QUANTIFYING THE EFFECT OF BED PERMEABILITY ON MAXIMUM WAVE RUNUP

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The magnitude of the wave runup is based on a number of contributing factors that have been the subject of numerous studies and a variety of research activities. Consequently, several parametric formulations already exist that can estimate runup magnitude in a variety of coastal conditions. However, the effect of swash-swash interaction and swash infiltration is not explicitly quantified in these existing parametric formulations. The current research aims to elucidate on one key aspect, namely, the effect of bed permeability on swash magnitude. Specifically, the aim is to find a relationship between infiltration rates and the maximum runup on the beach face. A series of experiments were performed at the Coastal Flume located at UCL, London, UK to characterize this effect of bed permeability on wave runup magnitude. The results from the series of experiments conducted favour a Hunt-type runup formulation and indicate that there is a clear relationship between bed permeability and the maximum wave runup. Other complicating factors make comparison to existing parametric formulations difficult and these will be discussed fully in the main paper.

Keywords: swash zone; wave runup; parametric modelling; bed permeability

INTRODUCTION

The evaluation of wave runup is of significant importance since it is used in a variety of applications such as beach morphological response, the design and maintenance of coastal structures and the assessment of coastal flooding risk. As expected, the magnitude of the wave runup is driven by a number of factors and there are several parametric formulations that already exist that can estimate runup on natural beaches (Vousdoukas et al., 2012; Stockdon et al., 2006; Ruggiero et al., 2001; Holman and Sallenger, 1985) and impermeable beds (Hughes, 2004; Kobayashi et al., 1990; Mase, 1989).

Processes such as the effect of the infiltration and exfiltration processes in the swash and swash-swash interaction have been known to affect the wave runup magnitude (Elfrink and Baldock, 2002; Butt and Russell, 2000). Unfortunately, there appear to be no current prediction formulae that specifically quantify the effect of these two processes on wave runup. As such, to aid in the development of an improved runup model, a series of experiments on permeable and non-permeable beaches have been conducted in the Coastal Flume at University College London (UCL), London, UK. This 20m long flume has a width of 1.2m and a depth of 1m and is fitted with a piston-type wave generator and an active wave absorber.

This paper will discuss the details of the first series of those experiments which were directed at quantifying the effect of permeability of the swash bed on the magnitude of the wave runup.

METHODOLOGY

Overview

The general methodology of this research is provided in Figure 1 below. The flow chart indicates three main phases of the research conducted: Step 1, Step 2 and Step 3.

Step 1 was initiated with the experimental design, which was not a trivial exercise. Consideration was given to limiting factors, such as speed of beach construction, allowable materials for beach construction, the suitability of materials to achieve desired experimental output and material availability. Once an experimental design was realized, the beach was constructed and the experiments performed.

Step 2 involved the data extraction and preparation of data for ease of manipulation and comparison to other empirical formulae. Comparisons were only made with the Stockdon et al. (2006), Ruggiero et al. (2001) and Douglass (1992) parameterizations for wave runup, primarily to gauge the extent to which the bed permeability affects the wave runup on beaches.

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Finally, Step 3 was ideally an assessment of the applicability of the experimental data collected to facilitate the establishment of a new formula that includes the effect of bed permeability. A simplified formula of Hunt (1959) format was produced that is a good predictor of the wave runup. The sections below provide some more detail on the experimental design and the analyses conducted.

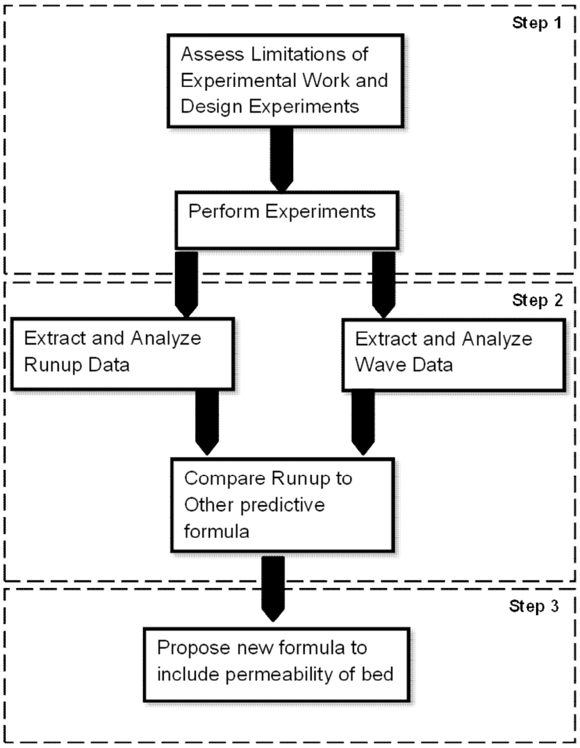

Figure 1. Research Methodology.

