-shore component of the model (refer to Figure 8):

1) The pre-nourishment beach profile is planar with a slope S_o.
2) The nourished beach features a steeper slope, S, that is time-dependent, but the profile remains planar as it evolves.
3) A depth of closure, h_*, exists, beyond which sediment does not move.
4) The toe of the nourishment project lies at a depth h_t that is higher on the profile than the depth of closure.
5) Wave forcing is assumed constant in time.

Some of these assumptions can be relaxed later when a numerical solution scheme is used.

It is assumed that the volume of material eroded from the nourished beach per unit length per unit time, $dV/dt \approx \Delta V/\Delta t$ (L^2T^{-1}), is dependent on incident wave power (represented by the square of the incident wave height, H), berm height B, native beach slope, S_o, nourished beach slope, S, or difference between these slopes, median grain size, d_{50}, sediment specific gravity, *s.g.*, number of waves hitting the beach per unit time, or inverse of wave period, T, and depth to the toe of the nourishment project, h_t. This dependence may be written as:

$$\frac{dV}{dt} = f(H^2, B, S - S_o, d_{50}, s.g., T, h_t) \tag{2}$$

Dimensional analysis considerations then suggest that:

$$\frac{dV}{dt} = K_c \frac{H^2 B}{h_t T} (S - S_o)^p \tag{3}$$

Where the coefficient K_c is a function of sediment size and specific gravity and may be treated as a dimensionless empirical calibration parameter, along with the exponent, p. This equation suggests that the rate of cross-shore evolution of the nourished beach will asymptotically approach zero as its slope approaches that of the pre-existing beach. This assumption, that the rate of response of the beach is proportional to the degree of disequilibrium, has been used successfully within other models, such as that developed by Kriebel and Dean (1985) and the U.S. Army Corps of Engineers' SBEACH model (Larson and Kraus 1989), as well as within models of other physical processes.

It would be possible for the depth at the toe of the project to be zero, but this would not lead to an infinite rate of beach evolution as predicted by Equation (3) and is not of interest. A more reasonable description is:

$$\frac{dV}{dt} = K_c \frac{H^2 B}{(B + h_t)T} (S - S_o)^p \tag{4}$$

Equation (4) describes the volume (per unit length of beach) per unit time removed from the nourished cross-section and moved in the cross-shore direction. The corresponding rate of movement of the waterline is:

$$\frac{dy}{dt} = 2 \frac{h_t}{(B + h_t)^2} \frac{dV}{dt} \tag{5}$$

Assuming uniform deposition, the seafloor between the toe of the nourishment project and the depth of closure will rise at a rate:

$$\frac{dz}{dt} = \frac{1}{\ell_*} \frac{dV}{dt} \tag{6}$$

The retreat of the shoreline, described by Equation (5), and the deposition on the seafloor, described by Equation (6), both lead to a gradual reduction in the beach profile slope. The deposition effect will be neglected here, since it occurs over a much larger area (distance) and is thus less significant. With this and the other assumptions defined above, it may be shown that for the case of $p = 1$ in Equation (4), the following solution for time-dependent beach slope, S, may be derived:

$$t = \frac{1}{D}\left(\frac{1}{S_i} - \frac{1}{S}\right) - \frac{1}{DS_o} \ln\left[\frac{(1 - S_o / S)}{(1 - S_o / S_i)}\right] \tag{7}$$

where

$$D = \frac{K_c H^2}{(h_t + B) h_t T} \tag{8}$$

and S_i and S_o denote the initial and equilibrium slopes, respectively. Unfortunately Equation (7) is not easily solved for time-dependent slope $S(t)$, but it is evident that it exhibits exponential decay as it approaches the equilibrium slope, with the constant D controlling the rate of decay. Also note that this solution is valid only for the case $h_t > 0$, i.e. the toe of the nourishment project is submerged.

If the shoreline position, *y(t)*, is desired, Equation (7) may be rewritten as follows:

$$t = \frac{1}{D}\left(\frac{1}{S_i} - \frac{w_t - y}{h_t}\right) - \frac{1}{DS_o}\ln\left[\frac{\left(1 - S_o(w_t - y)/h_t\right)}{\left(1 - S_o/S_i\right)}\right] \qquad (9)$$

Because of the exponential nature of these solutions, an infinite amount of time is required to reach the equilibrium condition, which is why half-life will be estimated. Considering only the cross-shore part of the problem, with the simple geometry defined above, the project half-life is:

$$t_{50} = \frac{1}{D}\left(\frac{1}{S_i} - \frac{2}{S_i - S_o}\right) - \frac{1}{DS_o}\ln\left[\frac{\left(1 - 2S_o/(S_i - S_o)\right)}{\left(1 - S_o/S_i\right)}\right] \qquad (10)$$

The fraction of the subaerial beach width remaining is given by:

$$M_c(t) = \frac{\left(y - B/S\right)}{\left(w - B/S\right)} \qquad (11)$$

The suitability of the approach outlined above for description of the laboratory models of beach nourishment will be discussed after coupling with the longshore component of the planform evolution model.

Planform Evolution due to Longshore Sediment Transport Gradients

A simple "one-line" model was employed to describe the portion of the planform evolution attributable to longshore gradients of longshore sediment transport. This type of model has been widely used to describe long-term (months to years) planform evolution (e.g. Hanson and Kraus 1989). The term "one-line" is used because it is assumed that the longshore sediment transport gradients that lead to erosion or accretion do not change the shape of the beach profile. With this assumption, in the absence of cross-shore sediment transport, only a single depth or elevation contour is needed to define the geometry of the beach. Normally some measure of the waterline is taken as this contour; here the still water level will be used.

A longshore sediment transport equation is required to apply this method, and this equation must describe the total longshore sediment transport, i.e. integrated across (and beyond) the surf zone. The equation proposed by Kamphuis (1991) was chosen, because it meets this requirement, and includes grain size, beach slope, and wave period dependence. The other required equation describes conservation of sediment mass (volume).

