A Study of Wave Breaking Turbulence and Sediment Suspension over a Barred Beach

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Abstract: A laboratory experiment was conducted over a period over three days at the O.H. Hinsdale Wave Research Laboratory at Oregon State University to test the hypothesis that sediment suspension occurs as a result of turbulence caused by breaking waves. Wave height, cross-shore velocity, and sediment suspension concentrations were measured by a horizontal array consisting of a single wave gage, three ADVs, and three OBSs. Three test cases with varying wave conditions were analyzed for across-tank variability, repeatability, and intermittency. Suspension events were defined and examined according to analysis done by *Jaffe and Sallenger* [1992]. It was determined that trends in average events characteristics were maintained across the tank. In addition, it was found that changing the wave characteristics affects the instruments in similar ways.

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1. Introduction

An essential part of coastal engineering is to develop a greater understanding of the causes of beach erosion as well as to find methods to prevent it from occurring. In order to accomplish this, it is necessary to examine smaller aspects of the overall problem. As net sediment transport has become an increasingly important aspect, nearshore sediment suspension has received much attention. Experiments aimed at measuring suspended sediment concentrations have been conducted both in the field and in the laboratory. Most of these share a common goal of determining a relationship between specific wave characteristics and the magnitude of the corresponding sediment suspension concentrations so that future predictions can be made.

Perhaps the most important finding of these experiments is the intermittency with which sediment suspension occurs [*Jaffe and Sallenger*, 1992]. In addition to this intermittency, researchers have also observed periods of extreme suspension, often referred to as "suspension events". While it has been suggested that suspension events occur as a result of passing wave groups [*Jaffe and Sallenger*, 1992; *Hanes*, 1991], this is not always the case. The same level of wave activity is often associated with both large and small suspended sediment concentrations [*Cox*, 2004]. Thus, the question of what causes suspension events still remains.

2. Objectives

In the present study, the hypothesis that suspension events occur as a result of turbulence caused by breaking waves has been tested. A series of experiments were conducted to determine if a correlation exists between wave breaking turbulence and corresponding sediment suspension over a barred beach. This paper first examines the experiment setup and procedures used to collect suspended sediment concentrations and specific wave characteristics including wave height, wave period, and velocity. The initial analysis of this data is then presented. Finally, a summary of the findings is included with suggestions for future research.

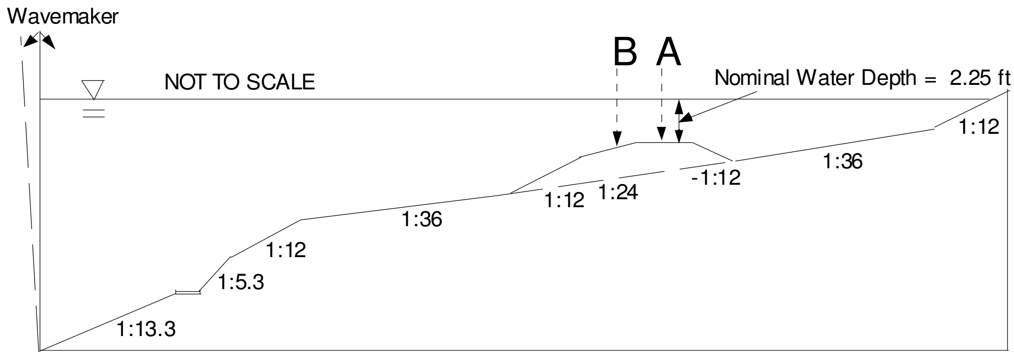

Figure 1: Beach profile and instrument location

3. Experiment Setup and Instrumentation

3.1 Facilities

A short series of laboratory experiments was conducted over a period of three days (July 22, 23, and 26, 2004) in the large wave flume at the O.H. Hinsdale Wave Research Laboratory at Oregon State University. The flume has a length of 104 m, a width of 3.7 m, and a maximum depth of 4.6 m. It is possible to control the depth with a system of adjustable 12 ft by 12 ft floor slabs thus creating various bathymetries in the flume. The underwater beach profile utilized in this project, shown in Figure 1, includes a bar over which data was collected. There were two locations at which instruments were placed, one directly over the bar (location A at bay 10.5) and the other slightly offshore of the first (location B at bay 11.5). These are also shown in Figure 1 and will be referred to in further discussion.