Experimental Design and Setup

The main aim of the experimental design was to investigate the maximum wave runup on beaches of varying permeabilities, at different beach slopes and subjected to varying wave conditions. These tests were conducted in order to derive a relationship which includes beach permeability, k, as a variable in a wave runup formula.

Four different beach slopes were used in these experiments where slopes were selected based on physical constraints in the wave flume and the need to maintain a common water depth for all of the various beach slopes. A water depth of 400mm was found to be suitable and the foreshore angles of the beach slopes used were 9°, 11°, 13° and 15°.

In the series of experiments presented, only regular or monochromatic waves were used. Five wave amplitudes and four wave frequencies were selected for a constant water depth, resulting in twenty wave conditions for each of the three slopes (9°, 13° and 15°). For the fourth slope (11°), five wave amplitudes and only three wave frequencies were used. The amplitudes and frequencies of the wave conditions were selected to have non-breaking waves arriving at the toe of the beach, which resulted in waves breaking on the beach face. Wave height to water depth ratios, based on incident wave expected from the wave generator, ranged from 0.15 to 0.35 for all wave conditions used.

Four differing degrees of bed permeability were investigated: an impermeable and three permeable beds with hydraulic conductivities (given in m/s) of 0.0311, 0.105 and 0.401. The impermeable bed was assigned a nominal permeability of $1\text{x}10^{-8}$ m/s for the purpose of inclusion in subsequent analyses. This permeability is equivalent to that of a clay layer that is considered to be impervious (Smith, 1981). The impermeable beach experimental layout is shown in Figure 2.

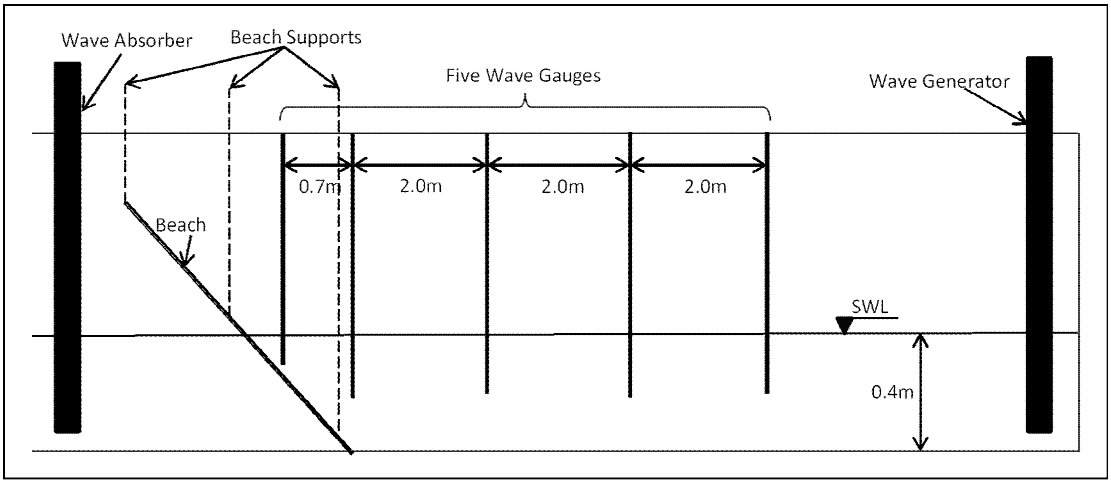

Figure 2. Experimental layout of the impermeable beach in the wave flume (not drawn to scale).