The governing equations in the longshore transport model may thus be summarized as:

$$Q = K\frac{H_b^3}{T}S^{0.75}\left(\frac{H_b}{L_o}\right)^{-1.25}\left(\frac{H_b}{d_{50}}\right)^{0.25}\sin^{0.6}(2\theta_b) \qquad (12)$$

and

$$\frac{\partial y}{\partial t} + \frac{1}{(h_* + B)}\frac{\partial Q}{\partial x} = 0 \qquad (13)$$

where x is the longshore coordinate, $Q(x,t)$ is the total longshore sediment transport rate (L^3T^{-1}), H_b is the breaking wave height, θ_b is the wave angle at breaking, relative to the local shore normal vector, and L_o the deepwater wavelength. K serves as a dimensionless calibration coefficient. Breaking wave heights were estimated using the approach of Weggel (1972), and depth of closure was estimated using the approach of Hallermeier (1978). Other terms are as described above in the cross-shore modeling section.

It is possible to solve the combined system of equations (12) and (13) analytically, given simple initial, boundary, and forcing conditions (e.g. Work and Rogers 1997). In this paper, a first-order, explicit, finite-difference scheme was used to solve the system of equations. This allows for time dependence in the forcing, time dependence in beach slope, and more realistic boundary and initial conditions. It also allows for coupling with the cross-shore model, as described below.

Coupled Longshore and Cross-Shore Models for Beach Profile Evolution

The two models described above were coupled to provide a model for the three-dimensional evolution of a beach nourishment project. A time step was defined, and the cross-shore and longshore models applied over that time step in succession. Thus the beach slope and width changes described by the cross-shore model affected the longshore sediment transport computed in the longshore model. The beach planform and the beach profile evolve together, although at different time scales. The beach profile does not remain linear, because the toe of the nourishment is assumed fixed, the berm crest moves due to cross-shore sediment transport, and the waterline moves due to both cross-shore sediment transport and longshore gradients of longshore sediment transport. Thus this could be considered a "three-line" model.

Each model contains at least one calibration coefficient. The volume of material lost during an experiment due to longshore gradients of longshore sediment transport was known for each experiment; the calibration coefficient in the longshore model, K, was chosen to replicate this amount of loss.

The cross-shore model was calibrated by noting that, on average, 25% of the nourishment volume was lost from the nourished template as a result of cross-shore transport, and that, again on average, this occurred during the first eleven minutes of the experiment. Note that this time scale is four percent of the mean project half-life that would be computed using a one-line analytical model and the solution for project half-life (see Work and Rogers 1997). Prototype-scale results will differ, but these results are consistent with field observations indicating the significance of cross-shore sediment transport.

After choosing an exponent p in Equation (4), and integrating in time over the duration of an experiment, the value of K_c may be determined for the cross-shore model. Tests were performed with p = 1, 1.5, and 2. A larger exponent forces the model to respond more slowly at larger times, as the beach slope approaches the equilibrium slope. In practice, a value of 2 for p was found to yield the best results, although the goodness of fit was not drastically different for the case of p= 1.5 in the laboratory data set.

The measured and modeled beach profiles at the center of the model beach nourishment project for Experiment 9 (d_{50} = 0.18 mm for both native beach and nourishment project) in the laboratory data set are compared in Figure 9. The model initially underpredicts the rate of evolution, but provides a better fit to the measurements at later times. It also replicates the trend toward a bilinear profile, with a milder slope near the water line and a steep face above. Similar results were found for other cases.

As can be seen in Figure 10, the result is similar near one end of the project, again for Experiment 9. Here, the laboratory result shows a more rapid loss of sediment from the subaerial portion of the beach profile. An initial loss occurs quickly, and then the evolution slows down, so that by the end of the experiment, the model and measured results are similar. The difference between the model and measured results for the early times is probably due to inadequate description of the strong longshore gradients of longshore sediment transport that exist early on at the ends of the project.

The planform evolution measured in the lab and predicted by the model for the end of Experiment 9 is shown in Figure 11. Being a diffusion-type solution, the model does not capture all of the longshore variability found in the measurements, but inclusion of the cross-shore sediment transport does improve model realism. The cross-shore sediment transport is a first-order effect at the time scales considered here, i.e. it is not negligible compared to the effects of longshore sediment transport. Root mean square differences between measured and modeled shoreline position within the nourished area are 3.0 cm and 2.2 cm for the longshore-only and coupled models respectively. The rate of loss of beach width at the berm crest (not shown) is higher by roughly a factor of $(h_t+B)/B$ because of the assumed geometry shown in Figure 8.

It is important that the models be applied in a coupled fashion as described above, because the cross-shore transport reduces the planform anomaly that controls the rate of beach evolution due to longshore sediment transport. Decoupling the models would lead to overestimation of the effect of the longshore sediment transport.

CONCLUSIONS

A model that describes the evolution of a nourished beach due to both longshore and cross-shore sediment transport was developed. The model was calibrated and compared to a series of laboratory experiments on beach nourishment behavior.

The laboratory study involved normally incident, monochromatic waves and constant mean water levels, and revealed the influences of wave height, period, sediment size and berm height on the behavior of a scale model beach nourishment project. The experiments clearly showed the significance of cross-shore sediment transport at early times. An initial loss occurs quickly, and then the evolution slows down as cross-shore sediment transport decreases in significance.

Project half-life, defined as the time required for 50% of the nourishment material to leave the nourished zone via longshore sediment transport, was found to be inversely correlated with wave height, and positively correlated with berm height and grain size. This half-life reflects only losses due to longshore gradients of longshore sediment transport. Typically, 25% of the nourishment material moved offshore, out of the nourishment template, resulting in an additional decrease in dry beach width.