3.2 Test Cases

In order to satisfy all research needs, a total of eight test cases, each ranging from two to nine runs, were completed using sediment from Florence Beach located in Florence, Oregon. The cases varied in sediment placement, instrument configuration and location, and duration depending on the analysis to be done. Measurements of wave height, wave velocity, and suspended sediment concentration were taken respectively by arrays of wave gages, Acoustic Doppler Velocimeters (ADVs), and Optical Backscatter Sensors (OBSs) for most of the eight cases. Although the ADVs remained in an across tank horizontal array for all cases, the OBSs were placed in either a horizontal or vertical configuration to record either across tank variations or water column variations in suspended sediment. Additionally, the OBS gain was adjusted from low to midrange after Case 3. The conditions for each of the eight cases are included in Table 1 as a reference. The scope of this paper, however, includes analysis for Cases 1, 3, and 4 only.

The three cases addressed in this paper each included seven test runs. The runs varied in wave height and wave period and included both regular and irregular wave cases. The difference in wave conditions for the regular runs is evident in their shifting break and plunge points as shown in Figure 2. It is clear that while the break points remained fairly consistent for each of the runs, the plunge points were much more variable. Cases 3 and 4 each have two additional runs (Runs 8 and 9) to serve as standards by which repeatability can be measured. Both the nominal wave characteristics and the characteristics as measured by a wave gage located in the same plane as the instrument array are given in Table 2. The table also includes values of surf similarity, ξ, a parameter that will be explained in further discussion.

Table 1: Conditions for eight test cases

Case	Location	OBS Configuration	Gain	Comments
1	A	horizontal array	low	no sand
2	B	horizontal array	low	------
3	A	horizontal array	low	------
4	A	horizontal array	high	------
5	A	--------	---	no OBSs
6	A	vertical array	high	------
7	A	vertical array	high	OBS 2 & 3 flipped toward ADVs
8	A	vertical array	high	all OBSs flipped, long run

3.3 Instrumentation

As previously mentioned, data was collected using an arrangement of wave gages, ADVs, and OBSs located throughout the tank. A figure illustrating their cross-shore locations is not provided as all measurements used in this paper were collected by instruments located in the same across tank plane (location A, *see Figure 1*).

The analysis presented in discussion to follow was completed using data from a total of seven instruments including one wave gage used to measure wave height and period, three ADVs, each of which measured velocity at one point in three directions, and three OBSs which measured turbidity corresponding to suspended sediment concentration in the water. Data collected by the instruments were compiled by two separate data acquisition systems, one for the wage gages and OBSs and another for the ADVs. Although the ADV system had a built-in calibration program, the remaining data were recorded simply as voltages. Wave height measurements in meters have been determined, however, since any change in the resistance of the current flowing through the wave gage corresponded directly to a change in wave height. It has been assumed that the calibration curves for the three OBSs are linear and nearly identical; therefore, suspended sediment concentrations will be analyzed in terms of voltages.

The across tank configuration of the instruments is shown in Figure 3. It was determined that the sample volume of an ADV is 5 cm from its transmitter. As it was necessary for each set of instruments to record measurements at the same depth, the face of each OBS was mounted 5 cm below the transmitter of the corresponding ADV. The question of proximity limits was addressed prior to mounting the instruments and determined not to be an issue.

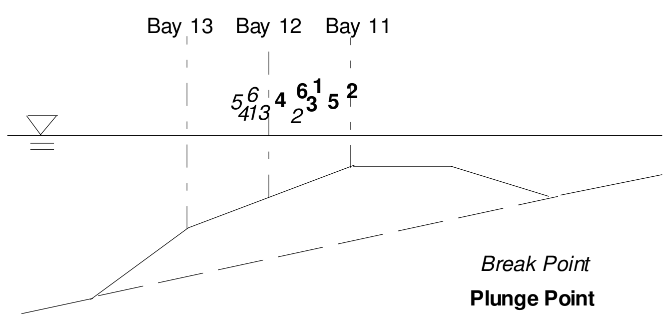

Figure 2: Breaking and plunging detail over the bar

Table 2: Nominal characteristics for each run with measured characteristics at location A

