

CHAPTER 137

THREE DIMENSIONAL MORPHOLOGY IN A NARROW WAVE TANK: MEASUREMENTS AND THEORY

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ABSTRACT

Results are described from movable and fixed bed wave tank tests to examine the characteristics and causes of three dimensional beach profiles occurring in a narrow wave tank. The movable bed tests demonstrated a strongly repeatable sequence in which both the hydrodynamics and sediment transport patterns were two-dimensional over the initial stages of testing; however, after approximately 200 to 240 minutes, a horizontal circulation appeared and strengthened and resulted in a narrow channel incised adjacent to one of the tank walls. This circulation was reminiscent of a rip current system and resulted in a net landward transport of sediment. During the later stages of profile evolution, an equilibrium was reached in which the profile was steeper and the channel adjacent to the wall persisted. The fixed bed tests were conducted to examine, under controlled conditions, the mechanisms and causes of the horizontal circulation. Tests were carried out specifically to examine generation and maintenance mechanisms for rip currents and edge waves. One set of the fixed bed tests induced a jet into the surf zone and examined its interaction with incident waves. The interaction was found to exert a torque which was counter to that of the induced jet and thus would reduce its circulation. Edge wave mechanisms were examined in the second set of fixed bed tests by generating incident waves with the wave period corresponding to the edge wave length equal to twice the width of the tank for various edge wave modes. No indication of edge waves were found in the experiments. It is concluded that the sequence of profile evolution documented in the movable bed model tests is most likely caused by a long term instability and is reminiscent of and may be representative of the beach recovery stages from a storm profile.

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INTRODUCTION

The nearshore coastal zone is characterized by complex hydrodynamic and sediment transport processes. With few exceptions, three-dimensional hydrodynamic flows occur in the natural system that are associated with three-dimensional bathymetry, including beach cusps, rip currents and some bar morphologies. There has been considerable conjecture and debate in the literature as to the formation mechanisms of the three-dimensional morphology in nature and the necessary conditions for their occurrence under laboratory conditions. It is generally considered that experiments conducted in a narrow wave tank will be free of three-dimensional circulation and morphology and this raises the question of how narrow a tank must be to preclude the formation of such features.

Various mechanisms and causes have been advanced for three-dimensional features in nature, including, for beach cusps: edge waves (Komar, 1973 and Guza and Inman, 1975) and instabilities (Werner and Fink, 1993); for rip currents: combinations of edge waves with synchronous incident waves (Bowen, 1969 and Bowen and Inman, 1969), wave current interaction (Dalrymple and Lozano, 1978), instabilities (Hino, 1974) and topographic control (Dalrymple, 1978); for nearshore three-dimensional features: interaction of edge waves with incident waves (Holman and Bowen, 1982).

The motivation for the experiments presented here resulted from tests in which three dimensional hydrodynamics were found to occur. This led to the program described herein in which experiments were conducted to investigate the causes of and mechanisms associated with the three dimensional features.

EXPERIMENTS

The experiments were conducted in both movable and fixed bed wave tank facilities.

Movable Bed Experiments

All experiments commenced from an initially planar beach with 1:18 slope. The tank is 15.5 m long, 0.9 m high and 0.6 m wide. The median sand size was 0.21 mm with a sorting coefficient of 0.58 and a fall velocity of approximately 2.3 cm/sec. The water depth in the horizontal portion of the wave tank was 0.275 m. Regular waves with a height of 0.11 m and a period of 1.5 sec were used. Profile evolution was documented by three lines measured along the tank centerline and at quarter points across the tank width. The profiles were measured manually with a point gage and are denoted, B1, B2 and B3 with B2 being located along the tank centerline. A total of six experiments was conducted with the conditions summarized in Table 1. The experiments are referred to as: (1) Reference Test (Experiment MT01), (2) Repeat Tests (Experiments MT02 and