Scaling effects arising due to the greatly reduced scale of the physical models mean that the time scales and response of the simulated nourishment projects will differ from prototype conditions. But analysis of the laboratory results reveals trends that are consistent with prior field observations, despite the presence of scaling effects that make conversion of, for example, laboratory time scales, to prototype conditions difficult. The observed correlation of beach and wave parameters with nourishment project half-life is also logical: a larger wave height implies greater energy, and thus longshore sediment transport, and more rapid evolution. A greater berm height, all other things being equal, implies a larger nourishment volume per unit length of beach, which improves durability.

An analytical model for cross-shore evolution of nourished beach profiles was proposed. The corresponding governing equation was applied within a numerical model, coupled with a model of longshore sediment transport, to provide a more realistic simulation of the three-dimensional evolution of a beach nourishment project. Despite providing a very simple representation of the morphology of a beach nourishment project, the resulting model does replicate characteristics of beach nourishment behavior evident both in the laboratory data presented here, and in previous field observations, specifically the trend for cross-shore sediment transport to result in the beach profile quickly decreasing in slope, followed by a more gradual distribution of sediments to areas up- and downcoast of the project via longshore gradients of longshore sediment transport.

The coupled numerical model describes the positions of the toe and crest of the beach nourishment project, as well as the waterline, and may thus be viewed as a three-line model. With this approach the model predicts a bilinear beach profile, with a steeper slope above the waterline, consistent with laboratory observations. Many beach nourishment projects have been designed or analyzed using one-line analytical or numerical modeling tools that neglect cross-shore sediment transport. The approach described here provides a more realistic description of the problem accounting for the significance of cross-shore sediment transport. The model has not yet been tested against field observations, but may prove suitable for performance predictions after appropriate calibration.

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NOTATION

The following symbols are used in this paper:

A = cross-sectional area of beach profile;

B = berm height;

D = decay coefficient;

d_{50} = median grain size;

H = incident wave height;

H_b = breaking wave height;

h_t = depth of toe of project;

h_* = depth of closure;

K = Kamphuis longshore sediment transport coefficient;

K_c = empirical coefficient in cross-shore sediment transport model;

L_o = deepwater wavelength;

ℓ_* = distance from depth of toe to depth of closure;

M_c = fraction of the subaerial beach width remaining;

p = exponent in cross-shore sediment transport model;

Q = longshore sediment transport rate;

S = beach slope;

S_i = initial slope of nourished beach;

S_o = native beach slope;

$s.g.$ = sediment specific gravity;

T = wave period;

t = time;

t_{50} = time at which beach slope is halfway between pre- and post-nourishment values;

w = beach width to waterline;

w_t = beach width to toe of beachfill;

x = longshore coordinate;

y = cross-shore coordinate, directed offshore;

z = vertical coordinate;

ΔV = volume of material eroded from the nourished beach due to cross-shore transport per unit length of beach;

θ_b = wave angle at breaking relative to local shore normal;

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Table 1. Wave and geometric parameters used in the beach nourishment experiments. Wave height and period were measured in the horizontal portion of the wave basin. Nominal slope = 1:15 and median grain size, d_{50} = 0.18 mm for the native beach for each experiment.

Experiment Number	Wave Period T (sec)	Median Fill Grain Size d_{50} (mm)	Berm Height B (cm)	Incident Wave Height H (cm)
1	1.2	0.40	8	5.5
2	1.2	0.80	8	5.5
3	1.2	0.40	8	4
4	1.2	0.80	8	4
5	1.2	0.18	5	4
6	1.2	0.80	5	4
7	1	0.40	8	5.5
8	1	0.80	8	5.5
9	1	0.18	8	4
10	1	0.40	8	4
11	1	0.80	8	4
12	1	0.18	5	4
13	1	0.40	5	4

Table 2. Percentage of nourishment material leaving nourished zone (Region A in Figure 2) and moving in cross-shore and longshore directions after ninety minutes of wave action subsequent to beach nourishment.

Experiment Number	**Lost Material (%)**	
	Cross-shore	**Longshore**
1	26	41
2	20	41
3	28	23
4	26	22
5	36	39
6	21	34
7	34	30
8	31	26
9	42	33
10	38	17
11	40	8
12	29	52
13	19	53

