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Laboratory Studies on Three-Dimensional Morphology in a Narrow Wave Tank
3次元 海底地形變換에 關한 造波 水槽에서의 實驗的 研究

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Abstract: When conducting movable bed tests in a narrow wave tank, the hydrodynamics and morphology are assumed to be two-dimensional; hence, any three-dimensional patterns such as cross-tank variations of the profiles are neglected or averaged to represent the mean profiles at the measuring time. In this paper, six movable bed tests were carried out with a fairly fine sand to investigate (1) whether or not three-dimensional features can occur in relatively narrow wave tanks, and (2) various possible interrelationships and causes of the three-dimensionality. These movable bed studies suggested that there was a relatively slow feedback between the hydrodynamics and the morphology that led to initiation and growth of 3-D *morphological features*, resulting in cross-tank profile variations under certain stages of profile development, especially when the profile approached an equilibrium with overall stability.

要 旨: 幅이 좁은 造波 水槽에서 海底地形變換에 對한 移動床實驗을 遂行할 때, 流體力과 海底地形變換은 波進行 方向으로의 2次元 平面內에 한하는 것으로 假定된다. 그러므로 海底地形의 水槽內 幅 方向으로의 變換등 3次元的인 形狀등은 대체로 無視되거나 또는 計測時의 平均地形등으로 代表된다. 本 研究에서는 상당히 微細한 土沙로 이루어진 海底地形變換에 對한 移動狀實驗을 通하여 (1) 相對的으로 幅이 좁은 水槽內에서 3次元 現象이 發生할 수 있는 지의 與否 및 (2) 3次元 現象 發生에 대한 여러가지 原因 및 그들의 相關 關係등을 調査하였다. 그 結果 流體力과 海底地形變換間에 서서히 發生하는 相互 干涉(slow feedback)을 通하여 海底地形의 水槽內 幅 方向으로의 變換등 3次元的인 形狀등이 發生 成長되며, 위 現象은 海底地形이 그 變換段階에 있어 平衡狀態(equilibrium)에 接近할 때 쉽게 發生한다는 것을 알게 되었다.

1. INTRODUCTION

When conducting movable bed tests in a narrow wave tank, it is usually assumed that the hydrodynamics and morphology are two-dimensional (2-D). Both water and sand particles are considered to remain within the plane of motion and to move horizontally back-and-forth only. Hence, any three-dimensional (3-D) patterns such as horizontal circulation of the water and/or cross-tank variations of the profiles are considered as 'errors' or extraneous features in the experiments and subsequently have not been documented extensively. However, several investigators have reported various degrees of 3-D morphologies in relatively narrow wave tanks (e.g., Bagnold, 1940; Beach Erosion Board, 1947; Kriebel *et al.*, 1986; Hughes and Fowler, 1990, etc.).

Through a series of narrow wave tank experiments and with very careful observations, Bagnold (1940) first observed noticeable 3-D circular water motions and resulting profile changes over the beach face. With coarser material like shingle, Bagnold observed that a 2-D beach was always formed with a straight shoreline parallel to the wave crests.

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When more material was added on one side of the tank, this soon became distributed evenly over the width of the mobile portion of the beach. With finer sands, however, 3-D beach face and resulting circular sweeping motion of the water were observed with sands always deposited on one side or the other side of the tank over the beach face. Bagnold found that the slope of sand deposition was 14 degrees and the other side of the tank, where there was no deposition, retained 5 degrees slope. It should be noted that the tank used in Bagnold's experiment was only 0.53 m wide.

Three-dimensional morphology in 2-D wave tank tests were also observed in earlier tests by the Beach Erosion Board (BEB, 1947). The experiments were conducted in a tank approximately 26 m long, 4.3 m wide and 1.2 m deep, and with a deep water wave height of 11.6 cm; hence, the experiments could be considered as 3-D since the ratio of the tank width to the wave height would suggest that the experiments were carried out in a relatively wide tank. Even though BEB considered the experiments as 2-D, BEB measured five profiles across the tank to account for observable three-dimensionality during the experiments and averaged to represent the mean profiles at the measuring time. Although BEB did not document those profiles, they presented photographs which clearly exhibited 3-D morphology.

During the investigation of vertical velocity profiles, Russel and Osorio (1958) stated; "It is probable however that the velocities would be disordered by circulations in a horizontal plane, if the waves were not confined to a narrow channel" (p. 183). Bagnold (1963) has observed when the channel width in Russel and Osorio's experiments exceeded a certain multiple of the water depth, that the wave drift along the bed, which was otherwise uniform across in channel section, showd signs of instability, becoming greater on one side than on the other. Bagnold suggested that in wider channels, horizontal circulation would appear and a random scattering of sediment would tend to be superimposed upon a smaller forward drift, which might result in 3-D morphology.

During the small-scale laboratory experiments, [illegible] et al. (1986) first noted 3-D cross-tank varia-

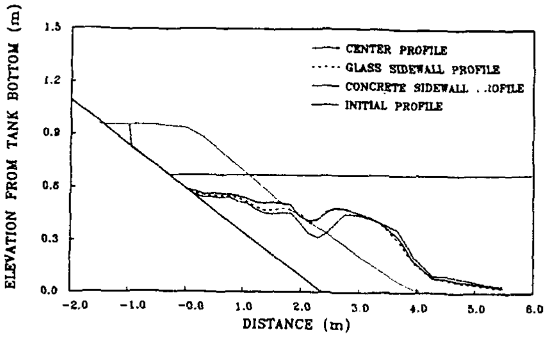

Fig. 1. Cross-Tank Variations of the Profiles after 1 hour Wave Run (modified from Hughes and Fowler, 1990). Note 3-D morphology inside the surf zone and near the bar area.

tions of the profiles over the entire surf zone, noticeable in the seeming lack of volume closure in several of the profiles. Hence, Kriebel *et al.* took several profiles across the tank and averaged to represent mean profiles. The tank used was approximately 30 m long, 1.3 m deep, and 0.9 m wide.

From a series of 2-D laboratory tests in a wave tank of 1.83 m width, Hughes and Fowler (1990) observed that noticeable cross-tank variations occurred after the profile reached a quasi-equilibrium condition and documented these variations by measuring three profiles across the tank, as shown in Fig. 1 which were measured after 1650 waves (equivalent to 1 hour wave run) in their experiment T03.