Table 1

Movable Bed Experiment Conditions and Objectives

Exp. No.	Duration (min)	Water Table Level (cm)	Objectives
MT01	0-476	0.0	Reference Test
MT02	0-407	0.0	Repeatability Test
MT03	0-545	0.0	Repeatability Test
MT04	0-821	0.0	Perturbations in Bar Topography
	(0-69)	0.0	(No Change)
	(69-138)	0.0	(Bar Trough Deepened)
	(138-352)	0.0	(Asymmetric Offshore Scour Area)
	(352-821)	0.0	(Half of Bar Crest Removed)
MT05	0-1166	+11.0	Initially 3-D Berm. Elevated Water Table Level
MT06	0-1166	+16.5	Higher Water Table

MT03), and (3) Perturbation Tests (Experiments MT04, MT05, and MT06); results are presented below.

Experiments MT01, MT02 and MT03 - These experiments were all conducted with the same general conditions and the results were approximately the same confirming the general repeatability of the tests. A bar formed rapidly as shown in Figure 1. At times ranging from 210 to 270 minutes, the profile appeared to become stable. However, soon after this time, a weak horizontal circulation appeared in the tank. The circulation became stronger and a depth variation across the tank was soon evident with a narrow channel approximately 5 cm deeper than the adjacent bathymetry through the bar on the tank side with the seaward flowing currents. At this stage, the horizontal circulation was quite reminiscent of a rip current cell in nature. The morphological response to this horizontal circulation was quite surprising. It was expected that the horizontal circulation would result in a net seaward transport of sediment; however, the contrary happened. Substantial landward transport occurred with a considerable portion of the material originating from seaward of the bar. As summarized in Figure 2 for Experiment MT03, the bar moved landward during the later times

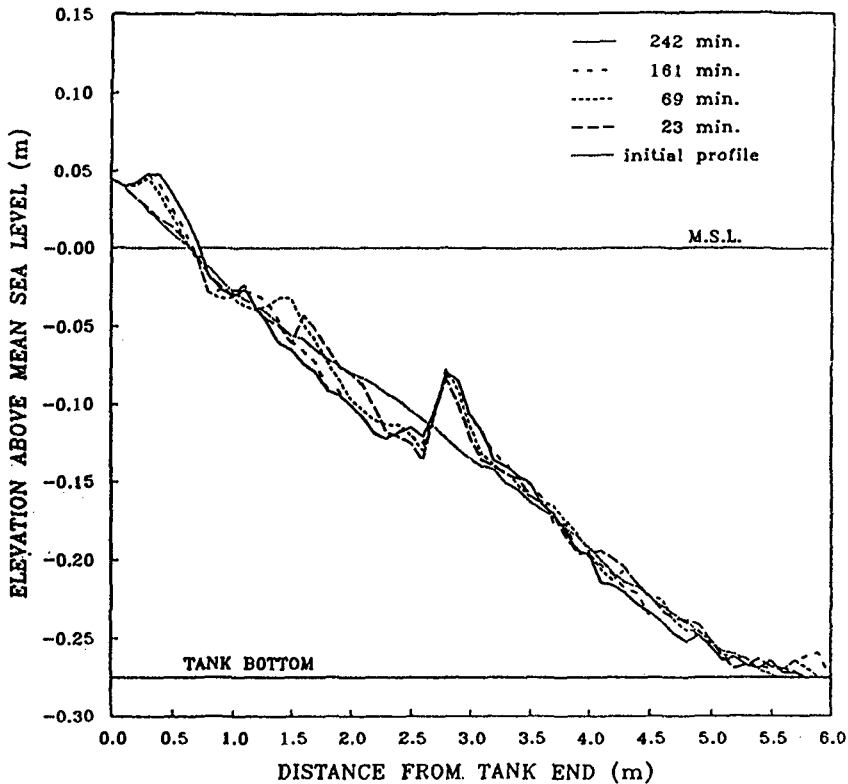


Figure 1. Mean profile evolution during early stages of Experiment MT01. Elapsed times = 0, 23, 69, 161, and 242 minutes. Note that the profile approached an equilibrium at 242 minutes.

of the experiment and the beach built seaward. At this time, the profile was essentially two-dimensional except for a narrow channel at one side of the wave tank. The remaining experiments in the movable bed tests were conducted to attempt to clarify the causes and mechanisms associated with the results, especially the circulation and transport patterns.