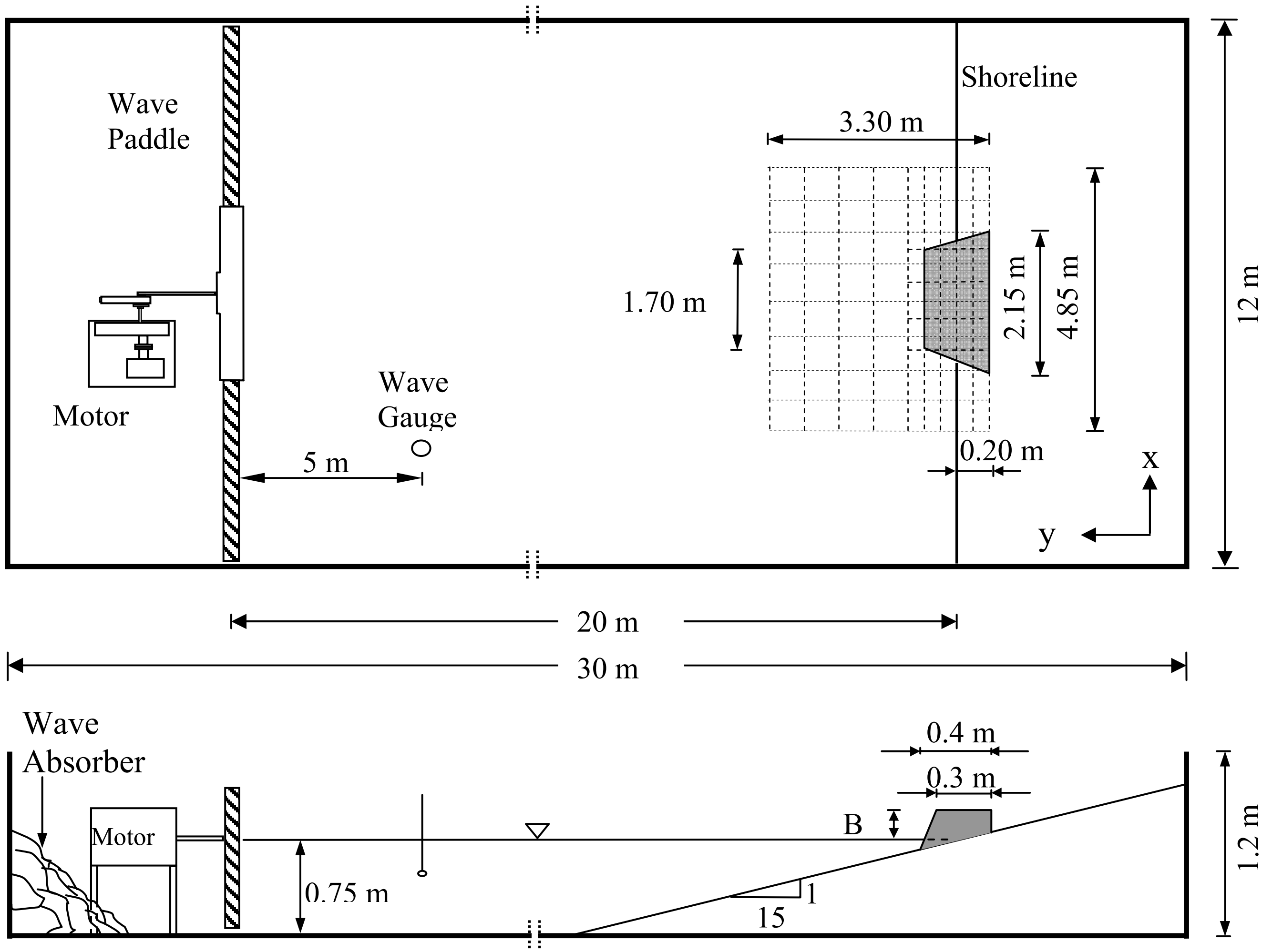

Figure 1. Wave basin geometry (not to scale). Top: Plan view and measurement grid for surveying. Bottom: Cross-sectional view through middle of basin.

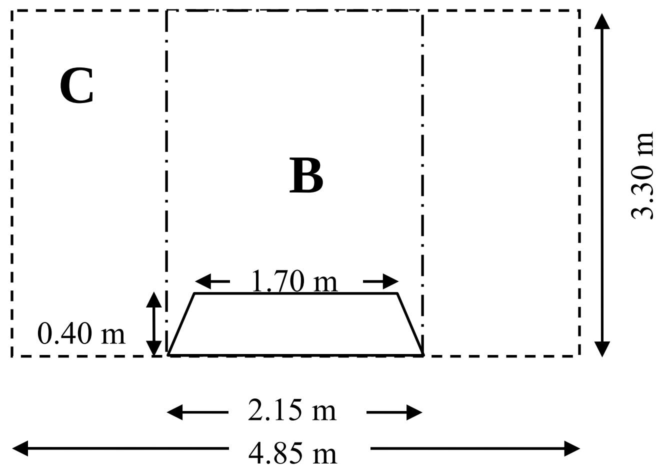

Figure 2. Plan view of Regions A, B and C considered for volumetric analysis of nourished beach behavior.

