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A Model Development for Swash Hydrodynamics Across the Shore
해안선 종단방향에서의 소상파의 수동학적 거동 예측모형의 개발

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Abstract

In a physically realistic but simplified manner, an attempt is made in this study to develop a predictive model for swash hydrodynamics across the shore due to the storm waves on an arbitrary beach profile. Data from the SUPERTANK Laboratory Data Collection Project are used for the model development, in which experiments were designed to simulate dune erosion under storm conditions at a prototype scale. The model predicts variations of swash height, velocity and period across the beach face in a swash zone. In general, the model proves to be capable of predicting variations of swash height, velocity and period across the shore. Quantitatively better predictions for the swash parameters could be achieved by improving the prediction of the beach face elevation, ymax, where the significant swash height becomes zero.

keywords : storm wave, swash height, swash velocity, swash period, modeling

요 지

본 연구에서는 역학적으로 실질적이면서도 단순화된 방법으로 폭풍과 같은 악후시에 임의의 해안단면에서 발생하는 소상파의 수동학적 거동에 대한 예측모델을 개발하고자 한다. 실제 크기의 폭풍파 조건하에서 사구의 침식을 모의하기 위해 수행된 대형조파수조 실험에서 계측된 실험자료가 모델 개발을 위해서 활용된다. 본 연구를 통하여 개발된 모델은 해빈 종단방향에서의 소상파의 파고, 속도 및 주기의 변화를 예측한다. 일반적으로 본 모델은 해안 종단방향에서의 소상파의 파고, 속도 및 주기의 변화를 예측할수 있음을 보인다. 정량적으로 보다 나은 소상파 변수들에 대한 예측은 유의 소상파고가 영이 되는 해빈면의 높이, ymax에 대한 예측향상을 통하여 이루어질수 있다.

핵심용어 : 폭풍파, 소상파고, 소상파 속도, 소상파 주기, 모델링

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1. Introduction

The quantitative understanding of the swash zone hydrodynamics is essential to develop accurate models describing the nearshore hydrodynamics and coastal sediment transport including dune erosion. Field measurements (Bodge, 1986; Beach and Sternberg, 1991) and laboratory experiments (Kamphuis, 1991) show a large amount of sediment suspension in the swash zone that is responsible for erosions of the beach and dune face. In fact, field measurements of sediment transport indicate that a considerable amount of sediment transport occurs in the swash zone (Kraus et al., 1981). In addition, field measurements (Fisher et al., 1986) and laboratory experiments (Overton et al., 1988) show that dune erosion is a function of swash force, in which the swash force is expressed in terms of swash height and velocity.

In spite of the important role of swash hydrodynamics regarding to sediment transport and dune erosion, most models for the nearshore hydrodynamics and sediment transport do not account for dynamic process in the swash zone, resulting in considerable errors in prediction of sediment transport near the shoreline. In most models calculations stop at a shoreline location which is shifted inland by the wave setup and in which the computational depth becomes zero. In nature, however, the wave (or bore) is not completely dissipated at this point; it rushes up the beach face until its kinetic energy becomes zero and then rushes back to meet with a next incoming wave. The amount of wave energy dissipated through friction and turbulence on the beach/dune face contributes to scour the dune toe, to strongly agitate sediment into suspension and to drive the sediment offshore. The importance of this aspect has been emphasized by Briand and Kamphuis (1993) who developed a quasi three-dimensional numerical model for the sediment transport in the surf zone and included the prediction of sediment transport in the swash zone using a simplistic global formula based on wave energy dissipation on the beach face. Their comparison of the model prediction with the laboratory measurements showed that a volume of sand eroded in the swash zone was significantly under-predicted because of the poor swash model, suggesting that more detailed swash calculations were required to improve a sediment transport model in the swash zone. Kobayashi et al. (1988) also points out that a quantitative understanding of sediment transport in the swash zone is required for better establishing the landward boundary condition for existing cross-shore sediment transport models such as those proposed by Stive (1986) and De Vriend and Stive (1987), indicating that existing hydrodynamic models such as those proposed by Battjes and Stive (1985) and Svendsen et al. (1987) are not applicable to the swash zone.