Experiment MT04 - In an attempt to clarify the processes, perturbations were introduced artificially into the morphology to observe the response. The experiment commenced as for the three experiments described earlier and the profile evolution was approximately the same. At a time of 70 minutes, a two-dimensional perturbation to the profile was induced by deepening the bar trough by approximately 4 cm with the sand placed seaward of the bar. The run was then recommenced and it was found that by 140 minutes, the profile had essentially returned to the pre-modification conditions. After 140 minutes, the seaward area

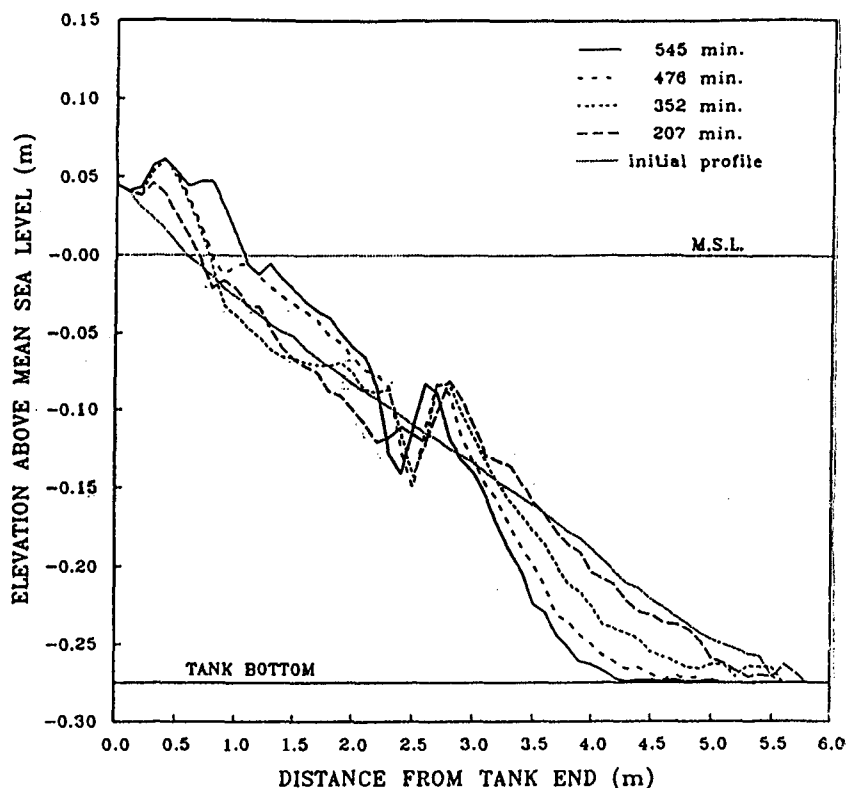


Figure 2. Mean profile evolution during Experiment MT03. Elapsed times = 0, 207, 352, 476 and 545 minutes. Note rapid change during 476 to 545 minutes with the landward movement of the bar and advancement of the beach face.

of the bar was intentionally modified from a two-dimensional to a three-dimensional area with approximately the same mean profile as before. It was expected that this modification would change the breaking and circulation characteristics over the bar region. Weak horizontal circulation occurred in the wave tank and was reinforced by a sedimentary feedback. This reinforced three-dimensional circulation transported sands from the higher perturbed area to the area immediately landward of the bar trough, and from there to the lower perturbed area seaward of the bar, resulting in a return to the pre-modified two-dimensional area at a time of 210 minutes. However, during this time, the three-dimensional flow remained too weak to cause onshore sand transport from the area seaward of the bar; hence, the profile remained nearly stable until 300 minutes at which time the bar had rotated by approximately 20 degrees. Here it is worthwhile to note that the circulation direction varied from experiment to experiment. The horizontal circulation strengthened from 300 minutes to 350

minutes and a three-dimensionality in the profile and a net onshore sand transport commenced. At 350 minutes, half of the bar crest was removed from the side of the tank with the channel present and this material was placed in the landward trough, resulting in a monotonic profile over one-half the tank width. This perturbation reinforced the three-dimensional morphology which had appeared in the tank. Within an hour, the morphology returned to its pre-perturbation condition. No additional perturbations were imposed during this experiment. During the remainder of the run, the subsequent profile evolution was approximately the same as in the three experiments described earlier. Sand was transported landward and the profile became nearly two-dimensional with the exception of a fairly deep channel adjacent to one of the side walls.