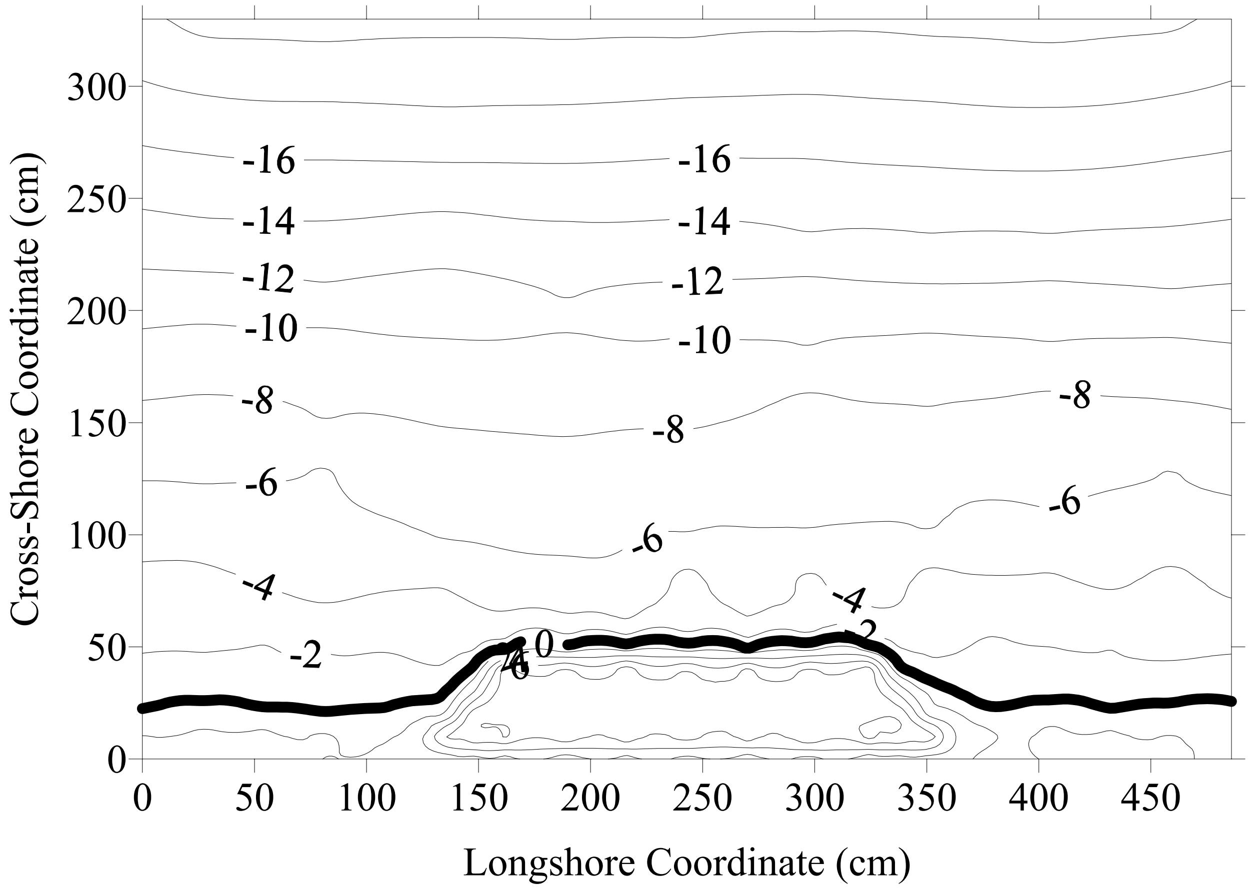

Figure 3. Contour plot of initial bed elevations for Experiment 9 (waterline shown as bold line). Contours in cm at 2 cm intervals. Still water level taken as vertical datum. Water depth at breaking is estimated at 3.3 cm for this case.

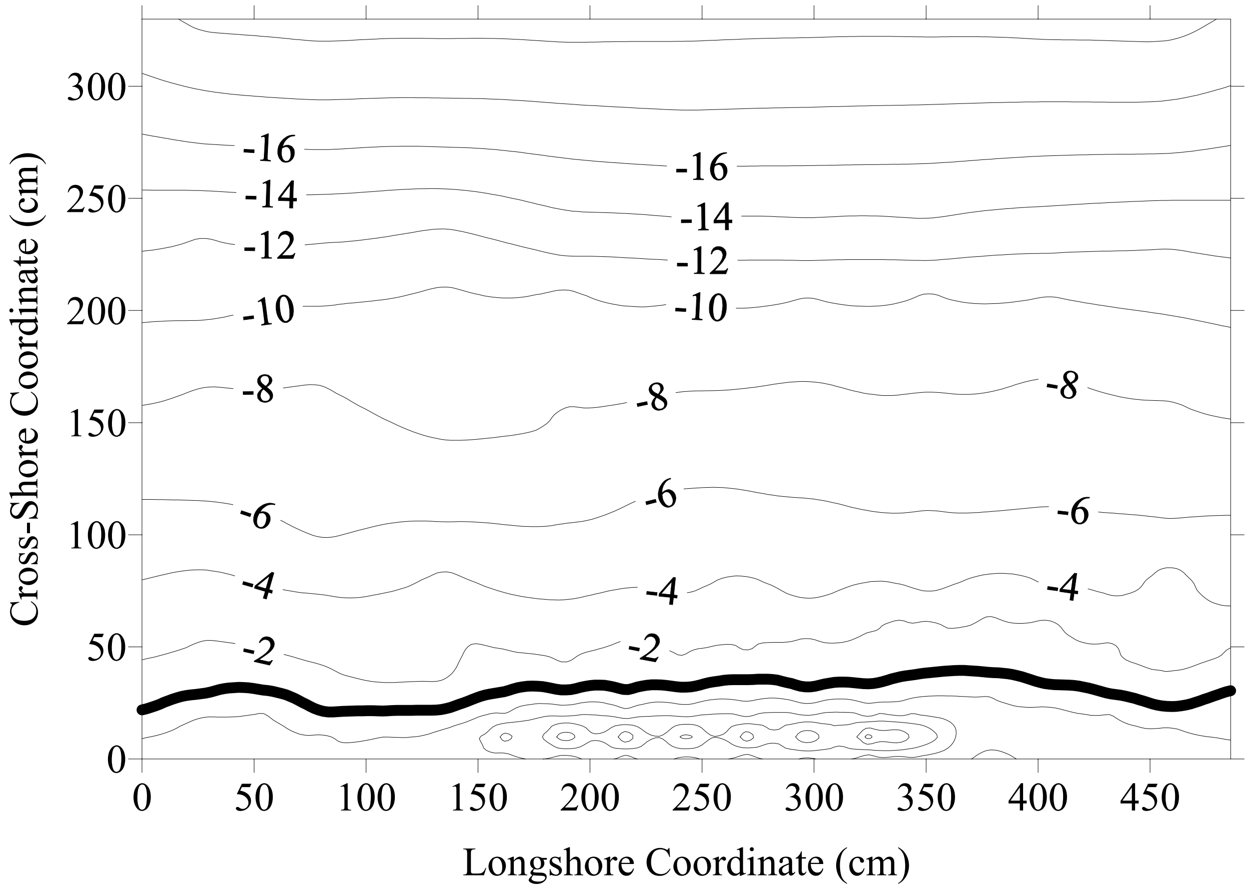

Figure 4. Contour plot of final bed elevations for Experiment 9 (waterline shown as bold line). Contour interval 2 cm and water depth at breaking is estimated at 3.3 cm for this case.