It was thought that these cross-tank variations have been caused by a small misalignment of the revetment in the flume which in turn caused reflection of waves from the exposed concrete revetment since similar variations were not present in the prototype scale tests of Dette and Uliczka (1986). However, Hughes and Fowler described that these variations did not materialize until after the profile was close to an equilibrium, which might indicate that the profile was more susceptible to cross tank perturbations when the profile had reached a quasi-equilibrium state. If the profile was not close to equilibrium, the onshore/offshore transport of sand seemed to overwhelm any cross-tank-induced sediment transport. Hughes and Fowler then related this trend to the field data of Howd and Birkemeier (1987), and stated "A prestorm breakpoint [illegible] at exhibited nonuniform alongshore variation became quite linear and moved offshore during the storm. Near the end of the storm, when presumably a near-equilibrium had been reached, alongshore variation in the bar began to reappear" (p. 37).

There are several possible causes of 3-D morphologies in a narrow wave tank, some of which could also be representative of those occurring in nature: (1) Instability of 2-D flows on 2-D morphology, (2) Organized longshore wave motions that could induce edge waves in nature or in a tank or cross-tank waves under laboratory conditions, and (3) A feedback between the hydrodynamics and morphology that reinforces 3-D morphological features under certain stages of profile development.

In the present study, movable bed experiments were carried out in a narrow wave tank to (1) monitor profile evolution and the resulting equilibrium, and (2) investigate various possible interrelationships and causes of the three-dimensionality, which included the effects of (a) induced perturbations in the bar topography, (b) elevated water table in the berm, and (c) an initially 3-D berm. Laboratory studies can isolate the selected governing parameters of the processes and can control their effects more easily than field studies. Furthermore, a narrow tank can remove any 3-D effects inherent to a wide tank, e.g., nonuniform wave crests in the longshore direction or cross waves. It should be noted that a relatively wide tank condition can be satisfied by reducing generated wave heights and periods, which makes the tests for edge waves mechanism possible in a narrow wave tank.

2. EXPERIMENTS

2.1 Laboratory Facilities and Experimental Conditions

A total of six experiments was carried out in a flume of the Coastal and Oceanographic Engineering Laboratory of the University of Florida. This tank is 15.5 m long, 0.9 m high and 0.6 m wide, and is equipped with a piston type wavemaker with a mechanically controlled motion and with one glass wall panel and one steel wall.

The planar beach of initial slope 1 : 18 was formed of well-sorted fine quartz sand with a mean diameter of 0.21 mm (2.25 in ϕ unit), a sorting coefficient of 0.58 and fall velocity of approximately 2.3 cm/sec. The grain size distribution include sizes ranging between 0.1 to 0.5 mm. The water depth in the horizontal portion of the tank was 0.275 m. Regular waves with a period of 1.5 sec and wave height of 0.11 m were utilized, and were measured by a capacitance-type wave gage. Fig. 2 shows a schematic diagram of the initial profile and other experimental details.

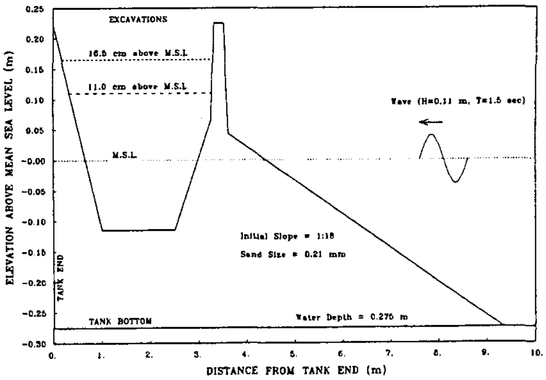

Fig. 2. Schematic Diagram of the Initial Profile and Other Experimental Details.

The profile was measured manually by a point gage modified by replacing the point with a small, rectangular foot (7.5 cm by 2.5 cm) which provided a flat surface to rest on the sand. In order to avoid consolidation at the measuring point, the gage was constructed of light aluminum. Three profiles, designated as B1, B2 and B3, were measured over the entire length of the beach to document the three-dimensionality at various times. As shown in Fig. 3, profile B1 was 0.15 m from the glass side wall while profile B3 was 0.15 m from the steel side wall. Profile B2 represented the center line profile along the tank. The profiles were documented at locations spaced 0.1 m along each of these lines, and then these three profiles were averaged to represent the mean profile at the measuring time. Since three profiles were not sufficient to document 3-D features when a fairly deep and narrow channel appeared near one of the tank walls, the profile elevations at both sides [illegible] the tank were measured a [illegible]

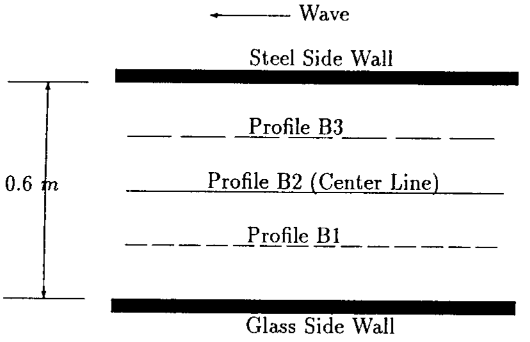

Fig. 3. Three Profiles B1, B2 and B3 across the Tank.

lly to document the maximum cross-tank variations of the profile.

The desired water table level in the berm was maintained by excavating 2-D depressions across the tank. These excavations were connected to the constant head reservoir through plastic tubes so that water was siphoned out of or into the excavated holes to maintain the desired water table level. During the experiments, this method has worked very well. However, bubbles appeared sometimes inside the tubes due to prolonged experimental duration; at which time, they were removed by allowing a small amount of flow from the excavated holes to the reservoir, or vice versa.

It should be noted that present experiments were performed with the fine sands which have been utilized during previous tests, thus have been subjected to continuous submergence. This prolonged submergence appeared to allow microorganism active although the experiments were carried out in winter season, resulting in unpleasant odors and black-colored cohered-looking sands inside the beach, especially near the tank bottom. Hence, one experiment was designed to investigate the effects of microorganism inside the beach on the profile evolution. Since the breaks between wave runs to measure profiles appear to retard the development of steady-state for a given beach system, an additional test was performed to examine the effects of continuous wave run without intermissions on the occurrence of the three-dimensionality.

