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CROSS-SHORE NET SEDIMENT TRANSPORT CHANGE TO EQUILIBRIUM: A WAVE TANK STUDY

M. Shah Alam Khan[1]

ABSTRACT: Beach profile evolution tests conducted at different scales in a 90 ft-long wave tank show that after an initial irregular profile change, the equilibrium condition is approached asymptotically in accretionary wave climate. Equilibrium is specified by insignificant temporal changes in the still water line location and average root mean square error between consecutive profiles. These changes exponentially decay to equilibrium. Spatial and temporal variations in the net sediment transport rate expressed in a dimensionless form are similar in all tests. The dimensionless transport rate gradually diminishes offshore from the wave break point, and exponentially decays to equilibrium from the time the initial foreshore slope is established. Transport rate variations are different in four zones where sediment transport processes are significantly different.

KEY WORDS: Net transport, equilibrium, profile evolution.

INTRODUCTION

Cross-shore net sediment transport resulting from onshore- and offshore-directed sediment movement over a wave cycle determines erosion or accretion at a location on the beach. Transport processes and relative magnitude of suspended or bed load transport are different at different locations across the beach. Dean and Dalrymple (2002), Larson and Kraus (1989) and Wang (1985) describe different zones where wave energy levels and transport processes are significantly different. Although sediment transport rate is different in each zone, net transport rate at all points on the beach gradually approaches an equilibrium with the wave climate, giving the profile a characteristic equilibrium shape.

In two-dimensional physical model studies on morphological changes of the beach, equilibrium is visually identified when the profile geometry does not change significantly with time. However, onshore and offshore transport may still occur that balance one another over a wave cycle. Larson (1988) and Larson et al. (1999) found that sediment transport occurs in laboratory experiments even when the profile attains an equilibrium shape. This transport occurs due to unsteadiness in experimental conditions, turbulent fluctuations and random sediment properties while the profile fluctuates about an average shape. In experimental and numerical studies, Kobayashi and Tega (2002) found non-zero net cross-shore transport rates, and a non-zero difference between the time-averaged sand suspension and settling rates at

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[1] Institute of Water and Flood Management, BUET, Dhaka 1000, Bangladesh.

equilibrium. Identification of the equilibrium endpoint and how the beach reaches this equilibrium condition are important considerations in model studies, and may be better understood from results of a series of tests conducted at different scales.

LABORATORY TESTS

Experimental Set-up

Movable-bed experiments were carried out to study transport rate and profile change characteristics in accretionary wave climate. Tests were conducted in a 90 ft-long, 3 ft-wide and 2.5 ft-deep wave tank. Geometric similarity, deep water wave steepness (H_o/L_o), wave Froude number (H/gT^2), densimetric Froude number ($F_* = v_*^2/(\gamma' g D_{50})$), and particle Reynolds number ($R_* = v_* D_{50}/\nu$) were preserved by selecting the same sediment size and density, and the same fluid, where H_o = deep water wave height, L_o = deep water wave length, T = wave period, H = wave height at a specified depth, g = acceleration of gravity, v_* = bed shear velocity, D_{50} = median sediment grain diameter, γ' = relative unit weight of sediment = $(\rho_s - \rho)/\rho$, ρ = fluid density, ρ_s = sediment density, and ν = kinematic viscosity of fluid.

Wave height was measured at four locations outside the offshore end of the beach using parallel-wire resistance gauges while a piston-type wave generator having active wave absorption capability produced sinusoidal waves. Silica sand having a median grain diameter of 0.212 mm was used to build the beach on a permeable frame so that percolation through the beach face simulated the natural groundwater.

Test Description

Each 'test' was conducted in a sequence of several 'runs' until the equilibrium condition was attained. Typical run durations were 20, 30 or 60 minutes. The wave generator operated continuously during a run. Beach profiles were measured with a semi-automatic profiler several times in a test during the interval between runs. Each test started with the same, appropriately scaled, initial profile shape. Wave height, wave period and still water depth were determined from the nominal scale and preserved test properties. Table 1 summarizes the basic variables of the tests.

