AN INTRODUCTION TO EVENT-BASED MODEL FOR THE STUDY OF SEDIMENT TRANSPORT IN THE SWASH ZONE

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Erosion and accretion of the beach face and consequently the movement of the coastline are the direct result of net sediment transport in the swash zone. Different models have been introduced in order to predict hydrodynamic parameters and, thereafter, movement of particles. However, the capability and comprehensiveness of the models in different conditions are still questionable. In reviewing models established for sediment transport in the swash zone, one can easily conclude that in the most cases the transport of bed load has been predicted traditionally by the application of quasi-steady formula. Scientists have identified many of the important physical processes driving sediment transport throughout the swash zone, but a detailed description of the small-scale sediment dynamics is still far from complete. In this paper the behaviour of coarse sediment particles in the bed load mode of transport in response to the flow regime experienced in the swash zone are investigated. Accordingly, a model called event-based model is introduced for prediction of the beach profile change, and the results of the model are compared with some laboratory data. The comparison between the results of the model and measured beach profile in the laboratory reveals that the results of the model developed in the present study on the basis of the event-based concept are very promising, particularly in the range of flow for which the behaviour of sediment particles is more accurately understood.

Keywords: swash zone, sediment, beach evolution, particle jump length, laboratory data.

INTRODUCTION

There has always been much concern over problems of beach erosion and long term coastal change. Erosion and accretion of the beach face and consequently the movement of the coastline are partly the direct result of net sediment transport in the swash zone i.e. the part of beach that is frequently covered by uprushes and exposed by return of water seaward. Hence, a quantitative understanding of the swash zone dynamics and sediment transport associated with wave uprush and backwash is essential for predicting morphological changes in the near-shore region.

The swash zone is one of the most dynamic parts of a beach. The processes occurring in the swash zone are important to the sediment budget and resulting morphological changes of the near shore and determine the possible erosion or accretion in this region and, as a consequence, the movement of the coastline. In addition, the swash zone is the boundary condition for the integrated domain of mathematical models of the coastal zone and therefore, better knowledge of the processes involved in the swash zone has a direct influence on the overall accuracy of the predictions of those models (Longo et al. 2002).

In the last two decades, several efforts have been made to elucidate the nature of the flow in the swash-zone and, consequently, sediment transport phenomenon in this area. Different models have been introduced in order to predict hydrodynamic parameters and, thereafter, movement of particles (Bakhtyar et al 2009). However, the capability and comprehensiveness of the models in different conditions are still questionable. In other words, the knowledge of the interaction between flow and sediment within the swash-zone and components influencing it, is still inadequate with respect to producing an accurate model for swash dynamics (Elfrink and Baldok, 2002). Several improvements are still needed before a general, robust, and reliable mathematical model of the swash zone transport is obtained (Larson et al 2004).

the sediment transport models applied so far for the swash zone, which are conceptually the modification of the existing models under oscillatory flow regimes, are not fully capable of incorporating all potentially important aspects in the swash zone, and as a result the agreements with observations are poor. Acute unsteadiness and non-uniformity of the flow in the swash zone, in addition to the phenomena of in/exfiltration and, more importantly, discontinuity of the flow are unique features of the swash zone. These make it different in behaviour to the surf zone and further seaward. This can be considered as the reason why the modification of the usual sediment transport formulae for oscillatory flow for application in the swash zone has not been conclusive.

In this paper the behaviour of sediment particles in the bed load mode of transport in response to the flow regime experienced in the swash zone are investigated in a different view. Accordingly, a model

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called event-based model is introduced for prediction of the beach profile change, and the results of the model are compared with some laboratory data. The model is generally capable of predicting cross-shore beach profile changes in the bed load mode of sediment transport.

The outline of the present study is as follows: the concept of event-based model is firstly introduced. The instrumentation, set-up and procedure of laboratory experiments for the measurement of particle responses in the swash zone and beach profile changes are described in the next section, followed by experimental results, analysis and discussion. Then the development of the numerical model called “Beach Profile”, for the evolution of beach profile is presents, followed by the analysis of the results and comparison with experimental data. Finally, the outcomes of the research are concluded and recommendations for further research on the subject are introduced.