Run	T_{nom} (s)	H_{nom} (m)	Case 1 T_M (s)	Case 1 H_M (m)	Case 1 ξ	Case 2 T_M (s)	Case 2 H_M (m)	Case 2 ξ	Case 3 T_M (s)	Case 3 H_M (m)	Case 3 ξ
1	2.7	0.6	2.706	0.445	0.211	2.756	0.356	0.236	2.721	0.386	0.226
2	4	0.6	4.005	0.399	0.33	4.06	0.397	0.331	4	0.425	0.319
3	5	0.6	5.138	0.461	0.383	5.06	0.395	0.414	5.051	0.378	0.423
4	2.7	0.65	2.72	0.371	0.231	2.744	0.328	0.245	2.744	0.334	0.243
5	4	0.65	4.034	0.434	0.316	4.1	0.384	0.336	4.01	0.381	0.337
6	5	0.65	5.008	0.44	0.392	5.093	0.378	0.423	4.995	0.448	0.389
7*	4	0.6	3.984	0.416	0.323	3.989	0.398	0.33	3.969	0.393	0.332
8*	4	0.6	----	----	----	3.986	0.404	0.328	3.974	0.407	0.326
9	4	0.6	----	----	----	4.025	0.384	0.336	4.016	0.391	0.333

*Irregular runs with γ =20

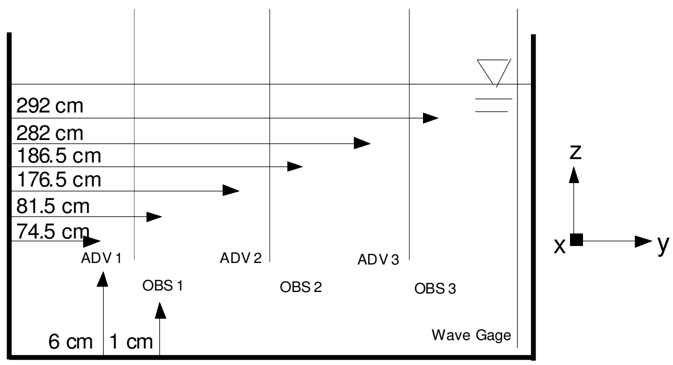

Figure 3: Across tank instrument configuration

4. Analysis and Discussion

The discussion that follows is based on initial analysis completed for Cases 1, 3, and 4. Due to synchronization problems between the data acquisition systems, each produced a time series of a different length for any given run. Therefore, it was necessary to develop a method for selecting what subset of the time series would be analyzed. The selection was based on the middle section of waves as recorded by the wave gage. Since only mean values of velocity are presented, the slight shift in the ADV time series does not have an impact on the analysis.

It is important to note that while Case 1 includes no sand, Cases 3 and 4 include sand that was graded only prior to collecting data for Case 3. This means that although the only difference in the two cases should have been the gain adjustment, it is probable that the beach profile for each run was also different.

In the sections to follow, variability across the tank is addressed first. Although similar analysis was done for all cases, only supporting data from Case 4 is included. Repeatability in Cases 3 and 4 is then discussed. Finally, intermittency of the suspended sediment concentration is presented with an emphasis on Case 4 since the higher gain setting resulted in larger measured voltages.