Table 1. Summary of test variables

Test ID	Duration of wave action (min)	Nominal scale	Wave period, T (sec)	Wave height, H (cm)	Still water depth at wave paddle (cm)
DSTi0_1	578	0.85	2.53	5.00	33.10
DSTi0_3	506	1.00	2.74	5.88	35.85
DSTi0_5	536	0.77	2.41	4.55	27.70

RESULTS AND DISCUSSION

Equilibrium Specification

Equilibrium is specified in two ways, the first when there is no longer any significant horizontal change in the still water line (SWL) location. Fig. 1 shows how the SWL moves with respect to the final SWL toward a mean equilibrium position. While the fraction of total movement approaches zero at equilibrium it decreases offshore as the beach accretes. This change is approximately represented by an exponential trend line fitted to the data.

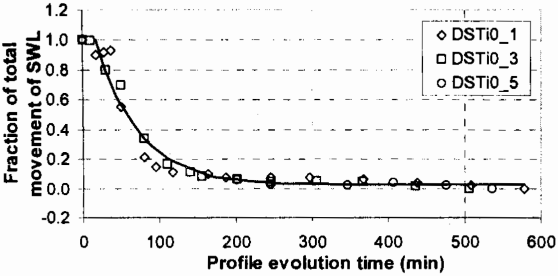


Fig. 1. Movement of still water line (SWL)

The second specification of equilibrium is based on the root mean square error (RMSE) of profile elevations between consecutive profiles. The RMSE is divided by the corresponding run duration so the average RMSE indicates the overall change on a profile during the run. Fig. 2 shows how the average RMSE exponentially decays to a non-zero equilibrium. Although initial changes in the three tests are different, changes at equilibrium are approximately equal. A zero RMSE would be a 'perfect' equilibrium or no profile change with time. At equilibrium, small movements of bed ripples contribute to the RMSE even though the general shape of the profile is unchanged. The change in net transport direction at equilibrium also causes relatively small changes on the profile, contributing to the non-zero RMSE.

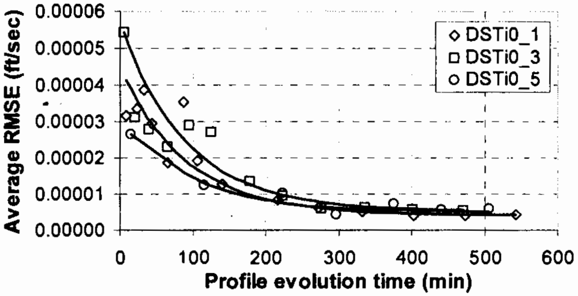


Fig. 2. Variation in average root mean square error (RMSE) between consecutive profiles

Transport Rate Variation

Net transport rate at a point on the beach is calculated from the profile difference before and after a run. An eroded volume contributes to offshore transport and an accreted volume accounts for onshore transport. The volumetric transport rate is converted to a weight transport rate and expressed as the average transport rate for the run at that point. When sand is conserved across the profile, the total onshore and offshore volume changes should be equal, and the cumulative volume change at the two ends of the profile should be zero. However, a non-zero cumulative volume change, or a closure error, at the offshore end results due to offshore losses and beach consolidation. The closure error is distributed proportionately to the local volume changes across the profile.

Dimensionless net transport rate is expressed as $q_{nd} = q/(\rho_s-\rho)gw^2T$, where q = net weight transport rate per unit width and w = fall velocity of sediment particles. Fig. 3 shows cross-shore variation in net transport rate during a run where onshore transport is positive. Fig. 3 also shows the corresponding profiles in dimensionless coordinates x/gT^2 and d/wT, where x = horizontal distance from equilibrium SWL and d = water depth. Transport rates are either a minimum or a maximum where the two profiles cross.