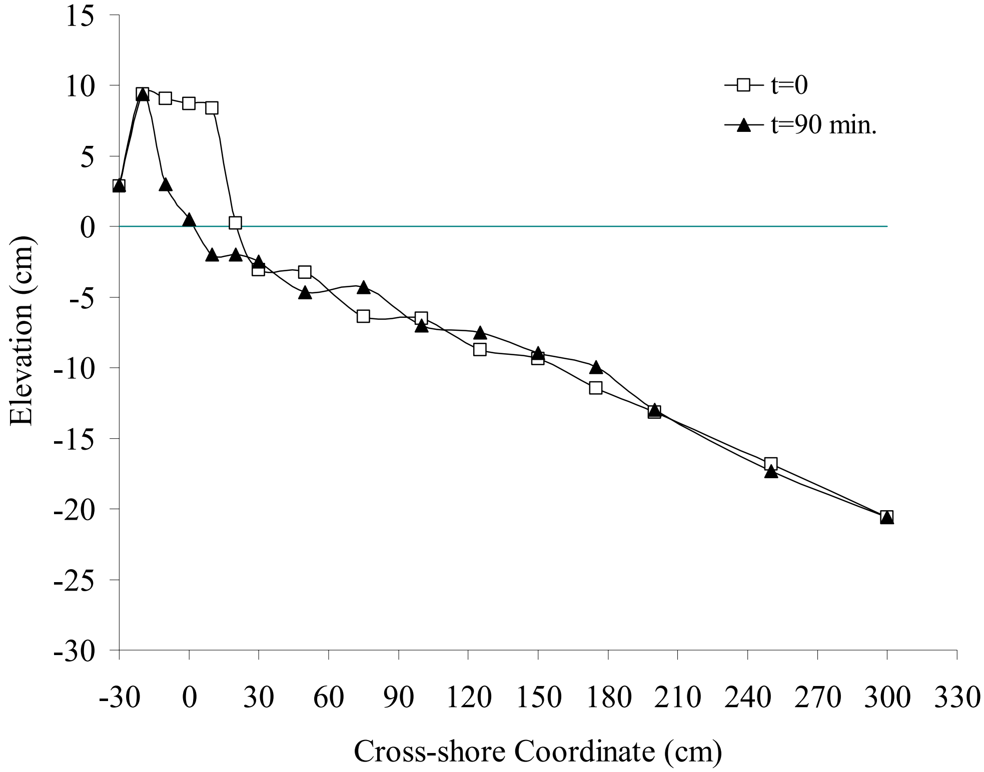

Figure 5. Beach profile evolution at the center (x = 243 cm) of the nourished region for Experiment 9. Water depth at breaking is estimated at 3.3 cm for this case.

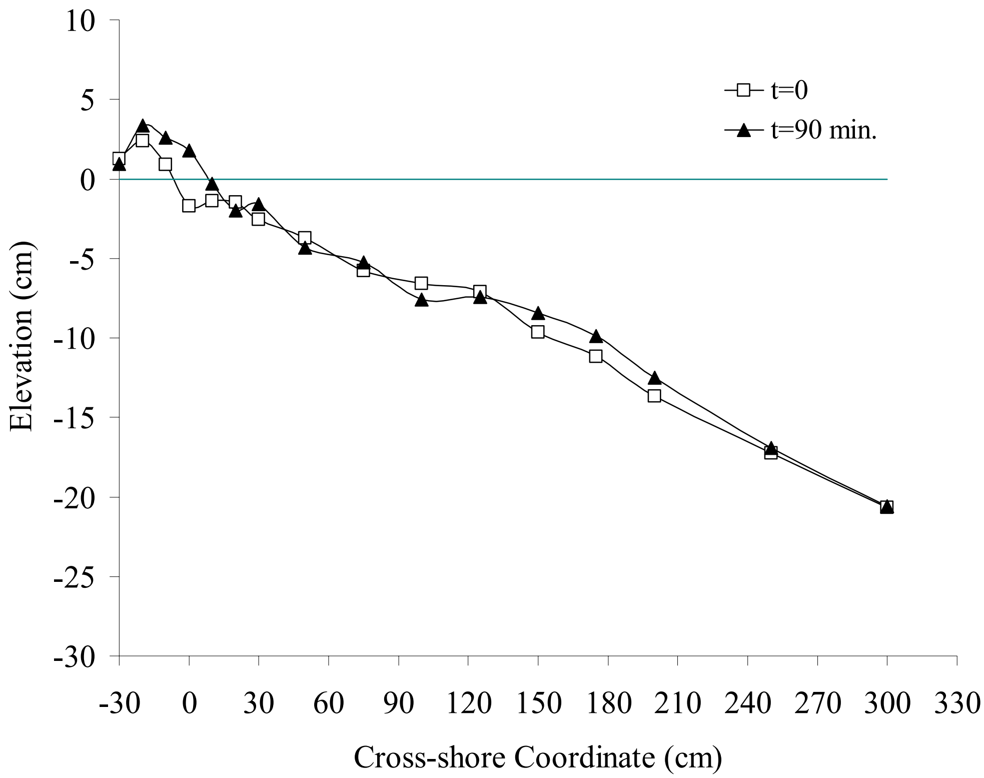

Figure 6. Beach profile evolution 28 cm away (x = 378 cm) from the nourished region for Experiment 9. Water depth at breaking is estimated at 3.3 cm for this case.