The impermeable bed setup involved the insertion of stainless steel panels into a stainless steel frame which was suspended into the flume. Superimposed on top of the impermeable stainless steel panel were perforated stainless steel plates. These perforated plates were the same as those used in the permeable beach experiments and hence were used over the impermeable bed to maintain a constant bed roughness across all the experiments.

An overhead camera was used to record wave runup while wave gauges were connected to data acquisition software to obtain wave parameters. Five wave gauges were used across the flume, with four of those recording wave parameters at the 400mm water depth and one gauge used to assess wave parameters over the bed before the runup process begins. A second camera was placed outside the flume near the still water line to record additional wave runup data.

There were other factors that affected the overall design for the permeable beach experiments. Firstly, one of the objectives of these experiments was to investigate the effect of the bed permeability on non-cohesive sand-sized to gravel-sized particles so that it can be applied specifically to beaches composed of granular material. However, to minimize any adverse effects of using sand-sized particles in the wave flume, the experimental design employed other materials to simulate changing bed permeability.

Figure 3 below is a sketch showing the details of the permeable bed. The permeable bed consisted of a rectangular block of reticulated polyether-based polyurethane foam which was placed directly below the perforated metal plate. This type of foam has a calibrated cell size and homogenous cellular structure with high porosity. In order to obtain the varying bed permeabilities, three different types of foams (R30H Beige, R45H Blue and R85 Beige) were used for the beach face. Based on laboratory experiments, the R30H and R45H foams had a porosity of 70% while the R85 foam had a porosity of 97%.

The perforated metal plate provided some necessary rigidity to the composite permeable bed, by limiting movement. The experiment was designed so that the permeability of the foam alone would control the bed permeability that affects the wave runup whilst still remaining cost-effective. The thickness of the foam was selected giving consideration to the maximum hydraulic conductivity of the foams and the experimental wave frequency range.

To support the foam and ensure that the bed remained permeable across the beach, the remaining beach was packed with hessian sacks filled with Expanded Polystyrene (EPS) beads. These beads were on average 5mm diameter and provided a hydraulic conductivity similar to that of coarse sand/fine gravel when adequately compacted (a value of 0.0126m/s).

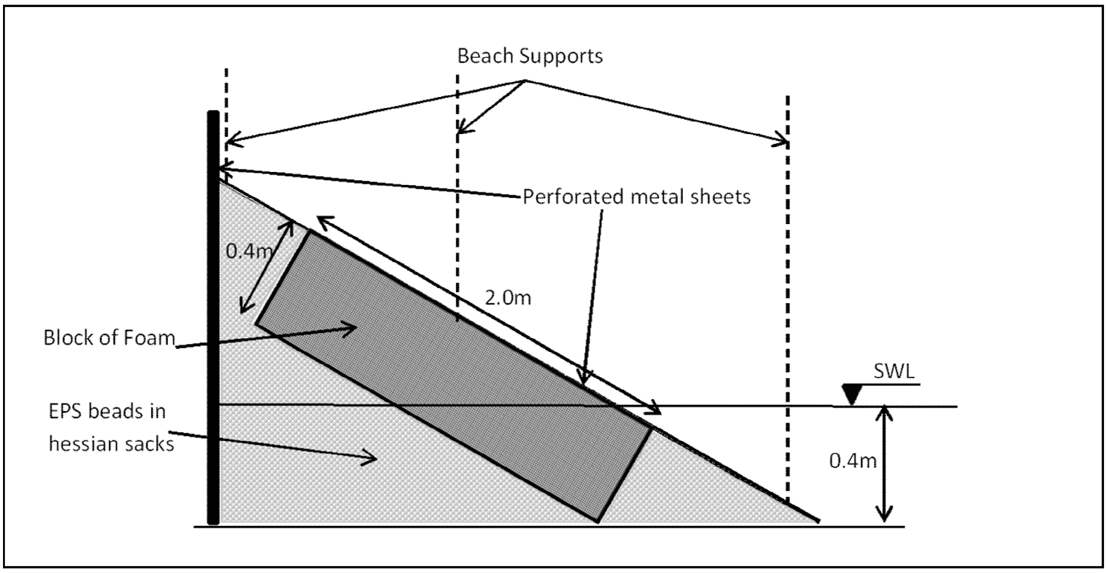

Figure 3. Details of Permeable Beach (not drawn to scale).