EVENT-BASED MODEL

A study of hydrodynamics in the swash zone reveals that there are fundamental differences between the swash zone and deeper parts of the near shore zone (Shanehsazzadeh et al. 2001). Flow in the swash zone is a discontinuous time-series of swash events from the action of wave run-up, which it is not the case further seaward where the flow is continuous and oscillatory. In other words, the orbital motion of water in the surf zone changes in the swash zone to the transport of a water mass up the beach face due to final bore collapse (Puleo et al. 2000).

Near-bed velocities in the swash zone are highly irregular, containing a large amount of vertical asymmetry i.e. high onshore acceleration at the beginning of the uprush and then steady decrease of the velocities to zero during the remainder of the uprush (saw-tooth shape). The velocity field has also horizontal asymmetry (skewness) i.e. the difference between uprush and backwash maxima and their durations. Infiltration, exfiltration and turbulence due to bore collapse are the other unique features of the flow, which are believed to affect directly the sediment transport process in the swash zone (Hughes et al 1997). It is now evident that all the processes involved in this area must be recognised and their relative importance needs to be re-evaluated as a pre-requisite for successful progress in modelling sediment transport in the swash zone (Butt and Russell, 1999).

In reviewing models established for sediment transport in the swash zone, one can easily conclude that in the most cases the transport of bed load has been predicted traditionally by the application of quasi-steady formula (Larson et al. 2001 and Masselink and Hughes 1998). Recently, several good conceptual models have also been developed that include one or more physical aspects of swash zone (Nielsen2002 and Turner and Masselink 1998). However, no conclusive model exists that incorporates all potentially important aspects, with reasonably good agreement with observations (Elfrink and Baldok 2002).

Sediment transport in the swash zone is the result of the action of a sequence of swash events. When a wave breaks and an event sweeps the swash zone, from each section of the beach face the flow carries some amount of particles in the landward direction due to uprush and conversely some amount in the seaward direction due to backwash. The number of particles in motion and their destinations depend on the characteristics of the swash events. If the influences of each event on the beach face are assumed independent of the other events, then within a particular time interval, the change in the beach profile would be the superposition of the resultant of the sediment particles’ response to the individual swash events which the beach has experienced in that time interval. This is the concept behind the event-based model for sediment transport in the swash zone.

It can clearly be concluded that with this point of view, the target of the study is not to find the rate of sediment transport (which is common in existing models), but rather it is the response of particles to a swash event. The response of particles in this context means the number of particles that move through a given cross section (in terms of weight or volume) and also their destination due to one particular swash event in one direction i.e. solely uprush or backwash. The influence of other aspects of flow in the swash zone such as bed slope, in/exfiltration, inertial forces, bore-generated turbulence is contained within these two parameters, “number” and “destination”. Therefore, to apply this model the following questions must be primarily answered:

What is the destination of a particle when it experiences a swash event? (Here termed “jump length”)

How many particles move from a given surface location in each event? (In term of “weight” moved)

The present study investigates sediment transport in the swash zone using this new viewpoint. In the following sections, the experiments which were conducted in the present research to provide information about the response of particles to swash events are described. This can supply the basic materials for the new model developed on the basis of the event-based concept.

EXPERIMENT

In order to generate a single, very highly accelerated asymmetric wave in the laboratory, similar to the flow over the swash zone, a mechanical apparatus called Single Asymmetric Wave Generator (SAWG) was designed and constructed. Figure 1 shows a sketch of the apparatus. A travelling carriage mounted on the sides of a long flume, moves a paddle very rapidly through initially still water in the flume and thus generates a single wave. The motive power of the carriage is provided by falling weights through a pulley system. Figure 2 shows a number of the near bed water velocity time-histories of the waves generated by SAWG. It should be noted that the generated waves are mostly not in the swash. Therefore, some aspects of the flow in the swash are not fully simulated, namely high turbulence and in/exfilteration. Furthermore, the apparatus at this stage can only generate uprush and as shown in the figure 2, backwashes are absorbed. However, the generated waves being highly accelerated is very close in behavior to the flow regime in the swash zone. Response of particles to such a wave condition is believed that can be implemented as a first stage in the study of swash zone sediment transport.