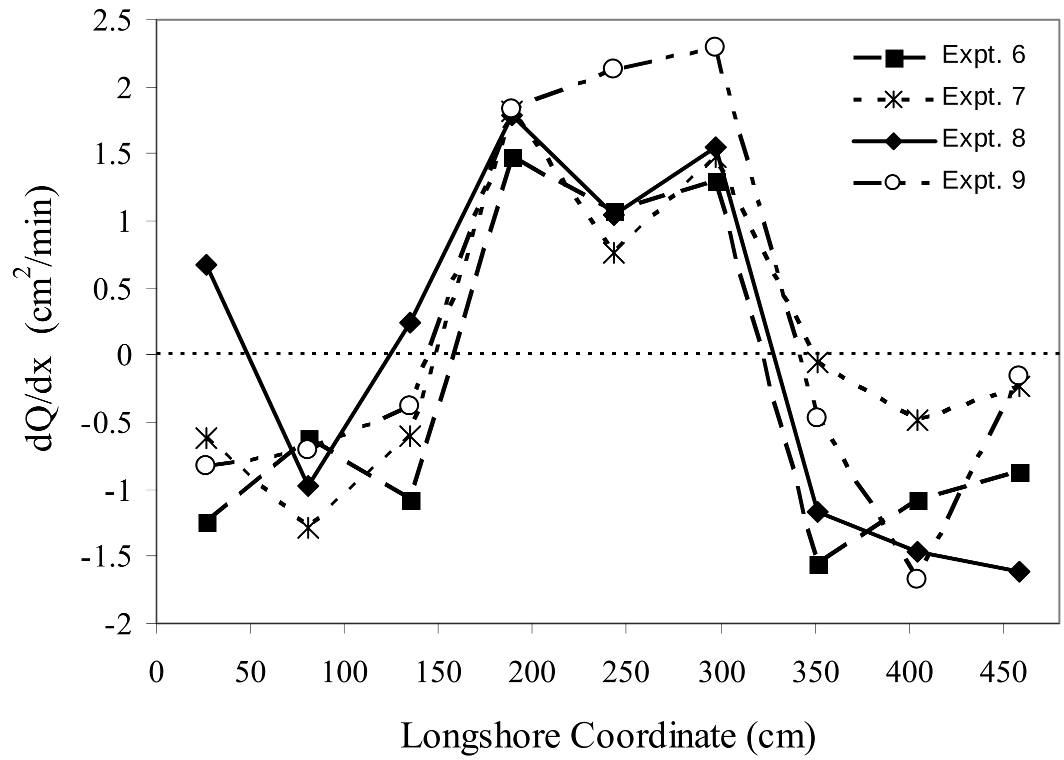

Figure 7. Longshore gradient of longshore sediment transport. Computed from initial (t = 0) and final (t = 90 min) surveys in four experiments.

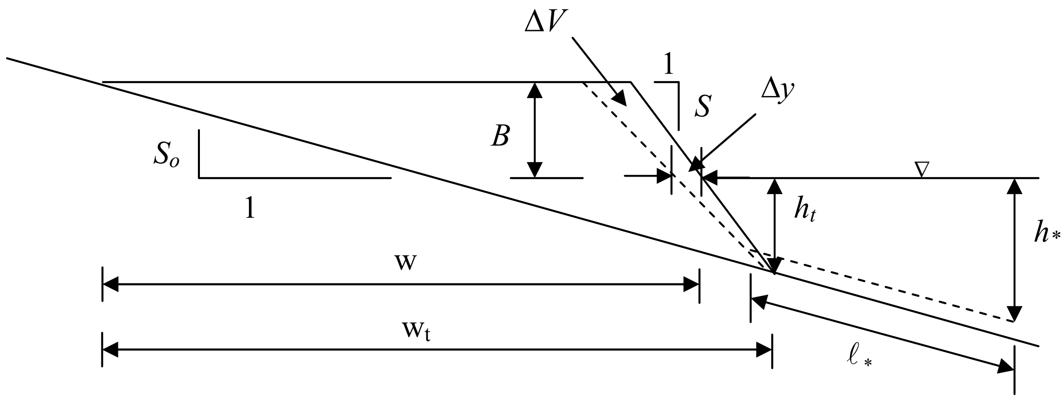

Figure 8. Idealized geometry of beach profile before and after nourishment.

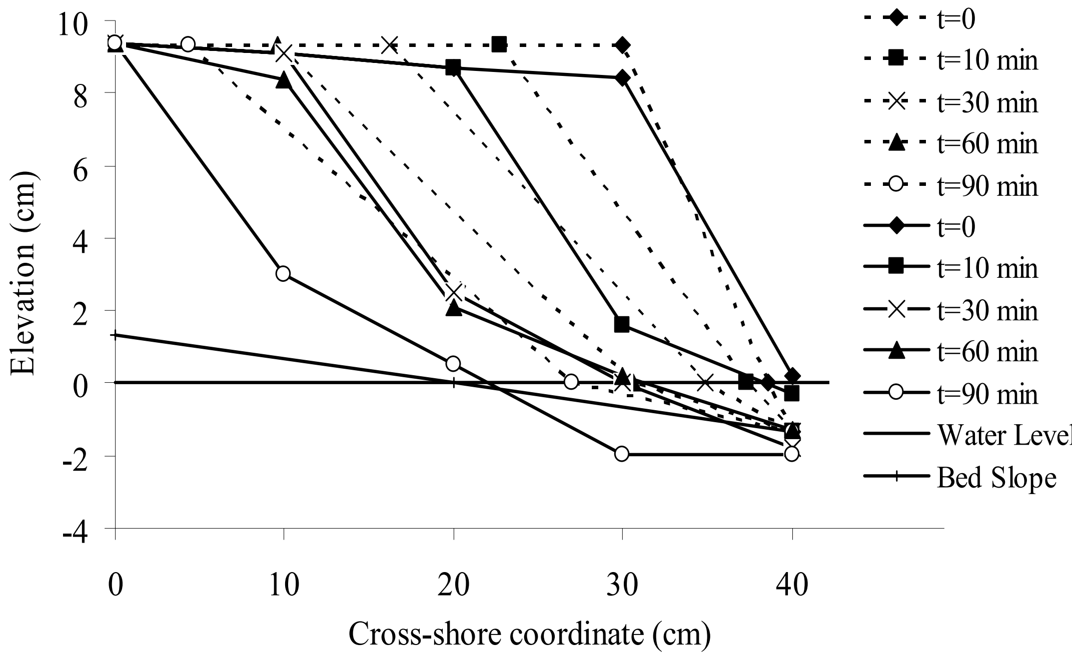

Figure 9. Beach profile evolution as measured in the lab (solid lines) and predicted by the coupled longshore and cross-shore numerical model (dashed lines) for the center of the nourishment project, Experiment 9. Model defines positions of three contours: berm crest, waterline, and toe of beachfill.