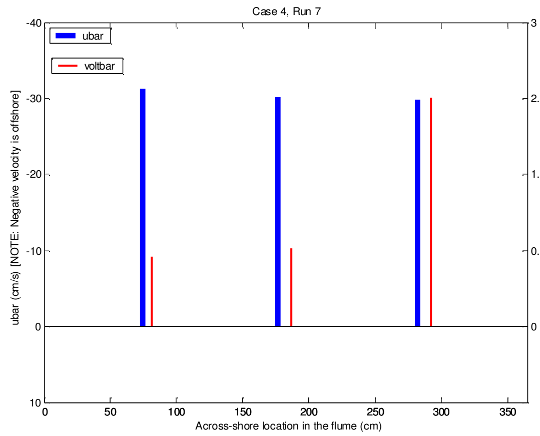

Figure 4: Sample plot of mean values

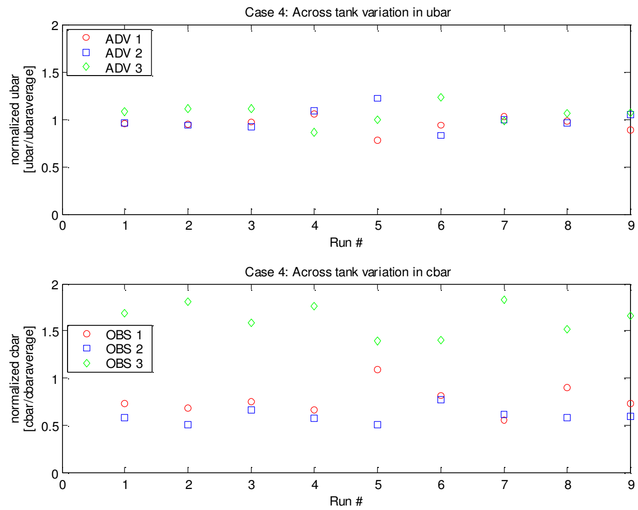

Figure 5: Variability plot for Case 4

4.1 Across-tank Variability

It was necessary to address the issue of variability in order to determine whether conditions were consistent across the tank. This was done separately for each case and involved cross-shore velocity, u (cm/s), measurements for Cases 1, 3, and 4, and suspended sediment concentrations, c (volts), for Cases 3 and 4. As an initial representation of conditions across the tank, the mean of u and c for each set of instruments was found for all runs in the case. A sample plot of these means is provided in Figure 4. In order to determine variability, the values for each run were then normalized by the average of the means for that run as shown in Figure 5.

It is clear from Figure 5 that mean velocity conditions were fairly consistent across the wave flume as indicated by relatively low variability among the ADVs. There was an apparent increase in variability for Runs 4, 5, and 6 but this may be due to the increased wave height. It is interesting to note that the lowest variability occurred in the two irregular wave cases.

Although the across-tank variation seemed to be significant in terms of mean concentration, it is important to note that the means themselves were smaller so that when normalized, smaller differences between the mean and the average of the means are amplified. There was an obvious high bias in OBS 3 which could possibly be due to imperfections in the grading of the sand. While the bias should be noted, it becomes less of a problem when considering the close relationship between OBS 1 and 2 for most runs in the case.

4.2 Repeatability

As previously mentioned, Cases 3 and 4 each had two additional runs which served as standards for repeatability. Such a measure was necessary in order to ensure that results were representative of given conditions and could be reproduced if needed. For balance, both a regular (Run 2) and irregular (Run 7) wave case were repeated in Runs 9 and 8 respectively. The $\overline{u}$ and $\overline{c}$ values for Runs 2 and 9 in both Cases 3 and 4 are shown in Figure 6. The corresponding values for Runs 7 and 8 are shown in Figure 7.

There are several important things to be noticed in these figures. First of all, it is obvious that the standard of repeatability for $\overline{u}$ was fairly high for both Run 2 and Run 7 indicated by the proximity of each run and its respective repeated run. Although Case 4 was clearly less variable than Case 3, the variability in neither of the cases was significant. Even more interesting than the high repeatability for $\overline{u}$, which can be expected, was the high repeatability for $\overline{c}$. This implies that although there was a lot of variability in the mean suspended sediment concentrations across the tank, as seen in Figure 5, the variability for each individual OBS was very low. This is especially true for Case 3 due to the lower gain setting which resulted in lower voltage readings.

The figures also give an important impression of variability between Cases 3 and 4. Values of $\overline{u}$ were reasonably consistent, especially for the regular wave case. It is also clear that even when values were not consistent, trends in values were. For example, ADV 2 in the irregular wave case seemed to have greater variability among its runs than the other instruments but the trend in high values for ADV 2 was consistent for all runs. The consistency in trends was also true for values of $\overline{c}$. These values could not be directly compared due to differences in gain but there was an apparent high bias in OBS 3 for all runs and cases, as observed previously for Case 4 in Figure 5. Likewise, values measured by OBS 2 are consistently low. These observations along with those of high repeatability indicate that conditions in the tank were similar for both cases and fairly repeatable.