Experiment MT05 - Experiment MT05 differed from earlier tests in that a constant water level of +11.0 cm was maintained in the berm and the tests commenced with a cross-tank perturbation in the beach face of approximately 4 cm vertically. The elevated water table in the berm was maintained by a siphon and weir arrangement from an excavation in the berm. The reader is referred to Oh (1994) for the details. The perturbed beach face returned to two-dimensionality within the first 23 minutes. During the remainder of the testing, it was found that the evolution was surprisingly similar to those of previous tests, including the appearance of horizontal circulation between 210 and 240 minutes, bar rotation and landward transport of sand, and formation of a fairly deep (6 cm relative to the adjacent bottom) channel adjacent to one side wall. This experiment was extended to 1028 minutes and the profile stabilized at nearly two-dimensional conditions with relative minor seaward and landward oscillations of the bar position. No substantial effect of the elevated water table was evident which led to a decision to investigate this effect further in Experiment MT06.

Experiment MT06 - The berm water table level was maintained at + 16.5 cm in this experiment. One difference between this and previous experiments was that there was some indication that the higher water table accelerated the sequence found in previous experiments. Additionally, it appeared that the higher water table may have resulted a somewhat milder equilibrium profile slope.

Summary of Movable Bed Model Tests - Taken in their aggregate, the six movable bed model tests demonstrated a repeatable sequence as follows. During the initial stages, a two-dimensional bar formed that was stable against induced perturbations. After approximately 240 to 300 minutes a weak horizontal circulation commenced and strengthened gradually. This circulation, reminiscent of a rip current circulation, caused rotation of the bar and a relatively deep channel to be incised adjacent to one of the tank side walls. Associated with the horizontal circulation was a net landward transport of sediment, an advancement of the shoreline and a steepening of the profile. During the later stages of testing, the profile was reasonably two-dimensional except for the channel adjacent to one side of the wave tank. Finally, the only noticeable effects of elevated water tables

in the berm were to cause a slightly increased rate at which the sequence of profile evolution occurred and a possibly somewhat milder equilibrium profile slope.

Fixed Bed Model Tests

The purpose of the fixed bed model tests was to investigate possible causes and mechanisms of known three-dimensional surf zone phenomena. Specifically, experiments were conducted to clarify the role of wave-current interaction versus wave sediment interaction in the observed rip currents and to determine whether edge waves were likely to have been caused in the movable bed model tests by periodic waves. The fixed bed wave tank is 20 m long, 0.6 m wide, and 1.5 m high and has a uniform slope of 1:20.

Rip Current Tests - One of the rip current theories is that the incident waves provide a reinforcing mechanism, eg. Dalrymple and Lozano (1978). Other investigators (LeBlond and Tang, 1974) have concluded that this interaction would be negative. Bowen (1969) and Bowen and Inman (1969) have attributed the cause of rip currents to the interaction of synchronous incident and edge waves. Hino (1974) has suggested an instability mechanism. A thorough review of rip current mechanisms has been provided by Dalrymple (1978).