2.2 Description of Movable Bed Experiments

Table 1 lists experimental identification number, total wave run duration, water table level conditions, and brief descriptions of each experiment. Each experiment was defined as a collection of sequential profiles for an initially planar beach subjected to regular waves. The six experiments were defined as: (1) Reference test (Experiment MT01), (2) Repeat tests (Experiment MT02 and MT03), and (3) Perturbation tests (Experiment MT04, MT05 and MT06).

2.2.1 Reference Test

The first movable bed experiment (Experiment MT01) was designed to monitor the profile evolution and to determine whether or not three-dimensionalities might occur, hence providing a reference for future experiments.

The profiles were surveyed at intervals of 23 min

Table 1. Descripton of Movable Bed Experiments

Exp. No.	Duration (min)	Water Table Level* (cm)	Note
MT01	0-476	0.0	Reference test
MT02	0-407	0.0	Biological effects (quick start)
MT03	0-545	0.0	Wave run duration effects (run waves without intermission)
MT04	0-821		Perturbations in the bar topography
	(0-69)	0.0	(no change)
	(69-138)		(bar trough is deepended)
	(138-352)		(asymmetric offshore scour area)
	(352-821)		(remove half of bar crest)
MT05	0-1166	+11.0	Initially 3-D berm with elevated water table level
MT06	0-1166	+16.5	Highly elevated water table in the berm

refers to the mean sea level (MSL). Hence, positive value represents the water table level above MSL.

during initial stages to document rapid evolution of the profiles. Later those were increased up to 69 min depending on the rate of profile change. The same intervals were used in the subsequent experiments to compare the profiles at the same elapsed times.

2.2.2 Experimental Repeatability

Experiments MT02 and MT03 were carried out to (1) provide experimental repeatability of Experiment MT01 and (2) investigate the possible effects of experimental conditions on the three-dimensionality occurred at Experiment MT01, which included the effects of the microorganism inside the beach and the effects of continuous wave run.

Experiment MT02 was conducted to investigate the effects of microorganism, of which presence could be perceived by unpleasant odors and black-colored cohered sands located near the tank bottom, as discussed earlier. Since the biological film inside sand was believed to be disturbed after long wave run, Experiment MT02 started with the remolding of the initial profile immediately after the last wave run of Experiment MT01.

The purpose of Experiment MT03 was to investigate the effects of required time for the beach system to reach steady-state on the occurrence of the three-dimensionality. In this experiment, hence, the wave was run continuously without intermissions to measure profiles.

2.2.3 Perturbation Tests

Experiments MT04, MT05 and MT06 represent the main attempts in the present study to investigate the three-dimensionality.

Experiment MT04 was carried out to investigate the effects of induced perturbations in the bar topography, which included (1) deepening of the bar trough, (2) asymmetric area seaward of the bar, and (3) removing half the bar crest, and was continued further to investigate resulting equilibrium.

Experiment MT05 started with an initially 3-D berm superimposed on a planar initial profile to investigate whether or not resulting 3-D flows in the beach face would facilitate the occurrence of three-dimensionality. This experiment also included the effects of elevated water table in the berm.

Experiment MT06 was carried out to examine the effects of highly elevated water table level in the berm on the profile evolution and resulting 3-D morphology.

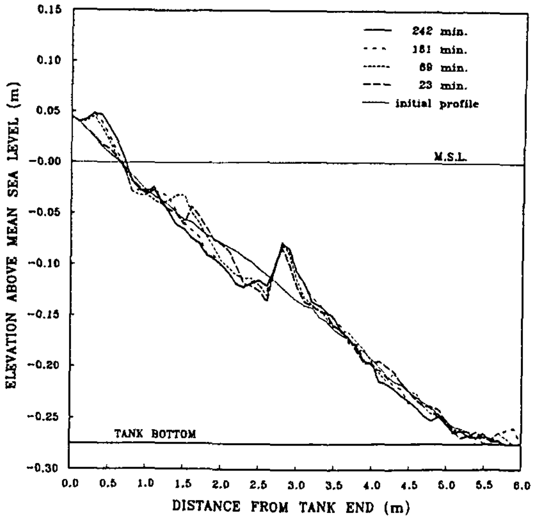

Fig. 4. Mean Profile Evolution during Early Stages of Experiment MT01. Elapsed Times=0 (Initial Profile), 23, 69, 161 and 242 min. Note that the profile approached an equilibrium and a level of profile stability had occurred at 242 min.

3. RESULTS AND DISCUSSIONS

This section briefly describes and discusses the results of all six experiments, of which details are included in Oh (1994).

3.1 Reference Test (Experiment MT01)

The mean profiles during early stages at elapsed times 23, 69, 161, and 242 min with the initial profile are presented in Fig. 4. During the early stages, the offshore bar formed quickly from a linear profile and remained stationary. However, the berm also started to accrete slowly at the initial times and more rapidly at the later times. A small bar appeared between the main offshore bar and the berm. This bar moved landward continuously and finally remained stationary just landward of the berm. T profiles appeared to approach an intermed librium with overall 2-D conditions. As s Fig. 5, the mean profile inside the surf zon was in good agre

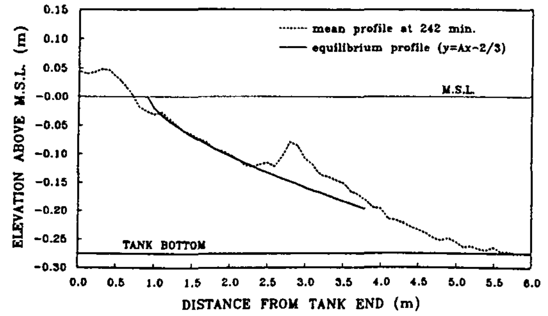

Fig. 5. Comparison of the Mean Profile at 242 min during Experiment MT01 with the Equilibrium Profile Proposed by Dean (1977). Note the similarity between two profiles inside the surf zone.

profile proposed by Dean (1977); this indicated that, after 242 min, the profile really approached an equilibrium for the given forcing.