Data Extracted and Analyses Performed

The video data from the overhead camera were examined and the frames representing the position of maximum wave runup were extracted. These images were assessed using a Matlab download, GRABIT, to extract the maximum runup values. For each wave condition, ten maxima were examined and the magnitudes of each wave runup were stored, which resulted in a maximum of two hundred data points for each type of permeable beach at a single slope. The maximum wave runup values were analyzed, and the runup magnitudes representing the average, the minimum and the absolute maximum were obtained for each wave condition. However, only the absolute maxima of wave runup were used in subsequent analyses. Matlab was also used to obtain the best-fit probability density function (pdf) for the runup maxima.

Firstly, the wave data were collected for each wave condition and were analyzed via Fast Fourier Transform (FFT) techniques to validate each of the waves produced by the wave generator. In addition, wave reflection in the flume was assessed via three different methods: with a moving wave gauge experiment, using the MIKE WSWAT and via the four gauge method outlined in Lin and Huang (2004).

The WS Reflection Analysis tool in WSWAT has the capability to insert the wave gauge time series for the four gauges and uses the least squares fit method of Goda and Suzuki (1976) and Mansard and Funke (1980, 1987) which was later extended by Zelt and Skjelbreia (1992).

The main advantage with using different methods to yield the wave reflection coefficients was to provide greater confidence in the wave reflection coefficient used in subsequent analyses. The wave conditions generated for the experiments had ratios of depth to deep water wave length ranging from 0.023 to 0.26 which indicated shallow- to intermediate- water wave conditions. The deep water wave amplitudes were estimated using Linear Wave theory, and the process of shoaling was assumed to be the only dominant process.

Both the wave and wave runup data were formatted and comparisons were made with the three afore-mentioned existing wave runup prediction formulae for assessment and comparison of the results.

New Formulation Generated

To facilitate the development of a formula to include bed permeability, Pearson correlations between the varying parameters and combination of parameters were obtained and compared to identify the combination of parameters that had the best relationship with the maximum wave runup. Both dimensional and non-dimensional parameters were used to assess the correlation between parameters. The combination of parameters exhibiting the best correlation was used as the fundamental equation form and the effect of bed permeability was closely examined. Finally, once the best general format of the new runup formula was obtained through the correlation analyses with parameter combinations, the permeability was included via regression analyses.

To aid in the assessment of bed permeability and for comparison with other data, firstly an equivalent sand size particle (d_{10}) was obtained via three methods: one method was based on a Hazen-type formulation (Carrier, 2003), the second method was based on a modified formulation presented in Shepherd (1989) for beach sands and the last method used the Kozeny-Carman equation (Carrier, 2003). The Hazen-type formula, the modified formulation presented in Shepherd (1989) and the Kozeny-Carman equation presented in Carrier (2003) are given by equations 1, 2 and 3 below, respectively.

$$k = c_H \frac{\rho g}{\mu} d_{10}^2 \tag{1}$$

$$k = c_S \frac{\rho g}{\mu} d_{10}^{1.75} \tag{2}$$

$$k = \frac{c_{KZ}}{180} \frac{\rho g}{\mu} d_{10}^2 \left(\frac{n^3}{(1-n)^2} \right) \tag{3}$$

where c_H, c_S and c_{KZ} are calibration coefficients, ρ is the density of water, g is the acceleration due to gravity, μ is the dynamic viscosity of water, n is the bed porosity and d_{10} is the grain size where 10% of particles are smaller by weight.

The Kozeny-Carman formulation required a value of beach porosity. Therefore, a porosity of 40% (n = 0.4) was assumed, which is similar to the porosity of local beaches in Trinidad, West Indies. Firstly, all three formulations were calibrated and then validated using local experimental soil data to ensure that predicted grain sizes obtained were realistic. Subsequently, the equivalent grain sizes associated with the permeability of each foam bed were obtained.

In order to obtain an equivalent grain size distribution, for the foams used on the beach, equivalent values of d_{50}, d_{60} and d_{90} were obtained using a synthesized grain size distribution which matched the grain size distribution of a beach located on the east coast of Trinidad (see Figure 4). This beach was selected since its sediments are well-sorted and a poorly graded (or well sorted) bed should better represent the foam used in the model beach since the foam had a homogenous cell structure. The Coefficient of Uniformity (d60/d10) of the east coast beach used was 1.40. Hence an equivalent grain size was established for the impermeable and permeable experimental beds.