Currently, it appears that there is no model applicable to describe the swash zone hydrodynamics quantitatively well in a simply but physically realistic manner. A numerical model based on the nonlinear shallow-water equations (Hibberd and Peregrine, 1979) describes the behavior of a uniform bore over a uniform sloping beach and the subsequent run-up and back-wash only in a qualitative manner but not in a quantity. Using the same concept, Kobayashi et al. (1988) developed a numerical model for prediction of the swash oscillation on a beach, which is a modified version of the model for the prediction of the waterline oscillation on a rough impermeable slope of a coastal structure (Kobayashi et al., 1987).

While most studies performed in the swash zone have concentrated on estimation or prediction of wave set-up and runup height (Guza and Thornton, 1982; Holman and Sallenger, 1985), most important hydrodynamic parameters in the swash zone for the better prediction of the sediment transport may be identified as a swash height, velocity and period (Fisher and Overton, 1984). In this study, therefore, a model for predicting the variation of these three swash parameters across the shore is developed using data from SUPERTANK laboratory experiments. Each individual swash is not considered and parameters for the individual swash are not predicted, rather, statistically representative (e.g., mean, rms or significant) swash parameters are predicted in this study.

2. SUPERTANK Laboratory Experiments and Data Reduction

In 1991, a set of experiments was conducted at a prototype scale in the large wave tank (LWT) at Oregon State University (OSU) as a part of the SUPERTANK Laboratory Data Collection Project (Kraus et al., 1992). The experiments were designed to simulate dune erosion under storm conditions, in which irregular waves were generated on an arbitrary sand beach profile. The channel of LWT is 104.2m long, 3.7m wide, and 4.6m deep. A sand dune of approximately 1.5m height was constructed with uniform-size quartz sands of 0.22mm median diameter. Time series of water surface variation in the swash zone were sampled at a rate of 16Hz from ten capacitance gages deployed in LWT.

Thirteen experiments were carried out successfully. Table 1 displays deepwater wave conditions with a beach face slope for each test. The wave period was assumed to be constant through the prebreaking and breaking zones, and the significant wave period measured at a specific point near the wave generator was taken as the deepwater significant wave period To. Using the significant wave conditions measured at this specific point, deep water wave height (Ho) and length (Lo) were computed from the linear wave theory. The beach face slope (?) in the swash zone was determined by estimating a linearly best-fit line to beach profile data over the distance of the beach face. Detailed descriptions on survey and experiments are given in Kraus et al. (1992) and Hwang (1999), respectively.

The swash zone, which is bounced between the surf zone and backshore, is specifically defined as that region on the beach face delineated at the upper level of the maximum uprush of the bore and its lower extremity by the maximum downrush. In the swash zone, the

Table 1. List of Deepwater Wave Conditions

Test #	$T_o(sec)$	$H_o(m)$	$L_o(m)$	θ
1	2.7	0.700	11.37	0.15
2	2.8	0.748	12.25	0.18
3	3.8	0.750	22.53	0.18
4	4.6	0.706	33.04	0.21
5	3.7	0.784	21.37	0.15
6	4.6	0.650	33.04	0.16
7	3.5	0.497	19.11	0.17
8	2.7	0.719	11.37	0.14
9	2.8	0.717	12.25	0.16
10	3.8	0.655	22.53	0.14
11	3.8	0.653	22.53	0.15
12	3.8	0.679	22.53	0.14
13	4.7	0.446	34.47	0.20

time series of water level variation are quite different from those of the surf or deepwater prebreaking zone. The water surface profile in the swash zone is no longer a wave form but of a tooth-shaped profile.