A jet with discharge distributed over the water depth was directed into the surf zone as shown in planform in Figure 3. Two current strengths and wave heights were tested. Two approaches were followed to investigate the interaction of waves and currents. The first was direct and consisted of suspending a freely rotating spindle with eight vanes into the surf zone and monitoring its rotations by video. This apparatus will be referred to as a "vorticity meter" in the following discussion and is shown as "V. M." in Figure 3. Results of these tests are shown in Figure 4 in which the rotation under various sequences and combinations of waves and currents are presented. Test F101 involved only the jet and it can be seen that the vorticity meter rotated in a counterclockwise direction at a fairly constant rate. Test F102 involved only waves and there was essentially no rotation. For Test F103, the jet was operated continuously and the wavemaker was activated from $t=60$ sec to $t=130$ sec. It is seen that during the time that the waves affected the nearshore system, there was a counter rotation of the vorticity meter (the cumulative rotation changed from a negative to positive slope). After cessation of the waves, the vorticity meter commenced rotating in a counter clockwise direction at the same rate as prior to wave commencement. In the initial stages of Test F104, waves were operated alone during which no rotation of the vorticity meter occurred. After a time, the current was started and the vorticity meter rotated in accordance with the jet induced momentum. Later still in this experiment, the jet was stopped and the rotation ceased.

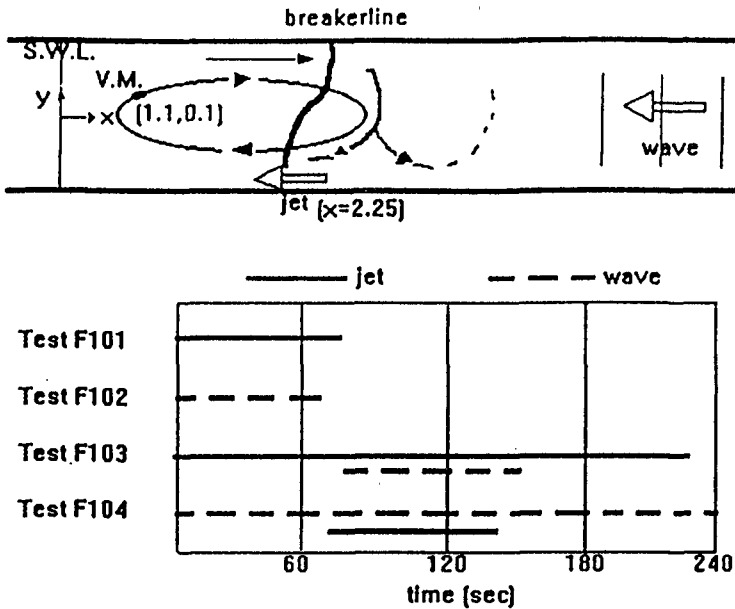


Figure 3. Schematic diagram of the vorticity measurement tests with a description of conditions for each test.

The second approach to documenting and interpreting the interaction of the waves and induced currents was through measurement of the wave height and direction fields. An example of the wave height field for the presence of the jet and a 9 cm wave height is shown in Figure 5. It is seen as expected that the wave height was enhanced in the vicinity of the seaward flowing current. The radiation stresses associated with the larger wave heights are believed to be responsible for the tendency of the waves to reduce the circulation induced by the jet. In addition to wave heights, wave crest orientations were documented by video, but are not presented here. The wave height and direction fields were used in conjunction with the mean vorticity equations to examine the driving torque due to the interaction. Due to space limitations, these equations will not be presented here; however, it was found, consistent with the vorticity meter results, that the interaction of the waves and currents exerted a torque that was counter to the induced current.

Edge Wave Tests - Experiments were conducted to evaluate the effects of edge waves by generating incident waves of the period associated with an edge wave length, L_r , of twice the width of the tank,