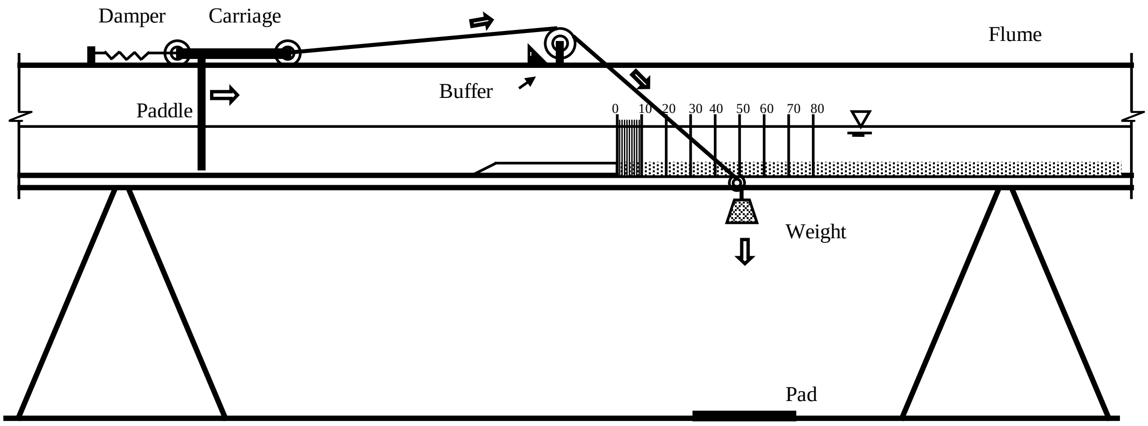

Figure 1: The sketch of the Single Asymmetric Generator (SAWG) apparatus.

The jump length (JL) and the weight (w) of well-rounded, very narrow banded particles of $d_{50} = 3mm$ were measured in various velocity profiles of solitary waves, provided by the SAWG. The particle motion of this size is confined to bed load. Jump lengths of particles were measured by monitoring the motion of a number of marked particles. Due to the effects of numerous variables on the motion of particles, the jump length in particular and the weight moved must be considered as stochastic parameters. Therefore the experiments in each flow condition must be repeated up to a sufficient number (sampling space) in order to achieve the reliable statistical parameters such as average jump length ($\overline{JL}$). In the present experiment this number was increased up to 280 data for each flow condition for this purpose. The experiments showed that the probability distribution of jump lengths was quite skewed, different from that of saltation length in steady unidirectional flow, which the latter is very close to a Gaussian distribution (Hu and Hui 1996).

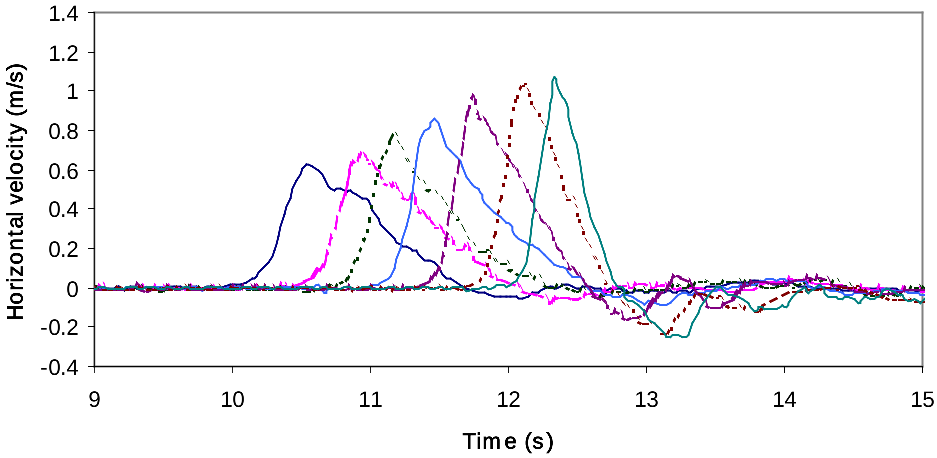

Figure 2: Velocity time-histories of the waves generated by Single Asymmetric Wave Generator, SAWG.

