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Measuring Longshore Sediment Transport in a Large-Scale 3-Dimensional Laboratory Facility

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ABSTRACT

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Aiming at improving present understanding on longshore sediment transport (LST), the U.S. Army Engineer Research and Development Center recently established a Large-scale Sediment Transport Facility (LSTF). The 3-dimensional movable-bed facility has the capability of simulating wave conditions that are directly comparable to annual averages along many low energy coasts. Wave, current, and sediment concentration are measured accurately at numerous longshore and cross-shore locations and throughout the water column. Depth-integrated LST rate and its cross-shore distribution are measured with 20 bottom traps installed at the downdrift end. These, along with beach-profile data, allow detailed analyses of LST processes. This paper focuses on the methodology of designing and implementing LST experiments. Each experiment consists of a number of wave-run segments. Each segment has a specific objective. The first few segments are designed to accomplish two tasks before the actual LST measurement. One is to achieve proper pump settings for the circulation of breaking-wave-generated longshore current. The other task is to allow the beach to reach equilibrium state. Successful accomplishment of these two tasks is crucial to ensure longshore uniformity of hydrodynamic and beach conditions, and to minimize interactions at the lateral boundaries. LST measurement is then accomplished with at least four wave-run segments, including one focusing on measurements at maximum number of locations alongshore, one on measurement of vertical current profiles, and two repeated measurements to ensure data quality. The first phase of LSTF experiments indicated that the above procedure was successful and should be valuable to the design of future laboratory studies.

ADDITIONAL INDEX WORDS: *Nearshore sediment transport, surf-zone dynamics, physical modeling,*

INTRODUCTION

Accurate predictions of longshore sediment transport rate and its cross-shore distribution in the surf zone are central to numerous coastal engineering and science studies. Present understanding and predictive methods are largely developed based on field studies (KOMAR and INMAN, 1970; INMAN *et al.,* 1981; KRAUS *et al.*, 1982; BODGE and DEAN, 1987; DEAN, 1989; WANG *et al.*, 1998a, 1998b; WANG, 1998). The very dynamic nature of the surf zone can introduce large uncertainties in field measurements (WANG and KRAUS, 1999). The non-controllable and non-repeatable field conditions increase the difficulties of separating and examining the contributions of individual parameters and their interactions.

In contrast to field studies, laboratory measurements have the advantages of being controllable and repeatable, allowing the isolation and study of individual parameters. The convenient laboratory instrumentation enables precise measurement of many parameters such as wave height, current, sediment concentration, and their spatial and temporal distribution. The disadvantages of existing laboratory studies, especially the 3-D movable-bed physical models, are their substantially reduced temporal and spatial scales and their limited capabilities of simulating real-world situations even at small scales.

KAMPHUIS (1991a, b, c) conducted a series of laboratory studies on longshore sediment transport. Irregular waves ranging from 0.05 to 0.14 m in significant wave height and 0.9 to 1.5 s in peak period were generated at 10 to 40 deg incident angles. Thirteen of the 21 cases were conducted with waves having a peak period of 1.15 s (KAMPHUIS, 1991a). There is a gap between the coverage of field LST measurements and laboratory studies, in terms of wave heights and periods. The smallest waves encountered in the field are still much higher than the highest waves in the laboratory measurements, with longer periods. This gap raises the question of compatibility between field and laboratory data and applicability of predictive methods developed based on the laboratory study. An overlap of wave conditions between field and laboratory studies would be valuable in examining the compatibility and to ensure that laboratory data can be used to approximate real-world situation.

In an effort to challenge the limitations of small scale and to bridge the gap between laboratory and field data, the U.S. Army Engineer Research and Development Center recently established a Large-scale Sediment Transport Facility (LSTF). The LSTF is specially designed for studies of longshore transport (FOWLER *et al.*, 1995). The facility has the capability of simulating wave height and period that are directly comparable to annual averages along many low energy coasts, e.g., a majority of estuary beaches (NORDSTROM, 1992), and many beaches along the Gulf of Mexico and the Great Lakes in the U.S. This paper discusses the capabilities of LSTF and the design and implementation of LST measurements in a large-scale 3-D movable-bed laboratory facility. Detailed technical description of LSTF can be found in HAMILTON *et al.* (2001).