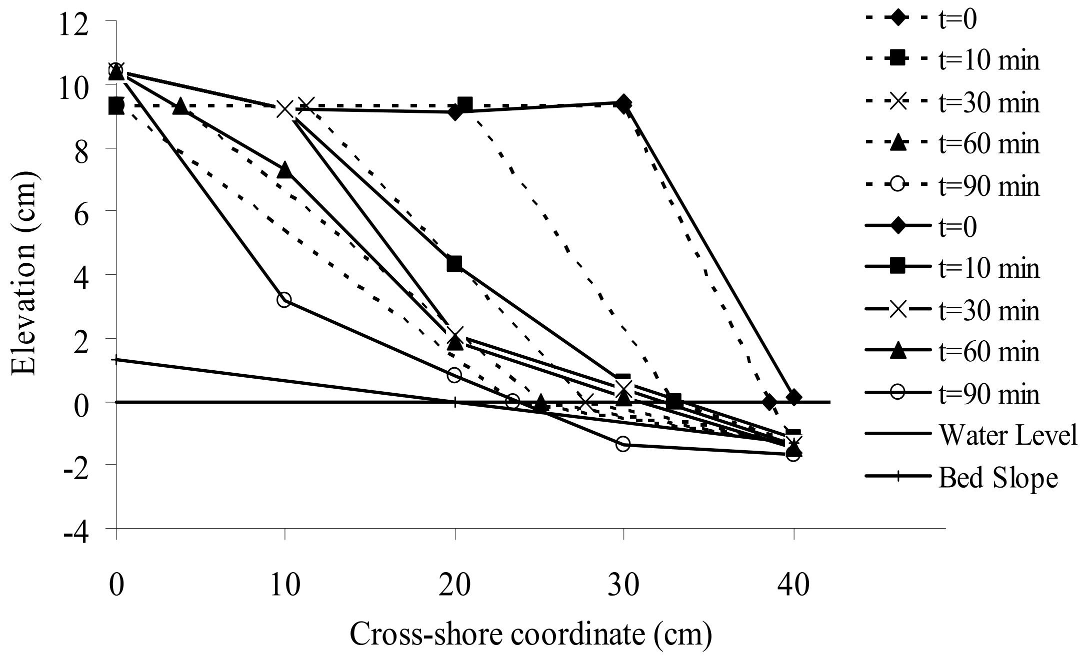

Figure 10. Beach profile evolution as measured in the lab (solid lines) and predicted by the coupled longshore and cross-shore numerical model (dashed lines) near one end of the nourishment project, Experiment 9.

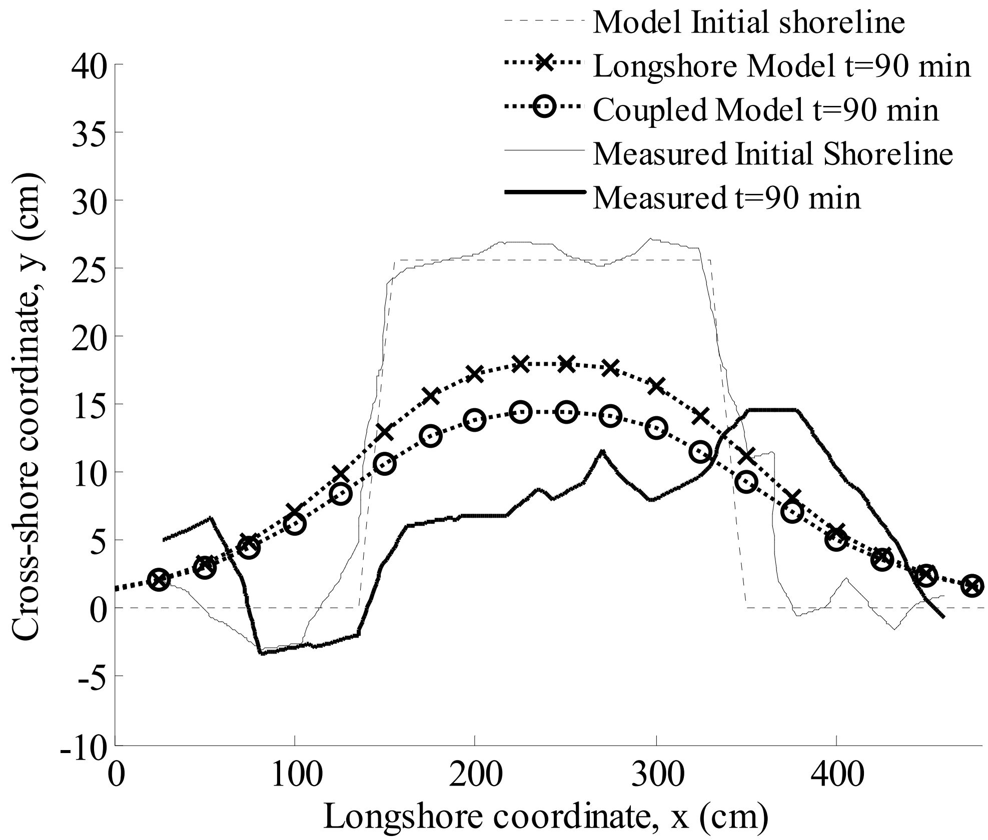

Figure 11. Shoreline evolution as measured in the lab and predicted by the model for Experiment 9. The one-line model result obtained when neglecting cross-shore sediment transport is also shown for comparison.

Figure Captions

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