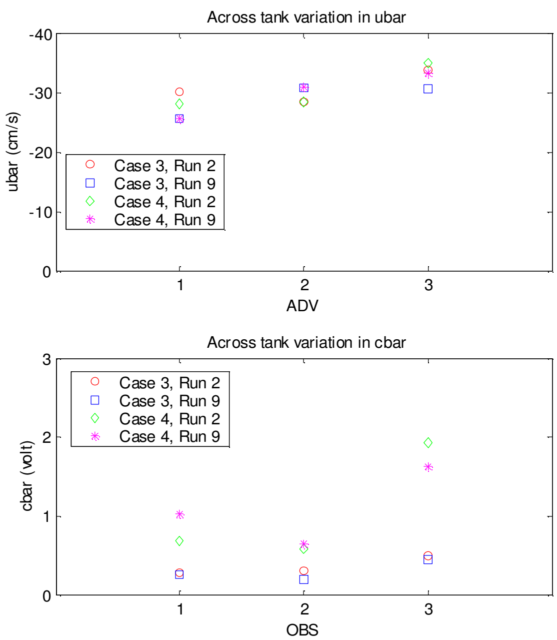

Figure 6: Repeatability for Runs 2 and 9

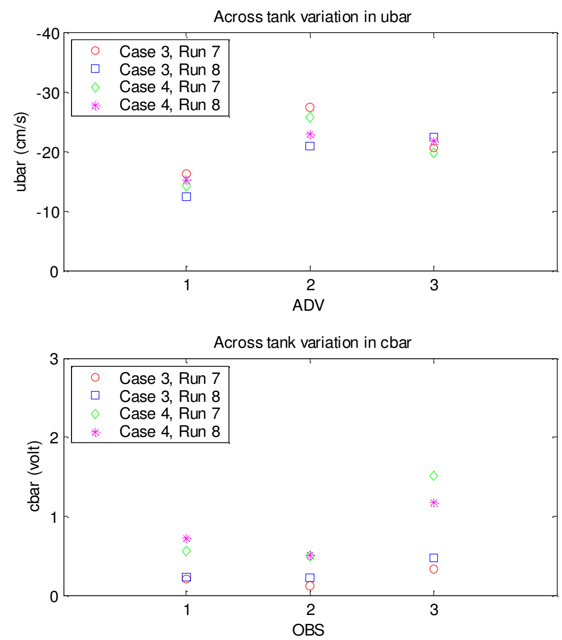

Figure 7: Repeatability for Runs 7 and 8

4.3 Intermittency and Suspension Events

A fundamental understanding of suspended sediment processes requires a study of the intermittence with which it occurs. Often concentration time series are marked by periods of intense concentration, referred to as "suspension events", followed by periods of relatively low concentration. Numerous experiments have been conducted to observe the conditions that cause such irregularity in measured concentrations [*Voulgaris and Collins*, 1998; *Sternberg, Shi, and Downing*, 1984]. This discussion will focus on the intermittency of suspended sediment concentrations for Case 4, with an emphasis on suspension events, both large and small. A definition for large and small suspension events will be provided. The events for each run will be compared so that a correlation to wave conditions may be determined.

Before examining the suspension events, a technique for comparing individual runs had to be established. The surf similarity, ξ, was selected and is defined as, $\xi = \frac{m}{\sqrt{H_b/L_0}}$ where m is the beach slope, H_b is the wave height at breaking as measured by the wave gage (*see Table 2*), and L_0 is the deep water wave length defined as $L_0 = \frac{gT^2}{2\pi}$, where T is the nominal wave period. For this discussion, m is taken as 1/24, corresponding to the beach slope directly adjacent to the instrument location. The values of ξ for each run are given in Table 2 as mentioned previously and will be referred to in further discussion.

In order to examine the intermittency of the concentration time series, a subset of the data was selected. In this selection, the beginning of the record was chosen according to the wave gage as described previously. Unlike the subset of data used in the variability analysis, however, in which the subset was ended after only a limited number of waves, the selection for intermittency analysis spanned nearly the entire length of the concentration series. This was done so as not to exclude any significant concentrations while only including those containing potentially valuable information. This selection was analyzed using a method followed by *Jaffe and Sallenger* [1992] in which it was first necessary to develop a strict definition for "suspension event", a term applied to any intense period of concentration. According to *Jaffe and Sallenger*, a small event was defined to occur when the concentration exceeds the mean of the series plus one standard deviation. In addition, a large event occurs when the concentration is greater than the mean plus three standard deviations. As it was important to determine a beginning and end to each event, the mean concentration was chosen to be the event start/end threshold. An average suspended sediment concentration time series illustrating event definitions is shown in Figure 8.