Both time and frequency domain analyses were performed on the time series of water level measured in the swash zone. For the frequency domain analysis, the spectral analysis was performed using a standard Fast Fourier Transform (Press et al., 1989). For the time domain analysis, definitions of swash parameters are consistent with those originally presented by Overton et al. (1990). Details on data reduction for swash parameters are given in Hwang (1999).

3. Model Development

3.1 Swash Height

Based on experimental measurements, a simple model was developed for the swash height variation in the swash zone. Fig. 1 shows variations of the significant swash heights (H_{sws}) versus the elevations of beach faces (y) from 4 different tests. In the figure, H_{sws} was estimated from the power spectrum analysis as given by 4σ and y represents the elevation above the still water level (SWL). From this result, Hwang (1999) suggested that H_{sws} tends to decrease linearly with y in the swash zone. Based on this observation, a prediction model for the swash height variation on the beach face is developed.

The significant swash height H_{sws} can be expressed as:

$$H_{sws} = c_1 - c_2 y \qquad (1)$$

where c_1 and c_2 represent the intercept and slope of the linear relationship, respectively. Defining the swash zone from y = 0 to $y = y_{max}$, the following boundary conditions are formulated and used to solve for c_1 and c_2

i) $H_{sws} = 0$ at $y = y_{mat}$ (2)
ii) $H_{sws} = H_{swso}$ at $y = 0$ (3)

where H_{swso} represents a significant swash height at y = 0 (SWL) and y_{max} is the beach face elevation where H_{sws} becomes zero. Appli-

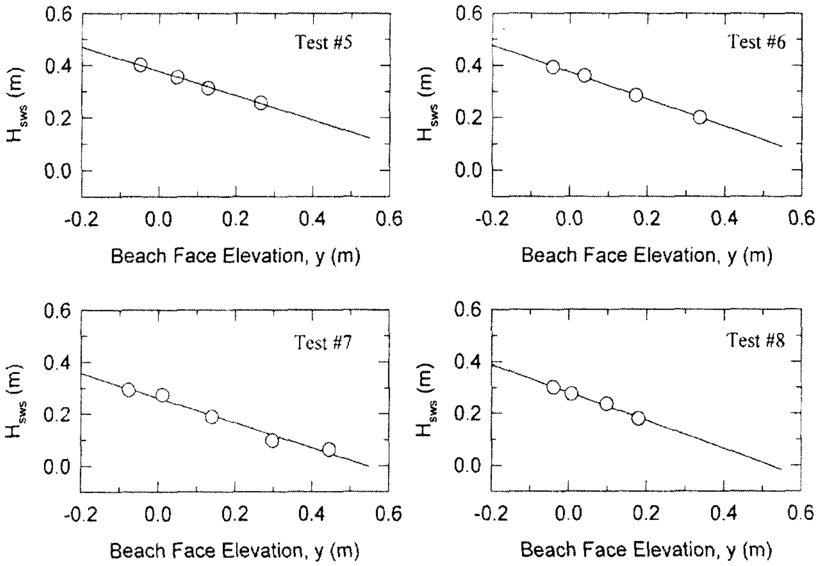

Fig. 1. Linear Variation of Significant Swash Height versus the Elevation of Beach Face for Tests #5, #6, #7 and #8

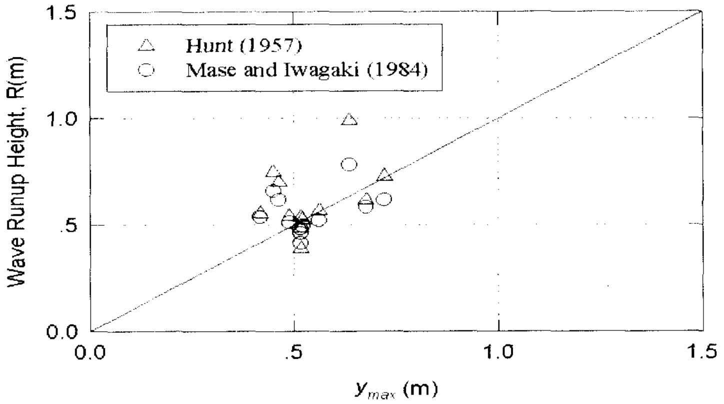

Fig. 2. Comparison of y_{max} to R by Hunt (1957) and Mase and Iwagaki (1984)