THE LARGE-SCALE SEDIMENT TRANSPORT FACILITY

The LSTF has dimensions of 50-m longshore, 30-m cross-shore, and has walls 1.4 m high (Figure 1). Long-crested and unidirectional waves, both regular and irregular, are produced by four synchronized wave generators oriented at an angle to the shoreline. The present design allows the incident wave angle to vary from 0 to 20 deg. Ten-degree angle was used during the first phase of experiments (WANG *et al.*, 2002a; 2002b; 2003). In the following, conditions used in this phase are discussed to demonstrate the experimental design and implementation.

The test beach is arranged in a trapezoidal plan shape corresponding to the obliquely incident waves. The beach is composed of approximately 150 m^3 of very well sorted fine quartz sand with a median grain size of 0.15 mm and a fall speed of 1.8 cm/s. The sand beach is roughly 25-cm thick over a planar concrete base and extends 27 m alongshore and 18 m cross-shore, of which 15 m are below still water level and 3 m are

Table 1. *LSTF instrumentation and typical sampling scheme*

Parameters to be measured	Instrument Type	Sampling rate	No. of cross-shore locations
Wave	Capacitance Gage	20 Hz	10
Current	ADV	20 Hz	10
Sediment concentration	FOBS	16 Hz	7
Beach profile	Bottom-tracking profiler	Every 5 mm cross-shore	3660
Sediment flux	Bottom sediment traps	Mode1: 4Hz Mode2: 1Hz	20 20

above. The relatively thick sand layer minimizes the influence of the impermeable concrete base on sediment motion. The breaking-wave-induced longshore current is circulated with 20 turbine pumps through 20 flow channels at the updrift and downdrift ends. Interference at the lateral boundaries can be minimized by properly circulating the wave-generated longshore current. Detailed procedures to regulate the pumps for the longshore-current circulation at LSTF are discussed in HAMILTON and EBERSOLE (2001). Twenty 0.75-m wide and 6-m long bottom traps, including 18 in the flow channels (except the two offshore most ones) and 2 landward of the shoreline, were used to measure depth-integrated longshore sediment flux (Figure 1).

The LSTF hosts a suite of instruments. Detailed capability and accuracy of the instrument are described in HAMILTON *et al*. (2001). The instrumentation and sampling scheme are summarized here in Table 1. The sediment-flux measurements at the downdrift bottom traps can be conducted in 2 modes.

Mode 1 consists of continuous weight sampling at a frequency of up to 4 Hz along with the wave run. Accuracy of weight measurement during the wave run is influenced by vibration and movement of the traps forced by the wave motion. Mode 2 trap measurements consist of two discrete sampling, 100 s each, before and after the wave run. Accurate weights are obtained in quiescent water.

Wave height and period are measured with capacitance wave gages sampling at 20 Hz. The Acoustic Doppler Velocimeters (ADVs) are used to measure current. The wave gages and current sensors are co-located in the longshore direction, and are synchronized. The breaker angle is measured visually using the angle-measuring device in an electronic total station transit.

Sediment-concentration profiles are measured using 4 arrays of the Fiber Optical Backscatter (FOBS) sensors (BEACH *et al*., 1992). Each FOBS array consists of 19 sensors, spaced roughly exponentially upward, ranging from a 1-cm spacing in the lower portion to a 6-cm spacing in the upper portion. The sampling system, during the first-phase experiments. There was a roughly 3-s delay of wave/current sampling relative to not included in the original LSTF design, were operated through a separate computer, independent of the wave-current bottom(WANG *et al*., 2002a). The FOBS have a vertical elevations of the FOBS sensors are controlled by referring the

Figure 1. The LSTF during a plunging-wave case, showing the flow channels (bottom) and the instrument bridge (top) carrying the current meters and wave gages (vertical rods).

resolution of sensors to the bottom one, which is deployed directly on the 0.5 cm (MILLER, 1999). The FOBS, which were sediment-concentration sampling, caused by different warm-up time of the sensors. The sensors have been synchronized thereafter.