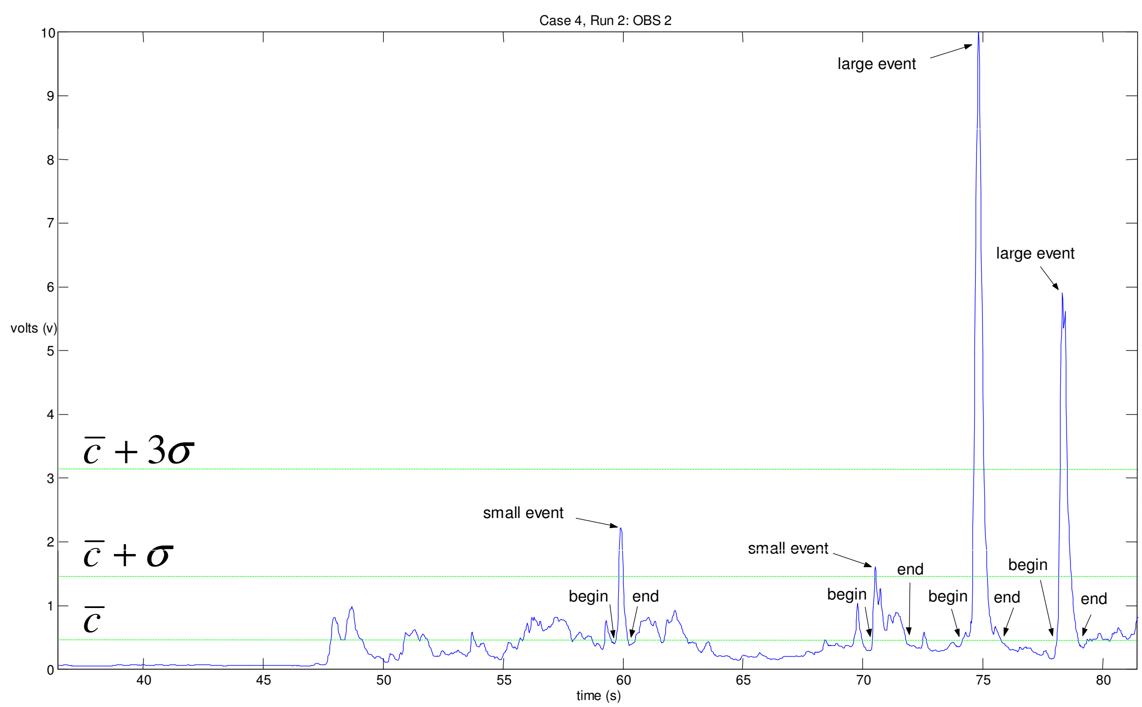

Figure 8: Concentration time series illustrating event definitions

After the suspension events were defined, an event time series was generated for each concentration time series as described in *Jaffe and Sallenger*. This was done in order to determine the number of events for each run so that average event characteristics, such as duration, rate of occurrence, and percentage of total time they occurred, could be found. The event time series were produced by establishing the beginning and end of each event as depicted in Figure 8. Each event was then represented in the series as a bar with a width equal to its duration. The time series of both all and large events for an average concentration series are shown in Figure 9. The clarity of this series allows for a straightforward analysis of the events.

Before looking at the analysis resulting from the event time series, it is beneficial to examine the time series itself. It is clear from the series that large events occur less frequently than small events. This makes sense since regardless of what causes an event to occur, it can be expected that the cause must be amplified in order for a large event to take place. The time series also indicates that small events are more likely than large events to occur in the onset of wave activity. Since the width of an event is equal to its duration, it can be observed that a large event lasts longer than a small event, on average. It can not be assumed, however, that large events occur a greater percentage of the time. In order to make such observations, more quantitative analysis is required. Such analysis is presented next.