cation of the two boundary conditions to Eq.(1) yields

$$\frac{H_{sws}}{H_{swso}} = 1 - \frac{y}{y_{max}} \qquad (4)$$

Note that if y_{max} is known for a given wave condition in deepwater, Eq. (4) can be used directly to compute H_{sws} for a given y. H_{swso} can be obtained from the existing prediction models for the wave height transformation across the shore for a given deepwater wave condition.

Since y_{max} can be physically interpreted as a representative runup height R for irregular waves climbing on a beach, it is interesting to compare the values of y_{max} with R. Eq. (4) was used to determine y_{max} for each test, while R values for each test were estimated from two existing runup height models: Hunt (1957) and Mase and Iwagaki (1984).

Both runup height equations by Hunt (1957) and Mase and Iwagaki (1984) have a similar form and are functions of the Iribarren number defined as $\xi = \tan\theta / \sqrt{H_o / L_o}$ where θ is the beach slope and H_o and L_o are deepwater wave height and length, respectively. Using data from experiments (Table 1), mean runup heights for each test were calculated from these runup height equations.

The comparisons between ymax and runup heights determined from Hunt (1957) and from Mase and Iwagaki (1984) are shown in Fig. 2. It is seen that ymax appears to match roughly with runup heights proposed by both Hunt (1957) and Mase and Iwagaki (1984), as ymax deviates by factor of about 2 from R. The deviations between ymax and R may be attributed to differences in beach profiles. The beach profile in the SUPERTANK experiments were natural (arbitrary shape) while the runup height model was derived based on experiments on linear beach profiles.

Currently, there is no reliable model for the computation of runup height on natural beaches due to the sparsity of good field data (Leenknecht et al., 1992). Despite discrepancies in the nature of the profiles, therefore, the runup height model by Mase and Iwagaki (1984) was employed to predict the value of ymax in this study. Clearly, the prediction of the swash height could be improved with a reliable runup model.

3.2 Swash Velocity

Predicting swash velocity in realistic situations is exceedingly difficult due to complexity of the swash phenomenon in nature. In considering swash velocity, it is essential to separate the swash motion into uprush and backwash since the initial boundary conditions are so different (Kemp and Plinkston, 1974). In the case of uprush, the velocity is determined by the kinematics of the bore generated after breaking of the wave. The backwash starts from zero velocity everywhere on the beach and then a leading edge of water moves down the beach. In this study, the model for the velocity of a bore during the uprush is presented.

In order to simplify the swash phenomena on the beach face, a water particle is idealized as a solid particle which retains its identity. Therefore, a particle under a given swash height, Hsw, was considered to move up and down a beach face as a solid particle would. If normally incident waves are considered, a force balance implies

$$m_w \frac{dV_{sw}}{dt} + m_w g \sin\theta + \frac{f}{8}\frac{m_w}{H_{sw}}|V_{sw}|V_{sw} = 0 \tag{5}$$

where mw is the mass of a water particle, V_{sw} is the swash velocity, g is the gravitational acceleration, and *f* is a friction factor. Assuming a frictionless planar beach for simplicity and eliminating common terms in Eq. (5) yield

$$\frac{dV_{sw}}{dt} = -g\sin\theta \tag{6}$$

Applying initial conditions of $V_{sw} = V_{swo}$ and $x=0$ at $t=0$ (where x is the distance in the direction of water particle translation from the location where $SWL=0$) and simply integrating this equation yield

$$V_{sw} = \sqrt{V_{swo}^2 - 2gy} \tag{7}$$

where y is the elevation above the SWL, expressed as $y=\sin\theta/x$ due to assumption of a planar beach. Since the maximum uprush (y_{max}) occurs when the swash velocity is zero, the initial swash velocity V_{swo} is given as

$$V_{swo} = \sqrt{2gy_{\max}} \tag{8}$$

Finally, substituting Eq. (8) into (7) yields

$$V_{sw}^2 = 2g(y_{\max} - y) \tag{9}$$

It is noted that swash velocity equation includes ymax as the swash height equation (Eq. 4) does.