The beach profiles are surveyed using an automated bottom-tracking profiler. During the first-phase experiments, the beach profiles were surveyed at 1-m alongshore spacing in the middle of the test beach. A closer spacing of 0.5 m was used near the lateral boundaries to monitor the boundary influence. The profiler is programmed to sample every 0.5 cm in the cross-shore direction. This fine cross-shore resolution allows measurements of bed ripples.

Transport measurements for a certain wave condition are conducted in a number of wave-run segments. Since the total amount of LST during individual wave runs is only a small fraction, less than 1%, of the total amount of approximately 150 m^3 of sand on the test beach, it is judged that continuous updrift sand recharging during the wave runs is not necessary (WANG *et al*., 2002b; (WANG and KRAUS, 2003). The beach is replenished and bottom traps cleaned after several segments of wave run. The wave basin is drained during this operation. The purpose of the beach replenishment is twofold, to recharge the sediment supply at the updrift end and to restore the beach to one with straight and parallel contours. The replenishment is mostly concentrated at the beach lying within 5 m from the updrift boundary. The main portion of the beach in the middle of the basin requires little attention owing partly to the uniform condition maintained by the longshore current circulation.

EXPERIMENT DESIGN AND IMPLEMENTATION

Each LST experiment is conducted in a series of wave-run segments. The duration of individual segment is determined by its objectives and the rate of transport. Generally, each segment is designed to focus on one of the following progressive goals, with the overall goal being acquisition of comprehensive and accurate measurements of the LST rate and its cross-shore and vertical distribution. The progressive goals in sequential order include:

1.) obtain optimal settings for the pump system to circulate longshore current to minimize interactions with the lateral boundaries;

2.) allow the beach to reach equilibrium, or stable, shape;

3.) provide adequate sampling coverage in the longshore and cross-shore directions;

4.) provide adequate sampling coverage throughout the water column; and

5.) repeat key measurements to ensure data quality and repeatability.

Each wave-run segment follows similar procedure to ensure data comparability. Data obtained after the achievements of proper pump setting and equilibrium beach state are used in transport analyses. The typical procedure for each wave run includes:

1.) pre-run beach-profile survey;
2.) pre-run bottom trap sampling (quiescent conditions);
3.) instrument check and initialization;
4.) start sediment trap sampling;
5.) start longshore current circulation;
6.) start waves;
7.) measurements of wave, current, suspended-sediment concentration, and trap weight;
8.) stop waves;
9.) stop longshore current circulation;
10.) post-run bottom trap sampling (quiescent conditions);
11.) post-run beach-profile survey.

The duration of each sampling event is determined by the peak wave period. It is generally accepted that averages of 150 waves or more provide reliable representation (NIELSEN, 1984; 1992). Ten-minute sampling has been used during the first phase of LSTF experiment.