Before going through the discussion about the results obtained for the JL and weight (W) under the action of solitary waves, choosing an appropriate flow parameter for this particular flow regime is essential; a representative parameter which can represent all major and effectual factors in the process. The parameter is used to provide a relationship between hydrodynamic induced forces and particles' movement.

Starting from the approach of Bagnold (1966) in which the motion of sediment particles is ascribed to the energy of the water motion, the excess energy of solitary wave contributing in the motion of particles is integrated over the duration of the wave. Parameter sigma defined as equation below is proportional to integral of excess energy over an arbitrary single wave with the assumption that a quadratic relationship exists between shear stress and near bed flow velocity ($\tau_0 = \frac{1}{2}\rho f u^2$):

$$\sigma = \int \frac{\left((u(t)^2 - u_{cr}{}^2)\right)u(t)}{u_{cr}{}^3} dt$$

In which u(t) is time history of near bed velocity (m/s), u_{cr} is the critical velocity at which particles start to move and t is time. The parameter sigma can be considered as a rational and appropriate parameter of a single asymmetric wave with an arbitrary near- bed velocity time history. The influences of slope and permeability are contained with the parameter sigma through the change in u_{cr}.

$\overline{JL} - \sigma$ Relationship

Figure 3(a) presents the relationship between $\overline{JL}$s and the flow parameter sigma for flow conditions of figure 2. A linear regression fits the data closely (R2=0.96). The figure also illustrates the uncertainties of $\overline{JL}$s. There are two sources for these uncertainties, firstly from the statistical estimate of the mean, using a 95% confidence interval. The second source of uncertainties is due to measurement error. This, for the case of JL, was ± 2.5 mm. The intervals displayed in the figure show the sum of the confidence interval and error due to measurement.

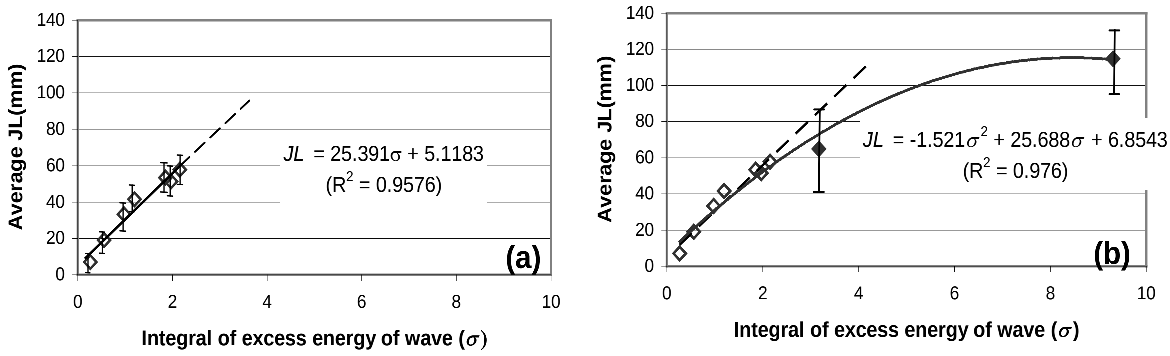

Figure 3: $\overline{JL}-\sigma$ **relationship. (a) Linear (b) Nonlinear.**

In figure 3(b) the $\overline{JL}$ data from two additional conditions have been added to the graph. These two data has been separated from the others because relatively different flow regimes have caused them i.e. more turbulent regime. As can be seen, these two do not follow the linear trend of the other data of less turbulent conditions. Two reasons can be conceived for this observation. Firstly, it can be assumed that flow fluctuations have a significant influence on the $\overline{JL}$, and $\overline{JL}$ reduces in highly varying velocity time history compared to the condition in which the flow is free from significant fluctuations. Another interpretation is that the trend of gentle increments of $\overline{JL}$ in the high-energy condition can be considered as the nature of JL regardless to the effect of fluctuation. More experiments in higher energy conditions with less fluctuation are necessary to explain this uncertainty.