After the profile approached an equilibrium and a level of profile stability had occurred at 242 min, a weak counter-clockwise 3-D circulation occurred after about 270 min, flowing from the steel side wall to the glass side wall inside the surf zone. This flow initiated a new stage of profile evolution. However, only small changes occurred between 242 and 297 min since the circulation was not sufficiently strong to transport the sediments. Fig. 6 shows the mean profiles at elapsed times 0 (initial profile), 242, 297, 352, 407 and 476 min.

After 297 min, the sedimentary feedback appeared to reinforce the circulation sufficient to transport sands landward. As shown in Fig. 6, the area seaward of the bar eroded with a substantial deepening and the eroded sand was deposited immediately landward of the bar trough, thus changing this area from mildly erosional to strongly depositional.

Furthermore, this area changed from overall 2-D conditions to 3-D features with higher parts near the steel side wall, as shown in Fig. 7 which presents three profiles, B1, B2 and B3 to document three-dimensionality occurred after 476 min. Bar started to move landward with counter-clockwise rotation of approximately 20 degrees about the direction of wave propagation. The bar trough became shallower at the later times as sand was deposited over the area landward of the bar. This profile morphology [illegible] a rip current present. After 476 min, the maximum cross-tank difference of the profile elevation at the depositional area inside the surf zone was estimated to be 6.0 cm.

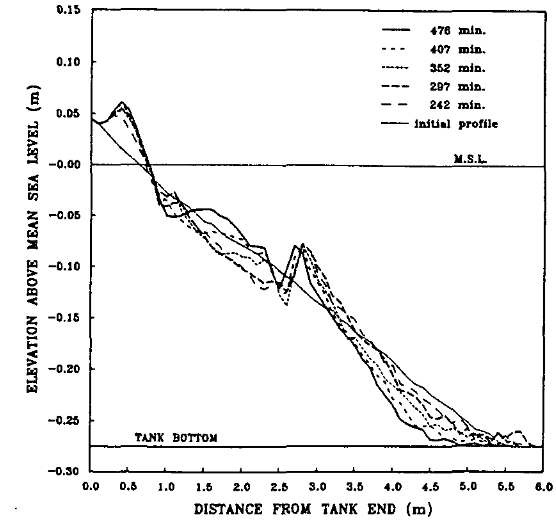

Fig. 6. Mean Profile Evolution after the Profile Approached an Equilibrium during Experiment MT01. Elapsed Times=0 (Initial Profile), 242, 297, 352, 407 and 476 min. Note the substantial erosion of the area seaward of the bar and the deposition of the area immediately landward of the bar trough. Note also landward movement of the bar.

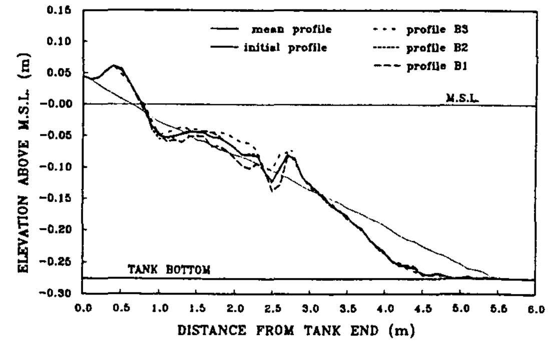

Fig. 7. Initial Profile and Three Profiles B1, B2 and B3 and Mean Profile at 476 min during Experiment MT01. Note three-dimensionality inside the surf zone and near bar area.

3.2 Experimental Repeatability

3.2.1 Experiment MT02

As explained earlier, Experiment MT02 started with the remolding of the inital profile right after

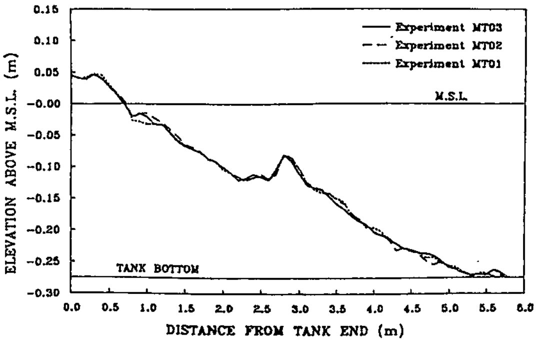

Fig. 8. Comparison of the Mean Profile at 207 min during Experiment MT03 with the Mean Profiles at the Same Time during Experiments MT01 and MT02. Note the similarity between those three mean profiles.

the last wave run of Experiment MT01, at which time biological film inside sand was believed to be disturbed. Although the three-dimensionality occurred slightly earlier at about 240 min than that during Experiment MT01, no clear conclusions could be drawn to the effects of microorganism on the occurrence of the three-dimensionality, which might be due to low temperature during this experiment, as explained earlier. Hence, Experiment MT02 has provided the experimental repeatability rather than proving the effects of microorganism.

3.2.2 Experiment MT03

Experiment MT03 was performed to investigate the effects of required time for the beach system to reach steady-state, as discussed earlier. Hence, the wave was operated continuously without intermissions for the first 207 min. As shown in Fig. 8, the mean profile at 207 min was amazingly the same as those during Experiments MT01 and MT 02. Also, three-dimensionality occurred at almost the same time (240 min) as Experiment MT02. These facts implied that the effect of continouos wave run was unexpectedly small.

Up to 476 min, the profiles evolved in the same manner as previous experiments. Counter-clockwise circulation occurred and transported sands from the area offshore of the bar to the depositional area immediately landward of the bar trough. As sand was deposited, the circulation seemed to be reinforced again. However, when the experiment was conducted continouosly beyond 476 min, strong circulation occurred, resulting in substantial onshore transport of the sands from the area seaward of the bar, thus causing the landward movement of the bar and rapid build up of the berm with another peak which moved seaward. Fig. 9 shows the mean profiles at elapsed times 0 (initial profile), 207, 352, 476 and 545 min.