3.3 Swash Period

In order to develop a prediction model for the swash period (T_{sw}), it is assumed conveniently that the runup height on natural beaches has a Rayleigh distribution. With this assumption, the probability of runup is given by

$$\Pr[R > y] = \exp\left[-\left(\frac{y}{R_{rms}}\right)^2\right] \tag{10}$$

where R_{rms} is the rms (root mean square) value of runup height R. This relationship can be used to develop a prediction model for T_{sw}. If No denotes the number of deepwater waves which occur during an interval of duration T_d, N denotes the number of runup waves at $y = 0$, and M denotes the number of runup waves at y, then it can be demonstrated that:, $N_o = T_d/T_{mo}$, $N = T_d/T_{swo}$, and $M = T_d/T_{sw}$ where T_{mo}, T_{swo} and T_{sw} are the deepwater mean wave period, the initial mean swash period at $y=0$, and the mean swash period at any elevation of y, respectively. Using these relations, the probability of runup (from the left side of Eq. 10) can be expressed as:

$$\Pr[R > y] = \frac{M}{N} = \frac{T_{swo}}{T_{sw}} \tag{11}$$

Combining Eq. (10) with Eq. (11) yields an equation for the swash period given as:

$$\frac{T_{sw}}{T_{swo}} = \exp\left[\left(\frac{y}{R_{rms}}\right)^2\right] \quad (12)$$

Note that Eq. (12) can be used for the prediction of T_{sw} if it is possible to express both T_{swo} and Rrms in terms of known deep water wave conditions or swash variables. Using the laboratory data by Mase and Iwagaki (1984), T_{swo} may be expressed in terms of T_{mo}. As shown in Fig. 3, their data indicate that N/No (or T_{mo}/T_{swo}) varies nonlinearly with Iribarren number, ξ. Fitting a second order polynomial to their experimental data yields

$$\frac{N}{N_o} = \frac{T_{mo}}{T_{swo}} = 0.69\xi^{(0.42-0.08\ln\xi)} \quad (13)$$

Using SUPERTANK laboratory data, Rrms for each test was calculated from Eq. (12) and (13). Along with the computed T_{swo} by Eq. (13), T_{sw} at two locations, y, were used in Eq. (12) to calculate R_{rms}. It was shown previously that R and y_{max} are closely related, and thus it is reasonable to expect that R_{rms} and y_{max} are related as well. A comparison between R_{rms} and

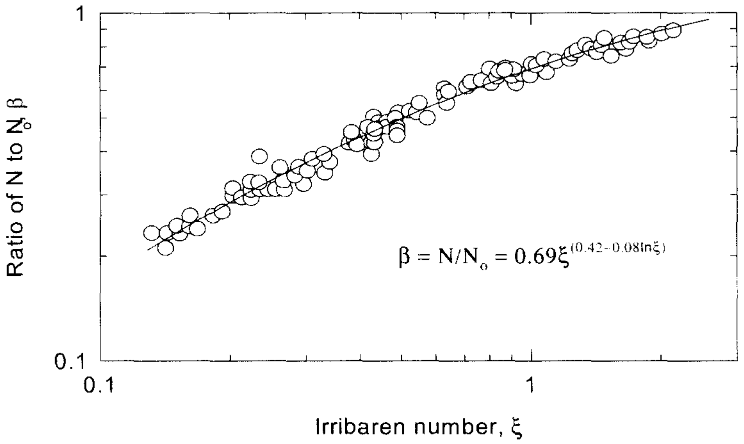

Fig. 3. Ratio of the Number of Deepwater Waves to the Number of Runup Waves, N/No (or T_{mo}/T_{swo}) ; Data from Mase and Iwagaki (1984)