The event time series were analyzed both in terms of surf similarity and in terms of across-tank location. This was done to give an impression as to how much altering the wave conditions would affect measurements of concentration across the flume, if at all. The average event characteristics including mean rate of occurrence, duration, and percentage of total time for each of the three OBSs are shown in Figure 10. Each subplot includes both large and all events. The characteristics are plotted versus surf similarity in order to represent the changing

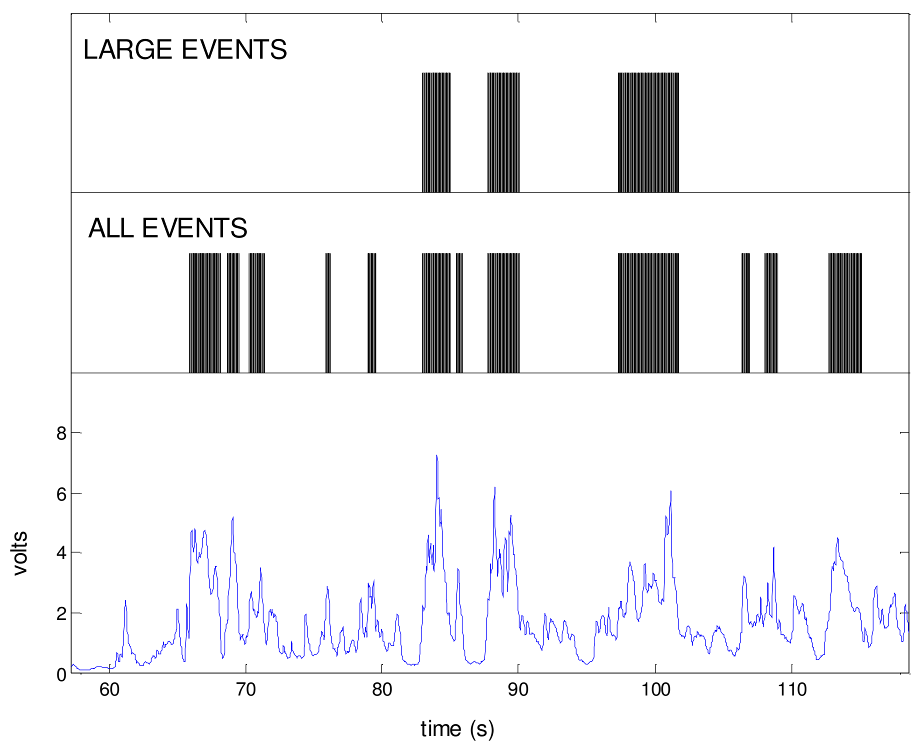

Figure 9: Typical event time series for an average concentration series

wave conditions. It should be noted that no large events were recorded by OBS 3 for Runs 3 and 6, represented by the two highest values of surf similarity.

The series of plots found in Figure 10 quantifies several of the observations made directly from the event time series in Figure 9. As expected, large events occurred less frequently than small events in all locations across the tank. In addition, OBS 3 recorded events more frequently than the other instruments. The mean duration of larger events was almost always longer than that of small events. This makes sense since it follows that a higher concentration of suspended sediment would require a longer period of time to dissipate than a lower concentration. A maximum duration of nearly 20 seconds was recorded in run 9 by OBS 1, indicated by a sharp increase in mean duration for the instrument. The similarity of trends in terms of both surf similarity parameters and across-tank location is striking. This suggests that while individual measurements may fluctuate, there is little variation in the response of the instruments to changing wave conditions. This observation is significant since it reveals that although the mean concentrations for OBS 1 were higher than those of the others, as indicated previously, events occurred roughly the same percentage of time in all locations across the tank.