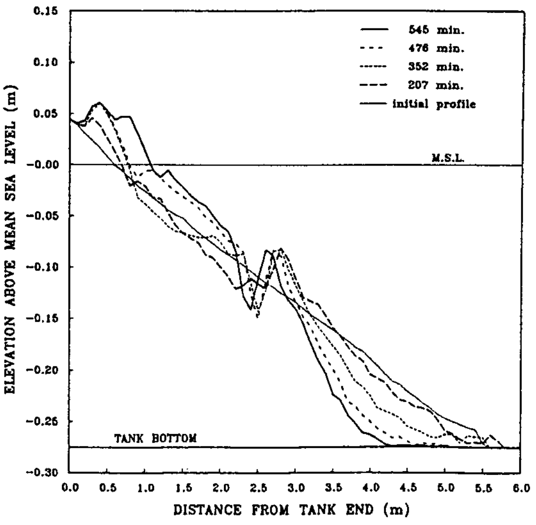

Fig. 9. Mean Profile Evolution during Experiment MT03. Elapsed Times=0 (Initial Profile), 207, 352, 476 and 545 min. Note rapid change during 476 to 545 min with landward movement of the bar and another peak of the berm.

During 476 to 545 min, the depositional area immediately landward of the bar trough changed from overall 3-D feature to overall 2-D one, as shown in Fig. 10, except a very narrow deep channel near glass side wall of tank, where the maximum depth was found to be about 5.0 cm below the mean profile. The overall slope of the profile at 545 min was estimated to be 1 : 10, which was defined as the slope between the seaward end of the profile and the peak of the berm. The slope of the beach face was estimated to be 1 : 7, which was approximately the same as that of the area seaward of the bar.

3.3 Perturbation Tests

3.3.1 Experiment MT04

Experiment MT04 was carried out to inves [illegible] ate the eff [illegible] o [illegible] erturbations in the [illegible]

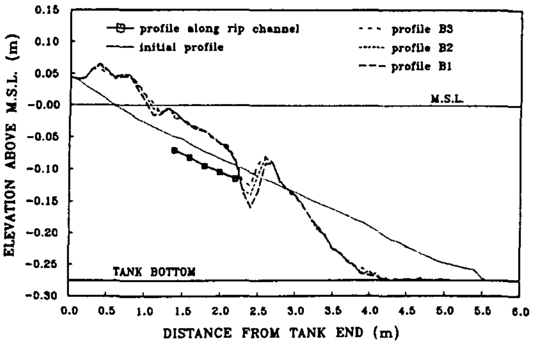

Fig. 10. *Initial Profile and Three Profiles (B1, B2 and B3)* and the Profile along Rip Channel inside the Surf Zone at 545 min during Experiment MT03. Note overall 2-D conditions inside the surf zone except a very narrow deep channel near glass side wall.

graphy on the occurrence of three-dimensionality inside the surf zone, and continued further to investigate resulting equilibrium.

During the first 69 min of wave operation, the trend was the same as previous experiments as the morphology was dominantly 2-D. As a first perturbation to the bar topography, the bar trough was deepened by approximately 4 cm after 69 min of wave run to investigate whether or not the morphology is stable against the perturbations during the initial phases on the profile evolution. During 69 to 138 min, the profile surprisingly returned back to the pre-modified profile at 69 min. The deepened 2-D bar trough completely filled in and the profile morphology was dominantly 2-D, which implied that the profile morphology was stable against the perturbation given by deepening of the bar trough.

After 138 min wave run, the area seaward of the bar, which was almost 2-D, was modified by relocating sand from the steel side wall to the glass side wall, resulting in asymmetric offshore area of the bar. However, the mean profile remained approximately the same. The maximum cross-tank difference of the profile elevation in this area at the two sides of the tank was about 6.0 cm. This asymmetric offshore area was expected to change wave shoaling and breaking characteristics over the bar region, hence resulting in longshore variations of the breaking wave heights.

Again the profile returned to pre-modified 2-D profile morphology at 138 min within an hour after resumption of wave action. The mean profile at 207 min agreed well with the pre-modified mean profile at 138 min. And the perturbed area seaward of the bar was changed to the pre-modified 2-D one. These again demonstrated the stability of the profile morphology against the perturbations. At this stage, it will be interesting to consider the direction of the sand transport during 138 min to 207 min. During this time, sands could be transported either (1) directly from the glass side wall to the steel side wall by gravity and/or 3-D circulation confined in the area seaward of the bar, or (2) by overall 3-D circulation starting at the higher perturbed area, passing over the bar, circulating inside the surf zone in clockwise direction, and returning to the lower perturbed offshore area; during the experiment, the sands appeared to be transported by overall 3-D circulation.

It appeared that modification of the area seaward of the bar caused different characteristics of the wave breaking at two sides of the tank (wave breaking occurred at first in the higher perturbed area), thus producing nonuniform distributions of the set-up across the tank, resulting in the clockwise 3-D circulation. At the begining, this 3-D flow appeared to be weak to transport sands; however, it was sufficiently strong to rotate the bar. As the bar was rotated, the 3-D flow was reinforced by the sedimentary feedback. This 3-D flow then started to transport sands from the higher perturbed area to the area immediately landward of the bar trough. Small portion of those sands were transported landward continuously and built up the berm slightly, while main portion of the transported sands were carried back to the lower perturbed area seaward of the bar, resulting in the pre-modified 2-D offshore area.

During 207 to 297 min, the 3-D flows remained weak to cause strong onshore transport of the sands from the 2-D area seaward of the bar and the profile was dominantly 2-D except the bar area rotated clockwisely by about 20 degrees. However, during 297 to 352 min, fairly strong 3-D circulations started to occur, thus causing a rapid landward sand transport, increasing the three-dimensionality inside the surf zone.

After 352 min of wave run, half of the bar crest was removed to fill the bar trough, resulting in a linear profile without prominent bar near the steel side wall. This was designed to impose an extreme three-dimensionality into the bar crest, thus accelerating the development of the 3-D features already existed inside the surf zone. The bar crest again recovered its pre-modified shape from the imposed 3-D feature over a testing time of approximately one hour after resumption of wave action, resulting in a smaller rotational angle of the bar crest line (less than 10 degrees). During the recovery, the other part of the profile remained almost the same as the pre-modified one, and no distinct circulation was observed.