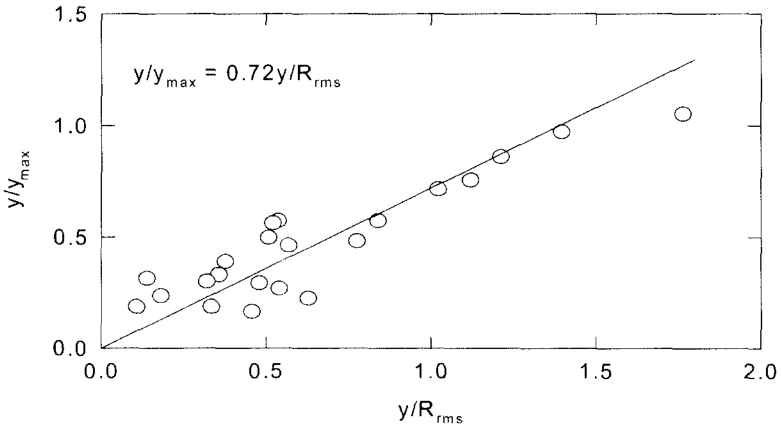

Fig. 4. Relationship of ymax to Rrms

y_{max} (non-dimensionalizing each by the beach elevation y) is shown in Fig. 4. The inverses of each non-dimensional parameter were taken in order to demonstrate the relationship. It is interesting to note that there is a linear relationship between y/y_{max} and y/R_{rms}, even though there is a considerable scatter in the range of y/R_{rms} less than 0.7. The linear regression fitting to the data yields

$$y_{\max} = \frac{R_{rms}}{0.72} \tag{14}$$

Finally, substituting Eq. (13) and (14) into Eq. (12) yields an equation for the mean swash period:

$$T_{sw} = \frac{T_{mo}}{\beta}\exp\left[\left(\frac{y}{0.72y_{max}}\right)^2\right] \tag{15}$$

where β represents T_{mo}/T_{swo} given by the right-hand side of Eq. (13). Note that the predictions of the swash parameters; i.e., swash height, swash velocity and swash period all depend upon the prediction of y_{max}. As noted previously, y_{max} is predicted using a runup height model due to the assumption of a linear beach profile so that the present model may cause considerable errors.

4. Modeling Results and Discussion

As noted previously, predictions of swash parameters depend directly on the value of y_{max}; however, the model developed in this study predicts y_{max} using the runup height equation by Mase and Iwagaki (1984). Depending on the runup height equation used for prediction of y_{max}, therefore, the present approach may cause considerable errors in calculating swash parameters due to discrepancies between ymax and R as shown in Fig 2. As a preliminary examination of the model, measured values of y_{max} were used eliminating the errors due to the prediction of y_{max}. Then, predicted values of y_{max} by the runup height equation were used to estimate the model.

4.1 Swash Height

For given dune/beach profiles, the swash height transformations across the swash zone were predicted for all tests using Eq. (4). The initial swash heights (H_{swso}) obtained from SUPERTANK experimental measurements were used as input to the model. Fig. 5 shows the comparisons between the measured and the predicted H_{sws} variations on the beach face for Tests #4, #6, #10 and #12. These tests were chosen as representative examples. In Fig. 5, the straight and dotted line represent the model predictions using the measured y_{max} and the predicted y_{max} from the runup height equation, respectively.

In Fig. 5, the model results using the measured y_{max} show that H_{sws} variation across the swash zone is predicted reasonably well. In some cases, the agreement between model predictions and the measurements is quite good, such as for Tests #6, 10 and #12. In case of Test #4, the agreement is not quite good, though still fair. In general, the swash height model appears to be capable of predicting the main features of the swash height variation across the swash zone, providing support for the validity of the model proposed herein.