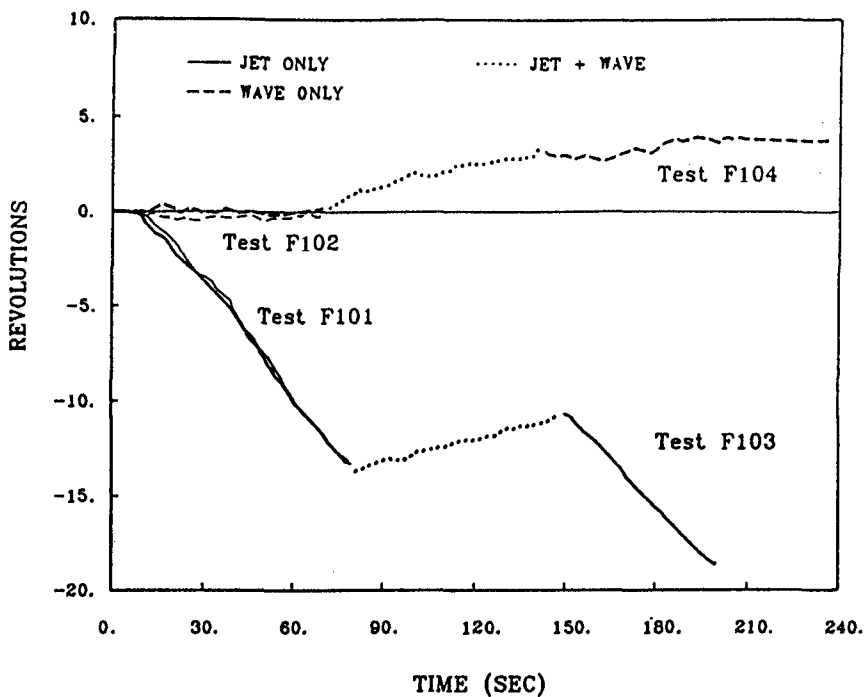


Figure 4. Cumulative rotation at a point within the surf zone as influenced by the jet and waves. Positive rotation corresponds to a counter-clockwise rotation of the vorticity meter.

$$T = \sqrt{\frac{2\pi L_r}{g \sin[(2n+1)\beta]}}$$

where g is gravity, β is the uniform beach slope and n is the mode of the edge waves. For the tank width of 0.6 m, the periods tested are given in Table 2.

Table 2

Required Incident Wave Periods for Synchronous Edge Wave Generation

n	0	1	2	3	4	5	6	7	8	9	10
T (sec)	3.92	2.27	1.76	1.50	1.33	1.21	1.13	1.06	1.01	0.97	0.94

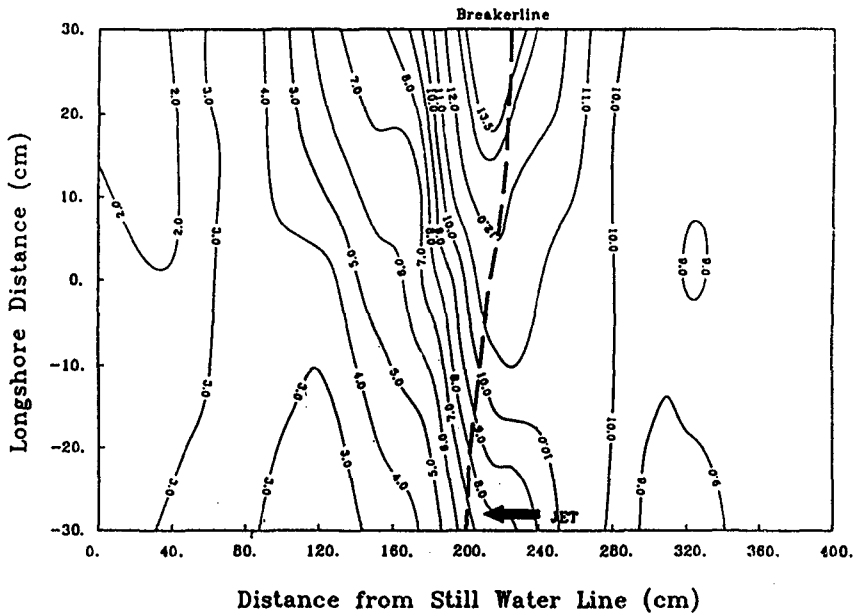


Figure 5. Wave height distribution in the presence of a jet-induced current when $H_0 = 9$ cm (Test F222). Wave heights are in cm. Note higher wave heights due to both refraction by current and wave-current interaction.