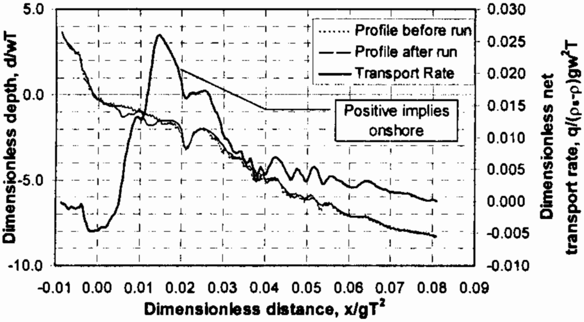
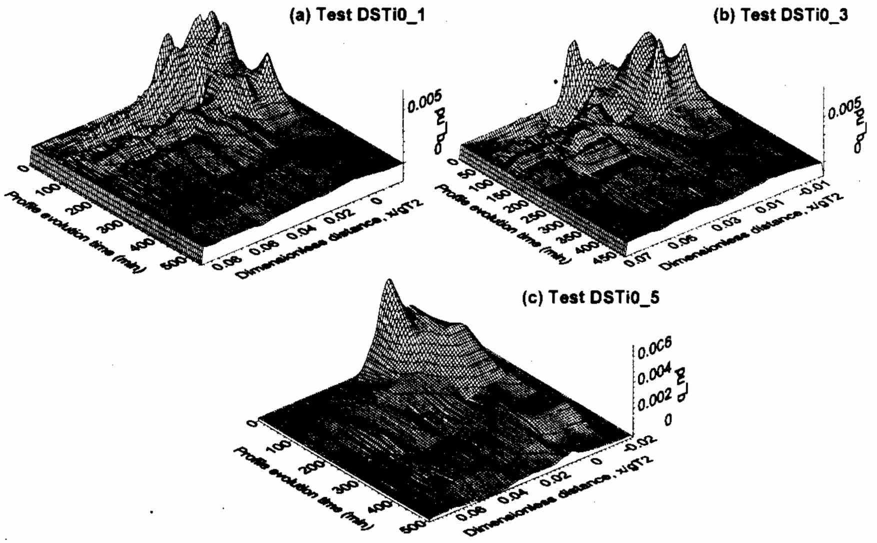


Fig. 3. Variation in net transport rate across the beach

Figure 4 demonstrates spatial and temporal variations in dimensionless net transport rate during the tests. Transport rates are relatively high and irregular initially when the profile is far from equilibrium, and are low as the profile approaches equilibrium. Onshore transport predominates over almost the entire test duration for these accretionary tests. Near equilibrium, the net transport fluctuates between offshore and onshore directions. This fluctuation and relatively low transport determines whether the profile has reached the equilibrium state. In all tests, the dimensionless net transport rate on the beach is within approximately ± 0.0005 at equilibrium.



(a) Test DSTi0_1

(b) Test DSTi0_3

(c) Test DSTi0_5

Fig. 4. Spatial and temporal variation in dimensionless net transport rate

Transport in Different Zones

Figure 5 shows four distinct zones across the beach where sediment transport processes are significantly different. In Zone I, the 'swash zone', transport occurs under oscillatory sheet flow. Broken incident waves propagate up the beach face to the runup limit and return under gravity. Below the SWL, in Zone II, the 'surf zone', the return flow meets the broken incident waves causing intense turbulence at the seaward limit of this zone. The turbulence creates a sharp discontinuity in slope, and suspends a significant amount of sediment. The suspended sediment moves partially onshore with incident waves and partially offshore by return flow or undertow. In Zone III, the 'breaker zone', offshore transport occurs by undertow while breaking waves carry the suspended sediment onshore. Because of the presence of undertow, both bed load and suspended transport are important, the latter dominating. In Zone IV, the 'offshore zone', bed load transport and bottom boundary layer processes are more significant than suspended transport.