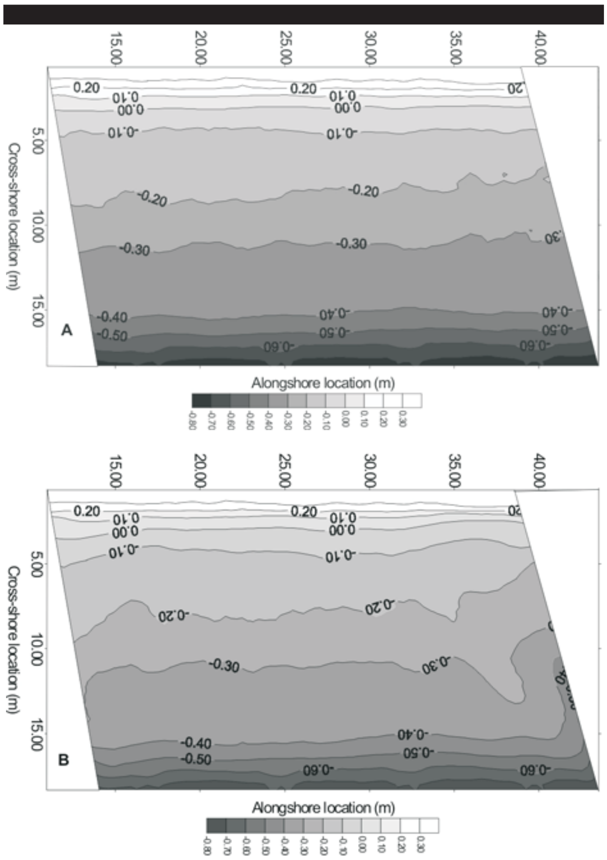

Figure 2. Uniformity of the test beach. A: directly after restoration; B: directly before restoration.

The main spatial resolution in the cross-shore direction is on the order of 0.75 m, determined by the width of the downdrift bottom traps. The vertical resolution of current and sediment-concentration measurements is roughly 1 cm.

RESULTS AND DISCUSSION

The following discussion focuses on the methodology of designing and implementing LST measurement in the large 3-D movable-bed laboratory facility. Results on longshore sand transport from the phase one study are published in WANG *et al*. (2002a, 2002b, and 2003) and WANG and KRAUS (2003).

Equilibrium Beach Conditions

To obtain consistent results on longshore sediment transport, it is crucial that measurements be conducted over equilibrium, or stable beach profile. Variations in beach profile shape may cause variations in wave condition, e.g., location of breaker line, breaker height and angle, and wave-energy dissipation pattern. Profile change may also alter the cross-shore distribution of longshore current. These changes may cause substantial variations of LST rate and its cross-shore distribution pattern. Therefore, a main goal of the first part of each experiment is to run the consistent input wave conditions to allow the beach to reach equilibrium. Once the beach profile reaches equilibrium, its shape remains stable during the rest of the experiment. Beach profile evolution and equilibrium during the first phase of the experiment are discussed in detail in WANG *et al*. (2003).

The amount of time it takes for the artificial beach to reach equilibrium depends on several factors, including 1) the wave energy and intensity of sediment transport, and 2) the initial shape of the beach profile. For example, during the first phase of experiment, it took 23 hours for the beach to reach equilibrium under the lower-energy spilling wave conditions. While under the higher energy plunging wave conditions, the beach reached equilibrium in 8 hours (WANG *et al*., 2003).

Longshore Uniformity of Hydrodynamic and Beach Conditions

One of the main objectives of the LSTF is to study the processes of longshore sand transport over a straight long beach. Variations alongshore and their influences on LST rate are assumed to be insignificant. To satisfy this assumption, longshore uniformity of hydrodynamics and beach conditions must be maintained over the main portion of the test beach.

The artificial beach is initially constructed with straight and parallel contours (Figure 2A). After several wave-run segments, some irregularities develop, especially near the lateral boundaries (Figure 2B). Typically, erosion occurs at the updrift boundary and accumulation at the downdrift boundary. The updrift erosion is caused by the lack of sediment recharge. The downdrift accumulation is induced by the less-than-unit trapping efficiency at the downdrift bottom traps due to boundary disturbance. The trapping efficiency is discussed in detail in the next section. The beach is restored to uniform conditions alongshore and its shape re-configured to equilibrium state after a certain number of wave runs. The downdrift bottom traps are cleaned at the same time. The interval between beach restorations is controlled by the length of the wave run and the transport intensity. Overall, the middle section of the beach has remained reasonably uniform (Figure 2). The transported amount between beach restorations is typically less than 2% of the total 150 m^3 of sand on the test beach (also limited by the capacity of the traps). The lack of sand recharge should not have significant influence on the overall sediment transport rate.