To investigate the influence of slope on the jump length, the experiments were also conducted on a 10% slope. With considering modification in sheer stress on slop, no distinct difference was observed between the jump length on the moderate slope and those on the horizontal bed (Shanehsazzadeh and Holmes 2002).

$\overline{w}-\sigma$ Relationship

In order to find the weight of sediment that moves with individual asymmetric waves, limited experiments were conducted. Figure 4 shows the relationship between the amount of sediment moved when an asymmetric wave passes a certain location (weight/area, $\overline{W}$) and the flow parameter sigma. With the definition of the average jump length, which includes the zero jump lengths, the nearly constant weight shown in figure 4, for the range of available flow velocities, is quite justifiable. In other words, almost all particles on the surface move with the average jump length, either zero or more.

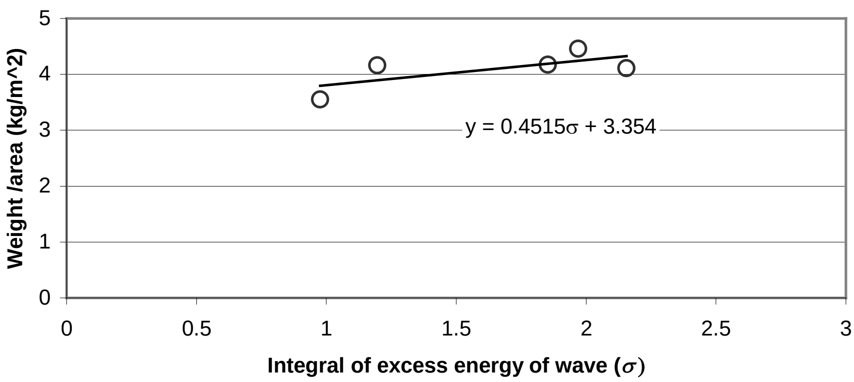

Figure 4: $\overline{w}-\sigma$ **relationship.**

NUMERICAL MODEL FOR BEACH EVOLUSION

A Numerical model called "Beach Profile" was developed based on the concept of event-based model for simulation of cross shore beach profile evolution due to action of uprushes and backwashes in the surf and swash zone. The model is applicable on the beaches where the bed materials consist of coarse sand or gravel.

In the model the cross-section of a beach is considered as a number of small sections with the width of δx (discretization of beach profile) in the cross shore direction. When the flow sweeps the beach, each section experiences its own velocity time history including a number of uprushes and backwashes during a particular time interval. If each section is considered as a container of sediment particles, the container would lose particles due to action of flow on the section, either landward due to uprushes or seaward due to backwashes. The destination and weight are calculated through equations presented in figures 3 and 4, respectively. On the other hand the container would gain some particles from the action of flow over other sections (containers) when their destinations are so that they land on this particular section. The final change in the number of particles in each container at the end of the time interval (the aggregate of losses and gains) –after converting to volume- demonstrates the change in the profile at the corresponding section of the beach. Destination and number (or weight) of particles moved due to one event, clearly depends upon the intensity of the velocity time-history of the event, of which parameter σ introduced above, is representative.