After overall recovery occurred approximately at 400 min, the bar started to move landward with increasing clockwise rotation due to reinforcing 3-D circulation and the area seaward of the bar eroded substantially, resulting in the deposition of sand at the area immediately landward of the bar trough and the increase in clockwise rotation of the bar crest. This morphology and hydrodynamics are strongly reminiscent of the morphology associated with rip currents, as shown in Fig. 11. Fig. 11 presents isolines of profile elevations at 545 min, which were taken at intervals of 1 cm by placing blank yarn along the waterline as the water was lowered. As shown in this figure, a deep and narrow channel appeared near steel side wall, of which floor was found to be decidedly irregular mainly due to the strong rip current. Also the depositional area occupied a large portion of the surf zone, which also can be observed in the field near shoal areas. It can be seen that the bar rotated clockwise as the results of clockwise 3-D circulation flowing from the depositional area to the channel. The maximum cross-tank difference of the profile elevations between the two sides of tank was estimated to be 4.0 cm at 545 min, which was slightly smaller than that during Experiment MT03.

The profile seemed to approach an overall 2-D equilibrium up to 614 min with a clockwisely rotated bar crest except slight deposition of sand at the area just seaward of the berm. The maximum cross-tank difference in the profile elevations remained almost constant as 4.5 cm even though the channel, shown in Fig. 11, became more distinct and clear. During 614 min to 821 min, the area seaward of the bar maintained its slope as 1 : 7 with actually no changes. The berm built up rapidly in the same manner as the profile at 545 min during Experiment MT03, as shown in Fig. 9. However, the slope of the beach face remained almost constant as 1 : 7, which was approximately the same as that of the area seaward of the bar. The overall slope of the profile after 821 min was about 1 : 10, which was actually the same as that of final profile during Experiment MT03.

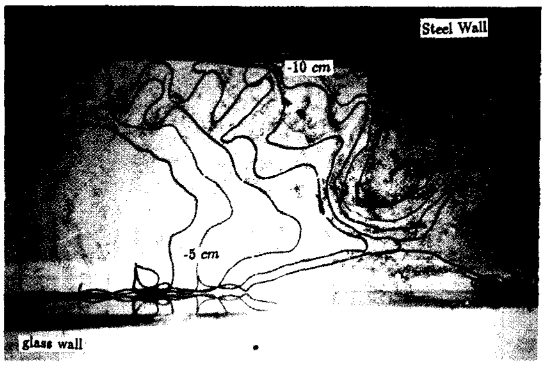

Fig. 11. Isolines of Profile Elevations at 545 min during Experiment MT04. These photographs showed: (1) deep and narrow channel near steel side wall, (2) depositional area occupying large portion of the surf zone, and (3) clockwise rotation of the bar. Elevation contours were established by placing black yarn at waterline during lowering of water level.

3.3.2 Experiment MT05

Experiment MT05 was conducted with an initially planar profile perturbed by a 3-D berm to investigate whether or not resulting 3-D flows in the beach face would facilitate the occurrence of the three-dimensionality, and was continued further to investigate profile equilibrium. The asymmetric berm was constructed by placing additional sands over the initially planar berm near the glass side wall. The elevation difference at the two sides of the tank was about 4.0 cm. This experiment also investigated the effects of an elevated water table in the n

(+11.0 cm above Mean Sea Level).

During the first 23 min, the initially 3-D berm changed to fairly 2-D without inducing any noticeable 3-D circulation inside the surf zone, which indicated that the beach morphology was again stable against perturbations during the initial phases of the experiment. However, the size of the berm was somewhat larger than that of previous experiments due to the initially deposited sand, as expected. The profile seemed to approach an equilibrium at 207 min. The results were almost the same as those of previous experiments, which implied that neither the effect of elevated water table level in the berm nor that of an initially 3-D berm was significant in this fine sand experiment.

3-D features appeared to start during 207 to 242 min, which was almost the same as the previous experiments. After 297 min, the bar rotated in counter-clockwise direction about 20 degrees and maintained its angle up to 407 min although 3-D circulation appeared to be continuously reinforced by sedimentary feedback. The three-dimensionality inside the surf zone continuously increased up to 407 min. The maxim cross-tank differences in profile elevations in he surf zone were estimated to be 5 cm at 407 min. The deepest part was located along the glass side wall of the tank, which could be expected from the counter-clockwise rotation of the bar crest, and this deep channel resembled a rip channel morphology in nature.

During 407 to 476 min, the profile changed to a fairly 2-D, which appeared to be associated with a fairly strong 3-D circulation. This strong 3-D circulation transported sands from the area seaward of the bar to the area immediately landward of the bar though and distributed sands evenly over that area across the tank. However, the return channel near the glass side wall of the tank remained with approximate dimensions of 6 cm depth below the mean profile and 8 cm width. During 476 to 614 min, the 3-D circulation has been continuously reinforced by the sedimentary feedback, resulting in very strong onshore transport. As strong landward transport occurred cintinuously, the channel finally filled in while the profile remained in a fairly 2-D. This strong landward transport resulted in the landward movement of the bar and a rapid build up of the berm with another peak which moved seaward, as shown in Fig. 12.

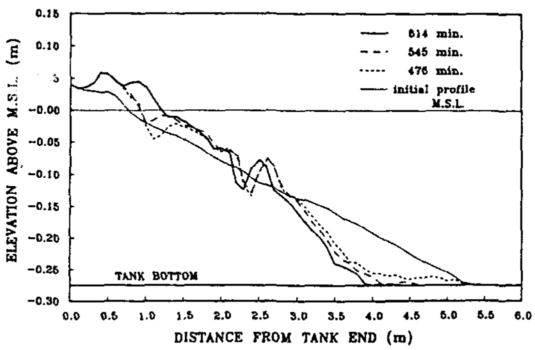

Fig. 12. Mean Profile Evolution during Experiment MT 05. Elapsed Times=0 (Initial Profile), 476, 545 and 614 min. Note rapid change during 545 to 614 min with landward movement of the bar and another peak of the berm. However, the overall shape of the profile was surprisingly unchanged.

The overall slope of the profile after 545 min was approximated as 1 : 10, which resembled those of final profiles during Experiment MT03 and Experiment MT04. The slope of the berm was estimated to be 1 : 7, which was again approximately the same as that of the area seaward of the bar. Even though the profile changed substantially during 545 to 614 min, the overall shape of the profile at 614 min remained approximately the same as that at 545 min, as shown in Fig. 12.

During 614 to 890 min, the new berm built up continuously, resulting in steeper slope of about 1 : 5. The area seaward of the bar eroded substantially due to landward transport with a slope of 1 : 5.5, which was again similar to that of the berm. The bar moved offshore at the initial times and, at the later times, remained stationary and changed to almost 2-D feature with rotation angle less than 10 degrees. As time approached 890 min, profile appeared to approach an another intermediate equilibrium.