Proper setting of the circulation pumps is essential to the uniformity of longshore current, which is crucial to accurate measurement of LST rate. VISSER (1991) and HAMILTON and EBERSOLE (2001) discussed in detail procedures of tuning the circulation pumps. A set of criteria, e.g., the tilt of the mean water surface and the magnitude of return flow in the offshore area, was developed to evaluate the pump setting. When proper pump circulation is achieved, longshore current is reasonably uniform across the entire test beach (Figure 3). The weak negative velocity at the seaward end indicates that the return flow is minimal, i.e., the longshore current is circulated through the pumps rather than returning along the seaward boundary.

Alongshore uniformity of wave condition is achieved over the straight and parallel contour. Wave conditions are not very sensitive to minor irregularities in beach profiles. For example, the minor updrift erosion and downdrift accumulation (Figure 2B) do not have significant influence on longshore uniformity of wave condition, as indicated by the short error bar (one standard deviation) in Figure 4. Also, once the beach reaches equilibrium, cross-shore distribution of wave condition remain constant during different segments of wave run.

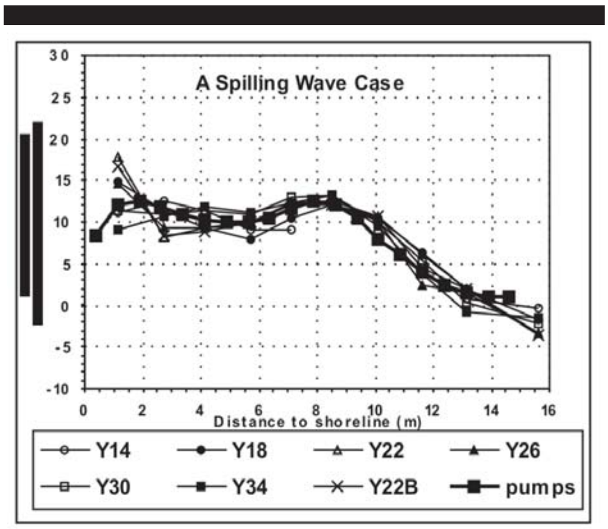

Figure 3. Pumps settings and the longshore-current uniformity. Numbers in the legend represent different alongshore locations.

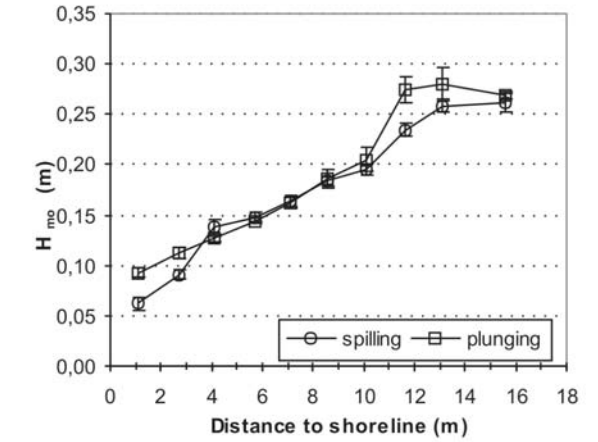

Figure 4. Alongshore uniformity of wave height.

Influences of Lateral boundaries

Twenty flow channels were installed at both the updrift and downdrift boundaries to guide the pump circulation of longshore current. To minimize the disturbance of the flow-channel opening to hydrodynamic conditions, wave-guides (smooth marine plywood boards) were installed along the openings of the flow channels, as shown in the right center of Figure 1. To allow adequate longshore current to flow into the test basin, the wave-guides extend to just below the wave trough. Measurements near the lateral boundaries indicate that the wave-guides do not impose significant restraint to flow. No substantially increased or decreased longshore current speed was measured near the boundary (Figure 3, Y14-downdrift boundary; Y34-updrift boundary). Visual observation indicated that the wave-guides successfully reduced the interactions between incoming waves and the flow channel openings.

It is not possible to completely eliminate the disturbance of lateral boundaries. The disturbance at the updrift boundary did not seem to have significant influence on longshore uniformity of hydrodynamic and beach conditions. The erosion measured at the updrift boundary was caused by the lack of sediment recharge rather than the boundary interactions.