Figure 5 shows the flowchart of the program. As can be seen in the figure, the program takes as input the initial beach profile and velocity time histories at selected sections of the beach. The time histories consist of a number of uprushes and backwashes for which the parameters, sigma, must be calculated separately through above equation. When the list of parameter sigma for each section is provided, the average jump length ($\overline{JL}$) and weight ($\overline{w}$) corresponding to the parameters are extracted from diagrams $\overline{JL}-\sigma$ and $\overline{w}-\sigma$, figures 3 and 4, respectively. Positive jump lengths are assigned for uprushes and negative for backwashes. Thus the weight of sediment emigrating from the section and its destination is known. The same procedure is followed for all sections of the beach in the discretisation. The output of the model is a new profile based on the changes derived by numerical summation of losses and gains in each section, converted to volume (calculation of dz). As the hydrodynamic parameters of flow change due to changes in the bed profile, the new profile i.e. the output of the program and velocity time histories from experimental data in the new condition would be the input to the program for the next stage. In general the velocity time history would be given by the numerical model. It should be noted that, similar $\overline{JL}-\sigma$ and $\overline{w}-\sigma$ relationship were used for backwashes as uprushes, with the assumption that the rate of velocity change (acceleration) is less influential with compare to velocity itself.

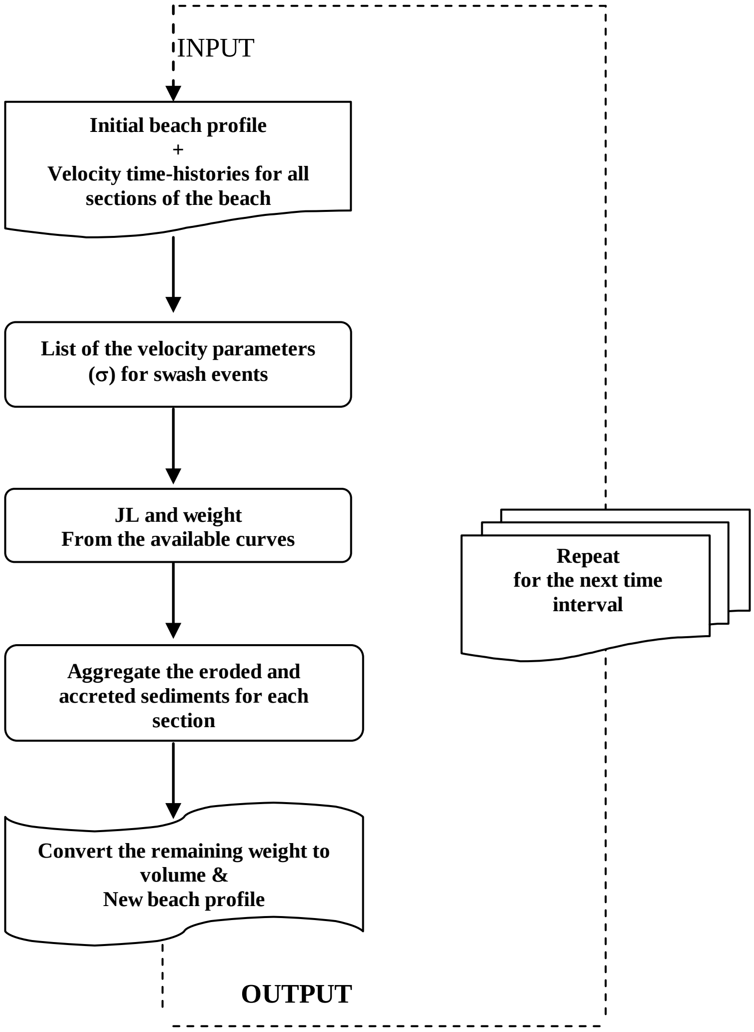

Figure 5: Flowchart of the program "Beach Profile".

EVALUATING MODEL RESULTS

The results of the Beach Profile model are compared to the measurements of beach profile change in laboratory. Figure 6 shows a comparison between the results of the model and measured beach profiles in three flow conditions. The original beach profiles are also shown in the graphs. The linear $\overline{JL}-\sigma$ relationship of figure 3 has been used in calculation of profiles. As can be seen in the figure, agreement between the prediction of model and the observation is very significant in flow condition (1), in both terms of trend and amount. However, this is not substantial in the other cases.

The reason why the results in the condition (1) are so remarkable and in the other conditions are not, probably stems from two facts, namely the range of basic information and accuracy of hydrodynamic inputs. The information about the $\overline{JL}$ and $\overline{w}$ of particles and their relationship with flow parameter sigma, is limited to narrow band of available flow conditions. In case (1), the flow regime is within the range for which the above mentioned information is available. The velocities in cases (2) and (3), are in an area beyond that range.