During 890 to 1028 min, the berm eroded slightly at the initial times and maintained its form with a slope of about 1 : 5, as shown in Fig. 13. The bar moved back d-forth with increased rotation angle of about 1 grees. wever, the profile ap-

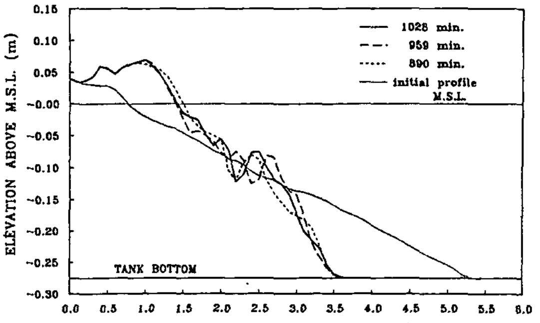

Fig. 13. Mean Profile Evolution during Experiment MT 05. Elapsed Times=0 (Initial Profile), 890, 959 and 1028 min. Note the back-and-forth movement of the bar, otherwise the profiles approached an equilibrium.

peared overall 2-D. The slope of the area seaward of the bar changed from 1 : 5.5 to 1 : 4.5. The bar moved onshore if slope was near 1 : 4.5, while the bar moved offshore if slope was near 1 : 5.5; these implied the equilibrium slope of 1 : 5. After 1028 min, the profile approached an equilibrium with overall 2-D morphology except the oscillation of the bar.

3.3.3 Experiment MT06

Experiment MT06 was carried out with a more highly elevated water table in the berm (+16.5 cm) since moderately elevated water table during Experiment MT05 appeared to produce no effects on the profile evolution and 3-D morphology.

Up to 138 min, the trend was the same as the previous experiments as the profile approached an overall 2-D equilibrium. Berm built up rapidly with onshore transport at the initial times. Bar moved offshore at the initial times and moved onshore back at the later times. From 138 min to 207 min, the bar remained stationary. At the later stages (about 180 min), the bar rotated quickly and a 3-D feature appeared immediately landward of the bar trough. At 207 min, the bar rotated approximately 25 degrees. The three-dimensionality at this experiment occurred earlier (about 180 min) than previous experiments, which might imply that the elevated high water table accelerated the beach profile evolution as it caus[illegible] more a[illegible] transport by reducing the stability [illegible] the b[illegible] particles.

Table 2. Maximum Cross-Tank Differences of the Profile Elevations at 352 min during Experiment MT06

Region	Location (m)	Maximum Difference (cm)
berm	0.5	2.0
shoreline	0.9	3.5
depositional area	1.8	4.5
bar through	2.3	6.0
bar crest	2.5	3.5

During 207 min to 242 min, the bar remained stationary. However, as the bar trough became shallower and the area seaward of the bar eroded mildly, weak onshore transport continued and the overall three-dimensionality inside the bar region increased continuously. During 242 min to 476 min, the bar moved slightly onshore at the initial times and stayed stationary at the later times. The bar trough deepened considerably and rapidly during the first 30 min and maintained its depth later. The area seaward of the bar eroded continuously and the sand eroded was carried up and deposited on the depositional area immediately landward of the bar trough. Up to 352 min, the overall three-dimensionality increased continuously. Table 2 presents a summary of the maximum cross-tank differences of the profile elevations at the two sides of the tank at 352 min. As strong onshore transport continued during this time, the depositional area continued to grow up and to move onshore, resulting in a deep channel across the tank at about the mean water line at 476 min.

During 476 min to 614 min, the depositional area moved continuously landward, as observed in the previous experiments. However, it should be noted during this time that the overall shapes of the profile amazingly agreed well with those of Experiment MT05, as shown in Fig. 14 which presents a comparison of mean profiles at 614 min. During 614 to 683 min, the depositional area finally attached to the berm, resulting in a large increase in the size of the berm and another peak of the berm moving seaward. Also the 3-D profile returned to a fairly 2-D one except the bar rotation of about 15 degrees and a narrow deep channel on the glass side wall of the tank. The water depth of th[illegible] n-

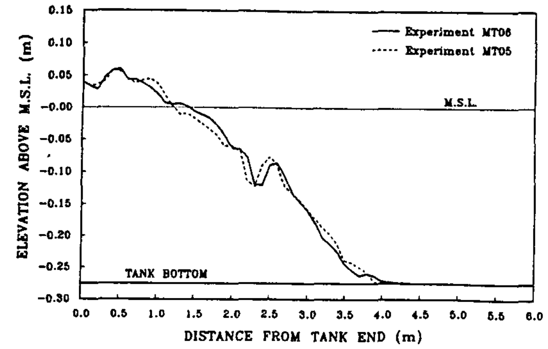

Fig. 14. Comparison of the Mean Profile at 614 min during Experiment MT05 with that during Experiment MT06. Note good agreement of the overall shape.

nel was estimated to be 7.0 cm, which was about 3.5 cm below its surroundings. The slope of the area seaward of the bar at 683 min was estimated to be 1 : 4.7, which was much steeper than that of the beach face (about 1 : 7.3).

During 683 min to 890 min, the bar moved onshore very quickly at the initial times since the slope of the area seaward of the bar was steeper than 1 : 5, as presented in the results of Experiment MT05. Hence, the back-and-forth movement of the bar around the slope of 1 : 5 was expected. However, the slope of the offshore area continuously reduced to 1 : 6.5 at 752 min and finally to about 1 : 11 after 890 min, as shown in Fig. 15. Also the slope of the beach face reduced from 1 : 4 at 752 min to 1 : 11 at 890 min continuously. Even the bar moved onshore, strong offshore transport occurred at the initial times, which resulted in erosion of the berm area and deposition of the offshore area of the bar. During this time, the bar moved onshore slightly and profile remained fairly 2-D. After 890 min, the profile approached an equilibrium with the overall slope of about 1 : 12.

It appeared that the elevated high water table had accelerated the beach profile evolution at the initial times as it facilitated sediment transport by destabilizing the bottom particles, resulting in earlier occurrence of the three-dimensionality than the previous experiments. Then the profile evolved as the same way as the previous experiments without introducing any significant effects of the highly elevated water table. However, when the profile became steeper, the elevated high water tabel level seemed to affect the profile evolution, resulting in the milder equilibrium slope.