During these tests, the wave height was set to result in both surging and plunging breaking conditions. Initially, a smaller wave height causing surging breaking wave conditions was generated and continued for ten minutes while the wave tank was monitored visually for edge waves. After ten minutes the wave height was increased such that plunging breaking wave conditions occurred and the run was extended for an additional ten minutes. During all these experiments, no evidence of edge waves was observed.

INTERPRETATION

The results of the tests requiring interpretation are: (1) The onset of the three-dimensional circulation after the profiles had reached a state of quasi-stability and (2) The onshore transport of sediment by the circulation that was reminiscent of a rip current. Prior to offering an interpretation, it is worthwhile to note the strong repeatability of the experiments and that the fixed bed tests demonstrated that interaction of waves and induced circulation tended to reduce the circulation rather than reinforce it. Additionally, the direction of the induced circulation varied from experiment to experiment. At any time, there are forces that tend to incise channels through the bar and other processes that tend to fill in any lower portions of the bar. The stability of the two-dimensional nature of

the profile for the early stages of the evolution from an initially planar form is believed to be due to the fact that the sand is quite mobile during this time and thus any increase in depth over the bar is rapidly filled by the available sand due to its high mobility. After some time, the profile approaches a quasi-equilibrium state and the sand is less in transit and becomes more consolidated and less mobile. On a subaerial beach, this transition from a poorly consolidated condition to a more consolidated condition is evident when, for a number of hours after accretion of a beach, the pressure due to walking will result in a depression of a centimeter or so into the beach surface. Later, after the waves have consolidated the surface, the sand is less mobile and deforms less in response to surface pressures. Returning to the wave tank results, after the material on the profile surface becomes less mobile, a local deepening of the bar will not be filled in so readily due to less material being readily available for this process. Since the local depression is more efficient hydraulically, the channel deepens gradually until a depth is reached which both relieves the mass transport within the surf zone and results in side slopes that preclude further deepening. With a substantial portion of the mass transport return flow now occurring through the deepened channel, the seaward forces that were present over the bar due to the return flow are reduced resulting in a predominance of the onshore transport processes and the occurrence of a net landward sediment transport, an advancement of the shoreline and deepening of the portions of the profile seaward of the bar. This mechanism is very similar to that of shoreline recovery through ridge and runnel systems and associated breaks in the bar through which the return flow (rip currents) of the mass transport occurs.

SUMMARY AND CONCLUSIONS

Both movable and fixed bed wave tank tests were conducted to investigate beach profile evolution and the causative hydrodynamic mechanisms. The movable bed experiments demonstrated a repeatable sequence in which, starting from a planar bed, an offshore bar was formed and the profile appeared to approach a quasi-stable two-dimensional form after approximately 200 to 240 minutes. Following this initial stage, a weak three-dimensional circulation appeared and increased in strength causing the bar to rotate. A narrow and relatively deep channel developed adjacent to one of the side walls as a result of this circulation which is reminiscent of a rip current system. The circulation caused substantial net onshore sediment transport and resulted in significant shoreline advancement. During two of the movable bed model tests, the profile was intentionally perturbed and the processes resulted in the profile soon being returned to the form consistent with the evolutionary time without the perturbation. Effects of increased water table elevation were small and resulted in somewhat smaller evolutionary time scales and possibly a milder equilibrium beach slope.

Fixed bed tests were conducted to investigate possible mechanisms that could cause the horizontal circulation experienced. It was found that the interaction of incoming waves with an incoming jet exerted a torque counter to and thus would suppress the circulation by the jet induced circulation. Additionally, experiments especially configured to excite synchronous edge waves were not successful leading to the conclusion that edge waves were not important in driving the circulatory system.

It is concluded on a preliminary basis that the evolution observed, including the appearance of three-dimensional circulation and the associated transport are relevant to the transformation of a two-dimensional bar system in nature to a three-dimensional form and the subsequent migration of the bar to the shoreline and its recovery. The instability mechanism proposed by Hino (1974) is supported by the experiments. If further testing confirms the mechanisms identified in these experiments, a substantial contribution to the clarification of the physics of the nearshore zone will have resulted.

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