The discrepancy between the predicted and observed beach profile in conditions (2) and (3) could be indirectly due to uncertainty of velocity data measured in these two conditions. This is because of the highly active particles of the bed, which can obstacle the sound ray of sensors when they pass through the ADV (velocimeter). This results in violent in recorded data (velocities of the particles are less than water therefore there are some fluctuation in recorded velocities when they pass the sensor). Although, the measurement was repeated several times, it was not easy to recognize whether the fluctuation in time history is due to real turbulence or particle passage.

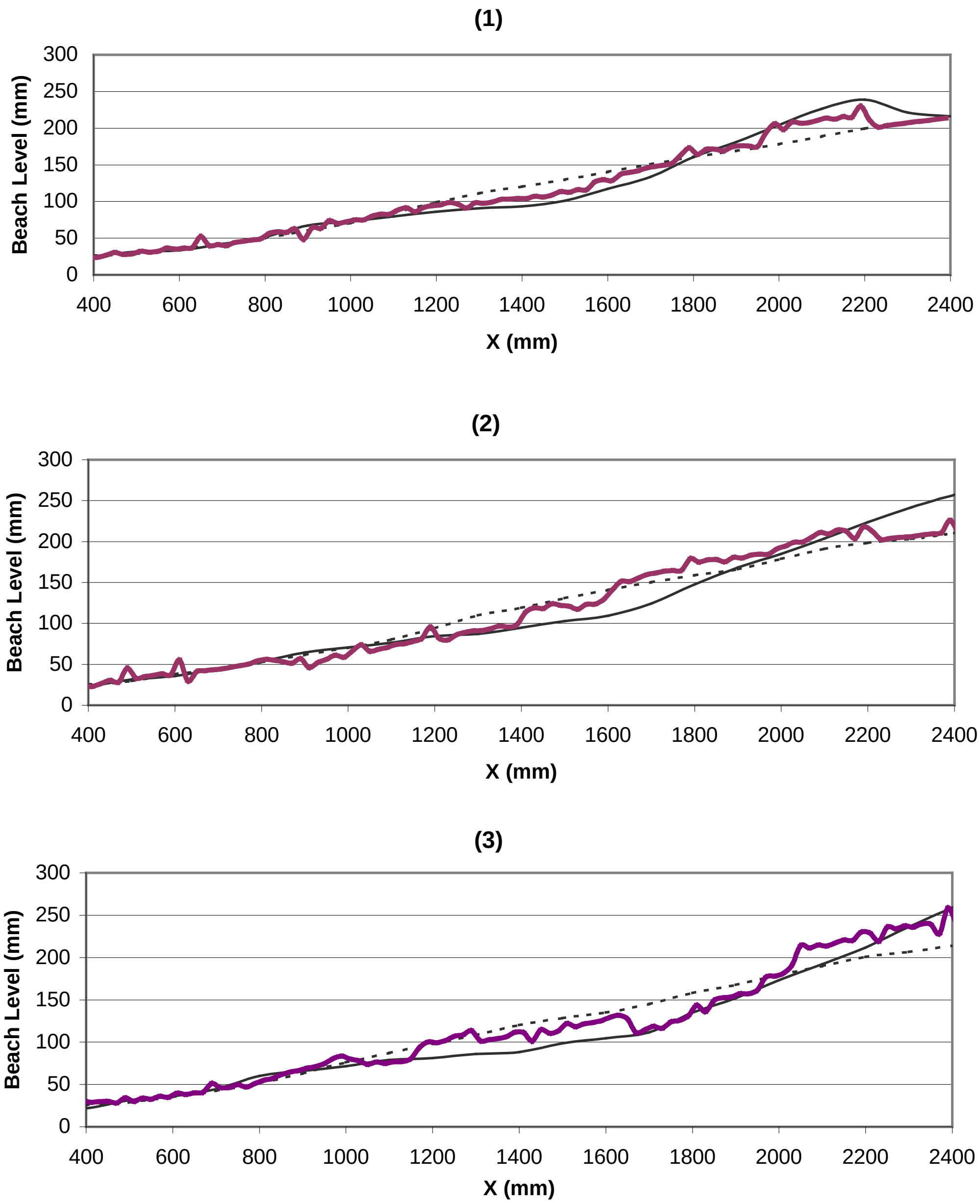

Figure 6: Change in beach profile; dashed lines are original beach profiles, light lines are measured and heavy lines (purple) are predicted by the Beach Profile model.