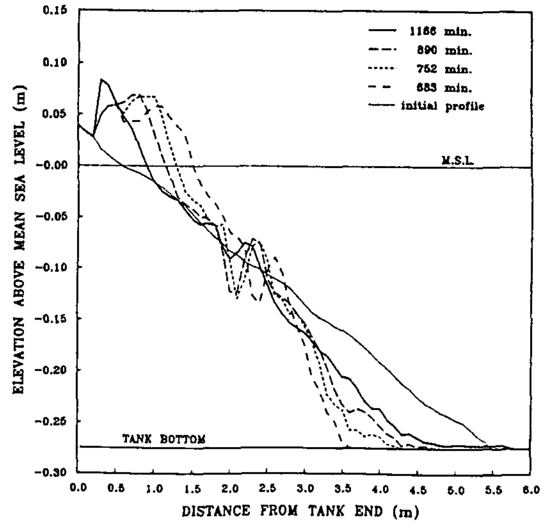

Fig. 15. Mean Profile Evolution during Experiment MT 06. Elapsed Times=0 (Initial Profile), 683, 752, 890 and 1166 min. Note that the profile approached an equilibrium with reduced overall slope.

3.4 Edge Wave Mechanism

As described earlier, there are several possible mechanisms to explain the occurrence of 3-D flows in a wave tank. Based on the results of these movable bed experiments, it was examined whether or not edge waves can generate the three-dimensionality in a tank. The range of periods that would be associated with edge waves was calculated as proposed by Bowen and Inman (1969),

$$L_r = L_e = L_o \sin[(2n+1)\beta]$$

where, L_r is the rip current spacing, L_e the edge wave length, $L_o = gT^2/2\pi$, the deep water wave length, g the gravitational acceleration, β is the planar beach slope, and n is the mode of the edge wave, which is equal to the number of zero crossings of the water surface elevations in the offshore direction. The caculated results are summarized in Table 3, where rip current spacing was given as twice the tank width, i.e., 1.2 m, and the slopes represented

Table 3. Periods(sec) Associated with Edge Waves

Edge Wave	Slopes			
Mode (n)	1/18	1/10	1/7	1/5
0	8.90	6.64	5.55	4.70
1	5.10	3.83	3.20	2.71
2	4.00	2.97	2.49	2.10
3	3.40	2.51	2.10	1.77
4	3.00	2.22	1.86	1.56
5	2.70	2.00	1.67	1.42
6	2.40	1.84	1.54	1.30
7	2.30	1.71	1.43	1.21
8	2.20	1.61	1.34	1.14

typical results from the present experiments. As summarized in this table, these experiments included the range of periods that would be associated with edge waves; hence, edge waves could induce the 3-D flows in the wave tank. However, during the experiments, no edge waves appeared even with very steep slopes (e.g., tan $\beta = 1/5$).

4. INTERPRETATION

The results of the tests requiring interpretation are (1) the onset of the 3-D circulation after the profiles had reached a state of quasi-equilibrium and (2) the onshore transport of sand by the circulation that was reminiscent of a rip current. Prior to offering an interpretation, it would be helpful to note the strong repeatability of the experiments and that there were forces tending both to incise channels through the bar and to fill in any lower portions of a bar.

At the earlier stages of the profile evolution from an initially planar beach, the sand appears quite mobile; thus any increase in depth over the bar is rapidly filled by the available sand, resulting in the two-dimensionally stable profile even with the intentional perturbations. When the profile approaches a quasi-equilibrium after some time, however, the sand is less in transit and becomes more consolidated and less mobile; hence, a local deepening of the bar would not be filled in so readily due to less material being readily available for the recovery. Since the local depression is more efficient hydraulically, the channel deepens gradually until at 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 occrring through the deepened channel, the seaward forces that were present over the bar due to the return flow are reduced and the onshore transport processes now predominate and landward sediment transport occurs resulting in an advancement of the shoreline and erosion of seaward portions of the profile. This mechanism is very similar to that of shoreline recovery in nature through ridge and runnel systems and associated breaks in the bar through which the return flow (rip currents) of the mass transport occurs, even though the laboratory wave conditions remained unchanged in constrast to the milder wave action associated with recovery in nature.

5. CONCLUSIONS

The experiments described herein were carried out with a fairly fine sand in a relatively narrow wave tank. Bar formation was expected from the given experimental conditions. Based on these experimental results, conclusions are described below.

It was found that during the initial phases of the experiments, the result of all experiments were almost the same with dominantly 2-D morphology. When 3-D perturbations were intentionally introduced into the berm and bar features, resumption of the waves rapidly reformed the profile to the previous 2-D morphology; hence, the profile appeared to be stable against those perturbations and to approach an equilibrium with overall stability.

However, after approximately four hours of testing when a level of profile stability has occurred, 3-D features appeared and were associated with a fairly strong horizontal cellular circulation and a rapid net landward sediment transport and shoreline advancement. This stage is reminiscent of rip currents and the 3-D features found in nature during shoreline recovery subsequent to an erosional event even though the laboratory wave conditions remained unchanged in contrast to the milder wave action usually associated with recovery in nature. Still later in the testing, the returne [illegible] rly 2-D conditions with the exception of a fairly deep and narrow return channel near one of the tank walls.

After achieving another intermediate equilibrium, onshore transport of sand occurred very strongly, resulting in the landward movement of the bar and rapid build-up of the berm with another peak which moved seaward. As waves were operated continuously, profiles were approaching an another equilibrium.

Whenever 3-D features appeared during the experiments, it was observed that 3-D circulation was always associated with those 3-D features, generated from the shoals and flowed toward the embayments.

In aggregate, these movable bed studies suggest that there is a relatively slow feedback between the hydrodynamics and the morphology that leads to initiation and growth of 3-D features, even in relatively narrow tanks. It is concluded on a preliminary basis that the evolution observed, including the appearance of 3-D circulàtion and the associated transport are relevant to the transformation of a 2-D bar in nature to a 3-D form and the subsequent migration of the bar to the shoreline and its recovery. If further testing confirms the mechanisms identified in these experiments, a substantial contribution to the clarification of the physics present in the nearshore zone will have resulted.

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