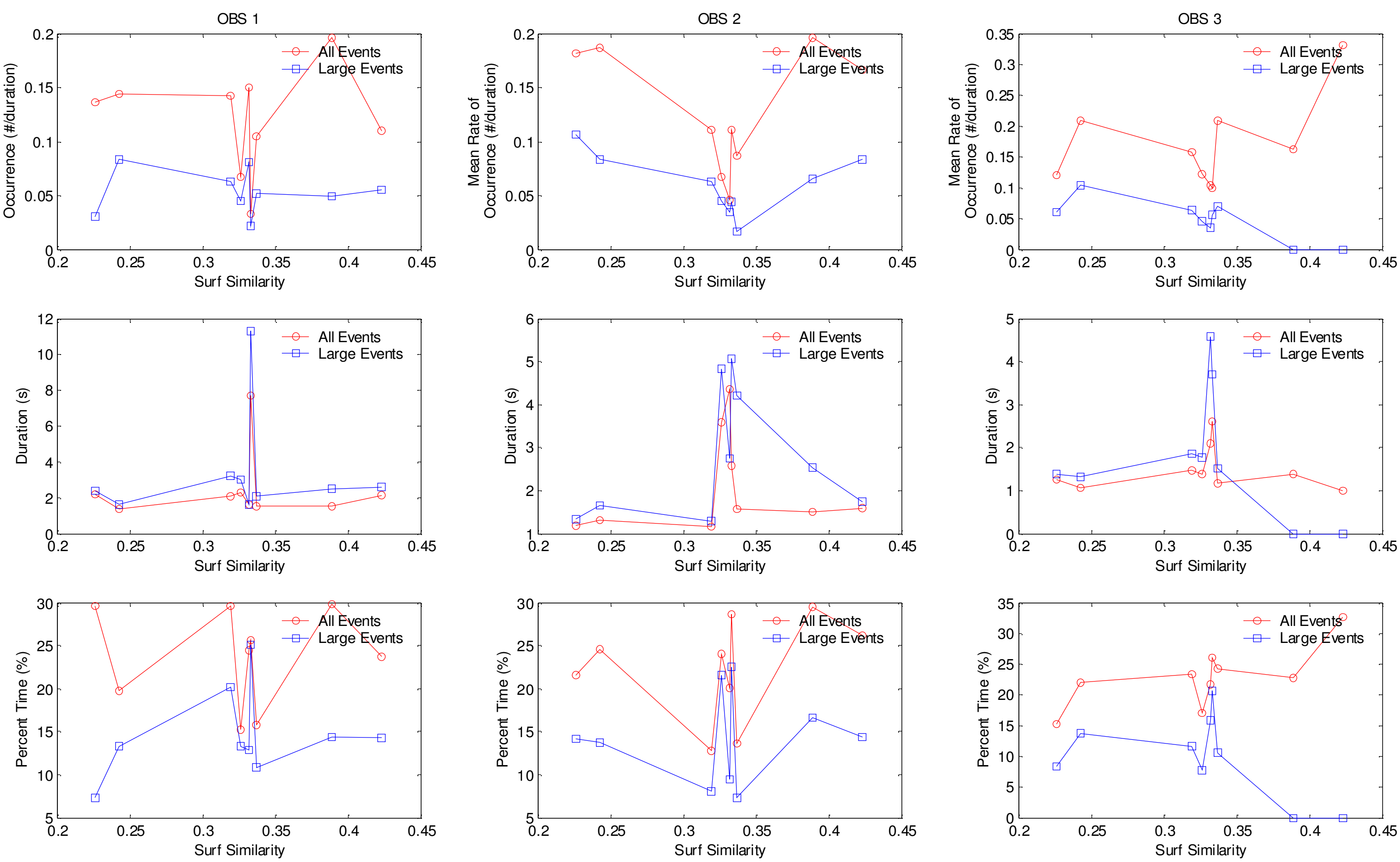

Figure 10: Average event characteristics for both large and all events in terms of across-tank instrument configuration

5. Summary and Conclusions

While the initial intent of the research project was to determine a correlation between turbulence caused by breaking waves and corresponding suspended sediment concentrations, the focus was shifted to sediment suspension processes under several different wave conditions. In addition, across-tank variations in individual instrument response under the same conditions were thoroughly examined. The analysis included variability, repeatability, and intermittency. Suspension events were defined according to *Jaffe and Sallenger* [1992] and average event characteristics were described.

It was determined that across-tank variability was low in terms of cross-shore velocity and slightly higher for suspended sediment concentrations. Repeatability of the experiment was fairly good. In addition, it was determined that trends in average events characteristics were maintained across the tank. Finally, it was found that changing the wave characteristics affects the instruments in similar ways.

6. Suggestions for Future Research

To improve the project, calibration of the OBSs is suggested in order to quantify the assumption that suspended sediment concentrations have a linear relationship to the voltages recorded by the instruments. An improved method of grading the sand is needed in order to ensure that grading is consistent across the tank. Finally, longer runs should be recorded to enhance statistical information relating to average event characteristics.

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