In addition to these reasons for discrepancies, the scattering of jump length data around the mean ($\overline{JL}$) i.e. the relatively wide confidence interval in figure 3, implies that considering $\overline{JL}$ as a sole representative of particle movements, should be improved by taking into account the distribution of jump length. This consideration can improve the accuracy of the model.

The substantial agreement between the results of the model and the measurement in condition (1) implies the credibility of the model when the basic inputs of the model are more reliable and accurate. Extrapolating those pieces of information in wider range needs more caution, requiring extra evidence from the response of particles to more severe regimes.

To investigate how the change in the key parameters of the model contribute in the accuracy of the results, sensitivity analysis are conducted for three main parameters, namely threshold velocity (u_{cr}), average jump length ($\overline{JL}$) and weight ($\overline{w}$). While the results are less sensitive to the amount of threshold velocity, they are indeed sensitive to jump length and weight and more to the latter. For instant, the profile change predicted by the model when the $\overline{w}$ in $\overline{w}-\sigma$ formula is doubled, matches more accurately than that with the normal $\overline{w}$. The same change in the amount of $\overline{JL}$s does not display such a remarkable improvement.

One of the important findings of the present investigation is that the flow regime at and immediately after the bore collapse (breaking point in the experiments), has a significant contribution in the formation of beach morphology. Indeed, the sediment transport in this region overwhelmingly overshadows the activities of the bed materials in other parts of the surf and swash zone in the cross-shore direction. Future study should be focused on simulation of the flow conditions and sediment transport in this relatively small region.

CONCLUSION

Despite the remarkable progress achieved in understanding the fundamentals of sediment transport in the swash zone, models of sediment transport based on quasi-steady bed load formulae appeared to be incapable of accounting for all the aspects of the governing physics. Sediment transport in the swash zone is in fact the result of a sequence of swash events which are discontinuous progressive waves, physically different from oscillatory waves. Considering this discontinuous feature of the flow in the swash zone, a new model was introduced in the present study, termed the event-based model, in which the change in the beach profile is considered as the superposition of the resultant of sediment particles' response to individual swash events which the beach experiences in a particular time interval. The response of particles in this context means the number of particles that move from a given location and also their destination due to one particular swash event.

For the calculation of the intensity of a single wave event, parameter sigma, a quadratic relationship between shear stress and velocity was considered and the influence of acceleration, although significant in asymmetric waves, was excluded in relation to sediment responses. As a result, the only variable in the flow parameter sigma is the near bed velocity. In the numerical model this allowed the uprushes and backwashes to be treated similarly. This is of significant importance that the flow in the breaking zone, in the area of bore collapse and in the swash zone generally is highly turbulent. In general, the flow parameter of a single asymmetric wave demands a broad study to take into account all influential factors in this particular flow regime including acceleration and turbulence (Nielson 2002).

The event-based model was found conceptually more realistic for simulation of sediment transport in bed load mode and beach profile change in the surf and swash zone with compared to existing modified quasi-steady models. The comparison with the laboratory data reveals that the results of the model developed in the present study on the basis of the event-based concept are very promising, particularly in the range of flow for which the behaviour of sediment particles are more accurately available.

The Beach Profile model is generally capable of predicting cross-shore beach profile change in a bed-load mode of sediment transport. However, at present the basic information of particle response to single swash events, which is the key part of the model, is only available for one particle size and in a limited range of flow regimes. Obviously, more experiments are necessary to provide wider range of information about the responses of particles of different sizes and in severe flow regimes of swash zone.

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