When values of y_{max} were predicted in the model, the model predictions generally show more deviations from the measurements. Particularly in cases of Test #4 and #6, the deviations between the model prediction and the measurement become larger as x_{SWL} (the distance from SWL=0) increases. However, cases of Test #10 and #12 show that the model predictions are still excellent. These model results imply that the predictions of H_{sws} are directly dependent on the quality of y_{max}, since the predictions of y_{max} using the runup height equation were quite good for Test # 10 and #12 but not good for Test #4 and #6.

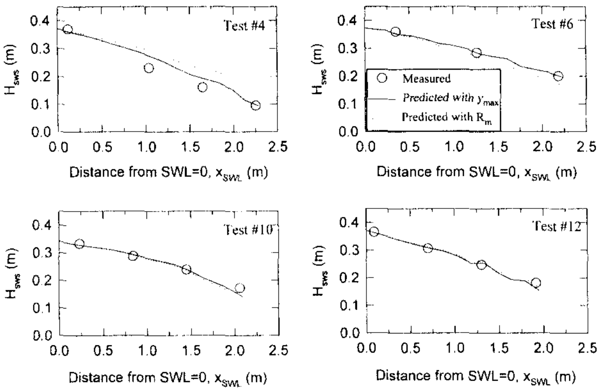

Fig. 5. Measured and Predicted Significant Swash Height Variations on the Beach Face for Tests # 4, 6, 10 and 12

4.2 Swash Velocity

The development of the swash velocity model is restricted due to the lack of swash velocity data. Only one velocity estimate per test was available from SUPERTANK laboratory data. Therefore, no definitive statement can be made for the prediction of the variation of swash velocity on the beach face. Nonetheless, the velocity data can still be used to estimate the general behavior of the swash velocity model.

For given dune/beach profiles, the swash velocity variations across the swash zone were predicted for all tests using Eq. (9). Comparisons between the measured and the predicted swash velocity variations on the beach for Tests #4, #6, #10 and #12 are given in Fig. 6.

The measured values of mean, rms and significant swash velocities were compared with the predicted values, and the measured values of significant swash velocity (V_{sws}) were closest to the model predictions. Thus, the model predictions are compared with measured values of V_{sws} in the figure. The agreement between the model and the measured V_{sws} is due to the fact that the model for swash velocity includes y_{max}, which is defined as the elevation where H_{sws} becomes zero. For the predictions using

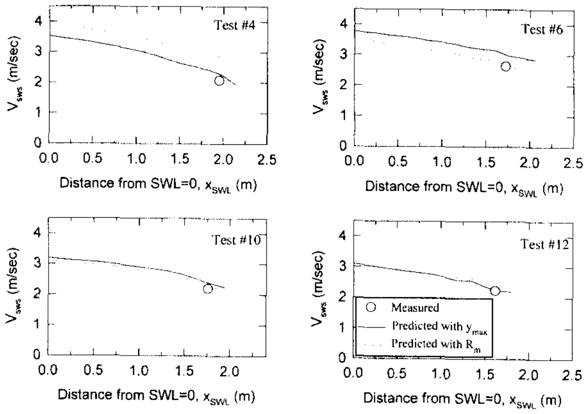

Fig. 6. Measured and Predicted Significant Swash Velocity Variations on the Beach Face for Tests # 4, 6, 10 and 12

the measured y_{max}, the agreement between model prediction and the measurement for Test #12 is quite good, while in other cases the agreement is not good (Test #6). In general, the results in the figure suggest that the model is capable of predicting the swash velocity during uprush of the bore. The variation in predicted swash velocities appears to be reasonable, showing a decrease in velocity approaching the dune toe.

The model predictions involving the predictions of y_{max} generally show more deviations from the measurements, while in some cases the model predictions are still excellent such as for Tests #10 and #12. Particularly the prediction for Test #4 shows that the considerable amount of deviation between the model prediction and the measurement has been introduced due to use of the predicted y_{max} instead of the measured y_{max}. It is interesting to note that discrepancies between two predictions (one with the measured y_{max} and the other with the predicted y_{max}) for V_{sws} appears to be constant as x_{SWL} (the distance from SWL=0) increases, while those for H_{sws} become larger.