The boundary disturbance at the downdrift end, where bottom traps were installed in the flow channels, cannot be neglected (Figure 1, bottom). Modest sand accumulation is measured in the immediate updrift of the downdrift bottom traps during most of the wave-run segments (Figure 2B, left side). This indicates that not all the longshore moving sand is being trapped, i.e.. The trapping efficiency is less than one. This accumulation immediately updrift of the bottom traps is added to the trapped amount, as a correction to the less-than-unit trapping efficiency, during the calculation of LST rate (Figure 5). This accumulation is removed during beach reconstruction. Generally, more sand accumulation, i.e., lower trapping efficiency, occurs during the wave-run segment directly following the beach re-construction (Figure 5, T1h, T1h_case7). The trapping efficiency improves as the beach at the downdrift boundary approaches quasi-equilibrium as the wave runs continue (Figure 5, T1h_case10). The trapping efficiency tends to be low when the pumped circulation is less than the wave-induced longshore-current flux (Figure 5, T1h_case5: purposely under-pumping). While the trapping efficient tends to be high when the pumped circulation is greater than the wave-induced longshore-current flux (Figure 5, T1h_case6: purposely over-pumping).

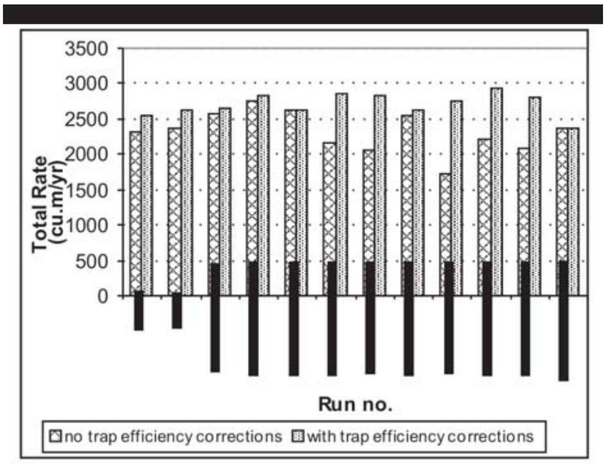

Figure 5. Trapping efficiency at the downdrift bottom traps.

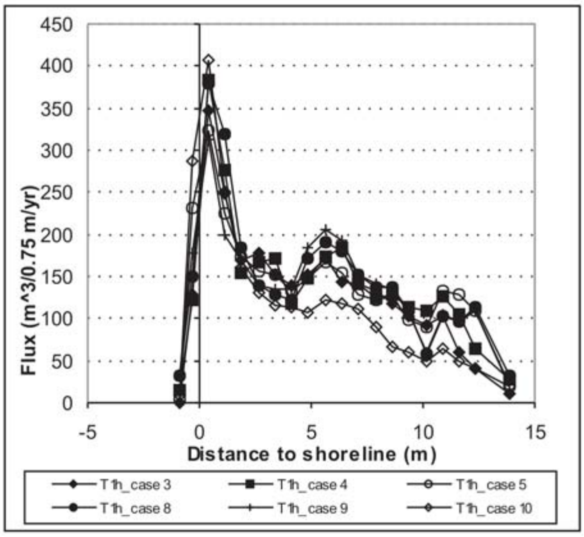

Figure 6. Repeatability of cross-shore distribution of longshore sand transport.

Temporal and Spatial Coverage and Measurement Repeatability

The duration of each wave-run segment is determined by its objectives and the intensity of longshore sediment transport. Typically, 3 to 4 wave runs are conducted between beach re-constructions and updrift sand recharge. Beach profiles are surveyed before and after each segment. To ensure that beach morphology has not changed significantly during each segment, its duration should not be too long. Therefore, the goals of each wave-run segment should be designed so that they can be achieved in a reasonable amount of time.