Most transport action occurs in Zones I, II, and III while transport rates change asymptotically offshore from a maximum at the wave break point. Figure 6 shows typical temporal changes in net transport rate at a point in each of the four zones. At the beginning of each test, relatively high transport occurs that reaches a peak at about 120 minutes into the test, approximately when the initial foreshore slope is established. During this initial period, relatively fast and irregular profile shape changes are observed. Exponential trend lines fitted to the data after the peak indicate that variation in dimensionless transport rate and time required to attain equilibrium are different in the four zones. Transport rate in Zone IV, the most offshore zone, reaches equilibrium the fastest.

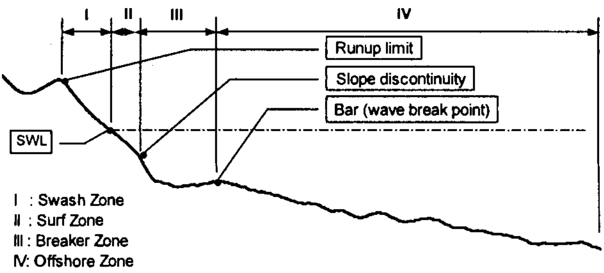


Fig. 5. Zones where transport processes are different

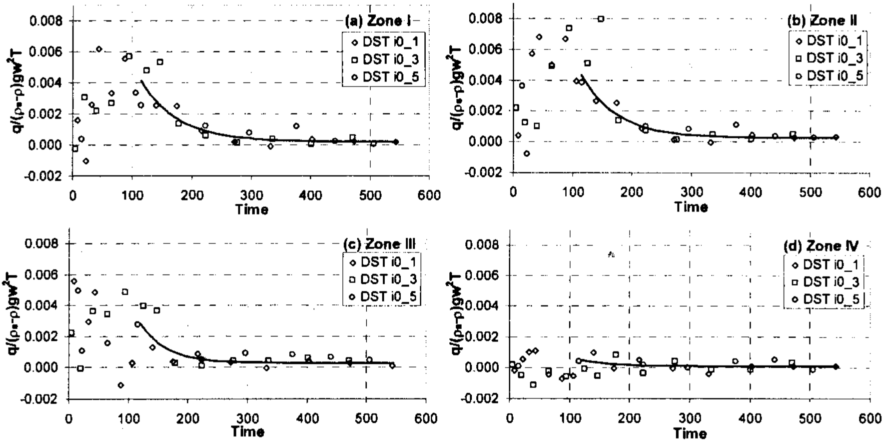


Fig. 6. Temporal variation in net transport rate

CONCLUSION

Beach profile evolution tests were conducted in a 90 ft-long wave tank equipped with a wave generator having active wave absorption capability. Three tests conducted at different scales and with accretionary sinusoidal waves show that the equilibrium condition is attained asymptotically after an initial irregular change of the profile shape. Equilibrium is specified by insignificant changes of the SWL location and average RMSE of elevations between consecutive profiles. Both of these changes exponentially decay to equilibrium.

Dimensionless net transport rate, $q/(\rho_s\text{-}\rho)gw^2T$, provides similar expressions for temporal variations in all tests. At equilibrium, the dimensionless net transport rate at all points on the beach is within approximately ± 0.0005 where positive indicates onshore transport. Net transport rate gradually diminishes offshore from the wave break point, and exponentially decays to equilibrium from the time the initial foreshore slope is formed. Changes to equilibrium are different in four zones where transport processes are significantly different. Further experiments at other scales and with erosive waves are needed to verify the general validity of the exponential trends.

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NOTATIONS

d = Water depth
D_{50} = Median sediment grain diameter
F_* = Densimetric Froude number
g = Acceleration of gravity
H = Wave height at a specified depth
H_o = Deep water wave height
L_o = Deep water wave length
q = Net weight transport rate per unit width
q_{nd} = Dimensionless net transport rate

R_* = Particle Reynolds number
T = Wave period
v_* = Bed shear velocity
w = Fall velocity of sediment particles
x = Horizontal distance from equilibrium still water line
γ' = Relative unit weight of sediment
ν = Kinematic viscosity of fluid
ρ = Density of fluid
ρ_s = Density of sediment

ABBREVIATIONS

RMSE = Root Mean Square Error
SWL = Still Water Line