4.3 Swash Period

For the given dune/beach profiles, the mean swash period (T_{swm}) variations across the swash zone were predicted for all tests using Eq. (15). Fig. 7 shows a comparison between the measured and the predicted T_{swm} variations on the beach face for Tests #4, #6, #10 and #11. In general, the predicted swash period agrees well with the measured T_{swm}. For the predictions using the measured y_{max}, the agreement between model prediction and the measurement for Test #11 is quite good, and in the case of Test #4 the agreement is not good. When y_{max} was predicted in the model, the model predictions show the similar trend with those for the swash height and velocity; the model predictions involving the predictions of y_{max} generally show more deviations from the measurements (Test #4), while in some cases the model predictions are still excellent (Test #6 and #11). Overally the results of model predictions suggest that the model is capable of predicting the main trend in swash period variations during uprush of the bore, showing an increase in swash period close to the dune toe.

It is interesting to note that the use of the predicted y_{max} in the predictions of swash period as well as swash height and velocity for Test #4 generated the relatively similar amount of deviation between the model prediction and the

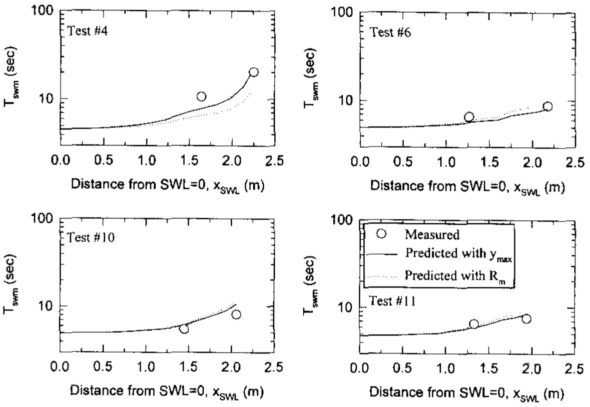

Fig. 7. Measured and Predicted Mean Swash Period Variations on the Beach Face for Tests #4, 6, 10 and 11

measurement, while each prediction model was developed independently. This aspect implies that y_{max} is the most important parameter governing the behavior of the swash parameters on the beach face and the better predictions of them can be achieved through the more accurate prediction of y_{max}.

5. Summary and Conclusions

A predictive model has been developed using the SUPERTANK laboratory data for the variations of swash velocity and period on the beach face. An advantage of the model developed in this study is its simplicity and ease of application since the model deals with statistically representative swash parameters, avoiding predictions for the propagation of individual waves (or swash). The model results on the swash height variation across the shore shows that the model is capable of predicting the main features of the transformation in swash heights over the swash zone. The model also appears to be capable of predicting the swash velocity during uprush of the bore.

Although no definitive statement can be made for the prediction of the variation in swash velocities on the beach face (since the swash velocity was measured at only one location for each test), the predicted features of the variations in swash velocity appear to be reasonable, as swash velocities decrease approaching the dune. The model is also capable of predicting the main trend in swash period variation across the swash zone, as the swash period increases approaching the dune.

The performance capability of the model developed was first examined using measured values of y_{max} and then using predicted values of y_{max}. Evaluation of models for individual swash parameter was basically conducted using measured values of y_{max} in order to minimize errors introduced by use of the predicted values of y_{max}. The parameter y_{max}, defined as the elevation where the significant swash height becomes zero, is a important parameter in modeling, since all of the swash parameter models (i.e., the swash height, the swash period and the swash velocity models) require y_{max} as an input parameter. For the prediction of y_{max} the present model uses the runup height equation proposed by Mase and Iwagaki (1984), assuming that y_{max} can be replaced by the runup height. An evident conclusion is that quantitatively good predictions for swash parameters can be achieved only by improving the ability to predict y_{max}.

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