For irregular wave experiments, each sampling event should be sufficiently long so that reliable average values can be obtained. NIELSEN (1992) suggested that representative mean values can be obtained by averaging 150 to 200 waves. Therefore, each sampling event should be at least 150 times the peak wave period. Another factor that influence the sampling duration is the length of wave-drive signal. The sampling duration should be at least one times the drive signal.

Temporal resolution is controlled by the sampling frequency. Although requiring large data storage space, high sampling frequency has several advantages, including 1) ensuring accurate average values; 2) allowing examination of detailed wave motion and relative sediment suspension; and 3) providing adequate resolution to study turbulence through ensemble averaging. At LSTF, wave and current can be measured at up to 20 Hz and sediment concentration at 16 Hz.

Spatial coverage in the longshore direction is achieved by stationing the instrument bridge at various locations alongshore. The bridge can be moved automatically and precisely (2mm) in the longshore direction (Figure 1) The number of longshore locations is controlled by the durations of the wave run and the sampling event. The longer the wave run and the shorter the sampling duration, the more alongshore locations can be measured, i.e., the better the alongshore coverage. Presently, wave and current can be measured simultaneously at 10 cross-shore locations in LSTF. The sensors can be moved across shore manually. Typically, it is not necessary to move the co-located wave and current sensors. The 10 sensors provide adequate cross-shore coverage, at roughly 1.5 m intervals (Figure 1). It is, however, necessary to manually relocate the 4 arrays of the FOBS to improve the cross-shore coverage of sediment-concentration measurements.

Spatial coverage in the vertical dimension, i.e., throughout the water column, is achieved by manually moving the sensors through the water column. This is only relevant for current measurement. The FOBS array provides measurements of sediment-concentration profile at 19 vertical locations. The mounting of the ADVs was designed such that the sensors can be moved easily up and down. There is a time gap, roughly the sampling duration, among measurements at different water levels. Given the steady input conditions, the slight time difference should not cause any significant uncertainties.

As discussed earlier, the LSTF experiments are conducted in a number of wave-run segments. Each segment has a specific objective. Typically, one segment is conducted to obtain maximum spatial coverage in the longshore direction. One wave run is conducted to obtain vertical current profiles. One wave run is a repeat of a previous run to ensure data quality. Because beach profiles are surveyed before and after each wave run, beach changes during the run are measured. Optimal sampling plan should allow adequate coverage but should not be too long to cause substantial beach changes.

Overall, the repeatability of the LSTF measurements is satisfactory. As shown in Figure 5, the total LST rates are quite repeatable among different wave-run segments after the trap efficiency correction. The repeatability of cross-shore distribution of LST is also satisfactory (Figure 6). These indicate that the present design of the LSTF longshore sand transport experiments is successful.

CONCLUSIONS

The recently established LSTF has the capability of simulating wave and beach conditions that are directly comparable to annual averages along many low-wave energy coasts. The assemblage of the state-of-the-art instruments allows accurate measurements of wave, current, suspended-sediment concentration, and beach profile. Measurements can be conducted at high frequency of 16 to 20 Hz. An instrument bridge, which can be moved precisely alongshore, allows the sensors to be positioned almost anywhere in the surf zone.

The breaking-wave-generated longshore current is circulated externally using 20 turbine pumps. This circulation system is crucial in minimizing the interactions at the lateral boundaries and maintaining hydrodynamic and morphological uniformity alongshore. Each LST experiment is conducted in a series of wave-run segments. The objectives of the first several segments are to achieve proper pump settings and to allow beach profile to reach equilibrium state. Present data show that once these conditions are achieved, the beach and wave-current dynamics remain uniform alongshore during the rest of the experiment. Boundary interference, although not completely eliminated, is minimized, due to the reduction of internal current circulation.

At least four wave-run segments are conducted to ensure accurate and detailed measurement of longshore transport. Typically, one wave run is conducted to obtain maximum spatial coverage in the longshore direction. One wave run is conducted to obtain vertical current profiles. One wave run is a repeat of a previous run to ensure data repeatability. This design has proven to provide optimal temporal and spatial coverage.

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