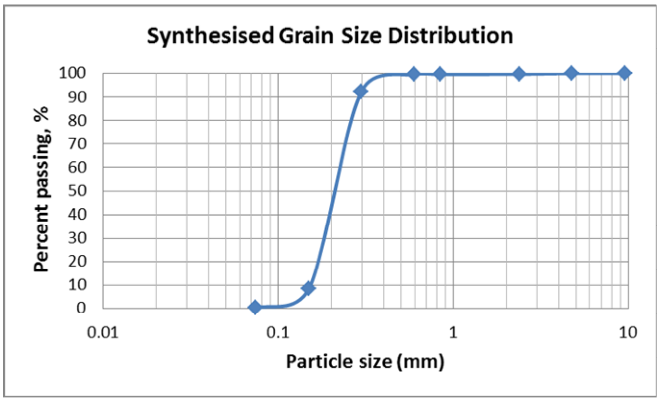

Figure 4. Grain Size Distribution of Manzanilla Beach, located on the east coast of Trinidad.

RESULTS

Experimental Runup Distribution

The maximum wave runup values were grouped and the best probability density function (pdf) fitted to these maxima. The wave runup results are presented below in Figure 5 and the best fit pdf was determined from the data. Figures 5(a) and 5(b) demonstrate that the maximum runup had the best fit with a lognormal distribution.

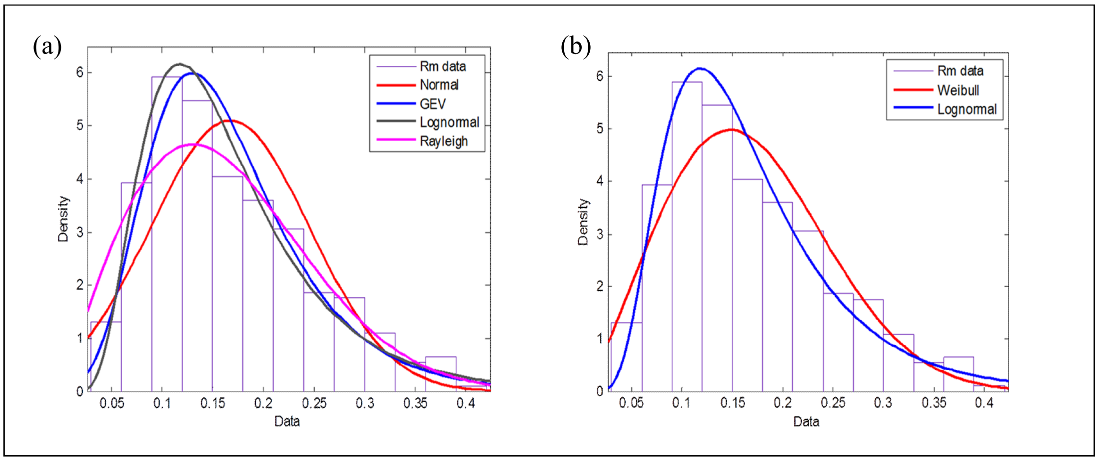

Figure 5. Best–fit distribution of the maximum runup.

Equivalent Sediment Sizes

The equivalent sediment sizes using the Kozeny-Carman formulation-based analyses are shown in Table 1 below.

Table 1. The equivalent sediment sizes using the Kozeny-Carman formulation.

k (m/s)	n (ratio)	Density of water (kg/m^3)	Dynamic Viscosity of water (Pa.s)	d_{10} (mm)	d_{50} (mm)	d_{90} (mm)
0.0311	0.4	996	0.000798	7.0396	9.6208	13.6099
0.105	0.4	996	0.000798	12.9349	17.6777	25.0075
0.401	0.4	996	0.000798	25.2779	34.5464	48.8706
0.00000001	0.4	996	0.000798	0.0040	0.0055	0.0077

A comparison of the equivalent d_{50} sediment sizes from the three grain size equivalence techniques highlighted in the methodology is given in Table 2 below.

Table 2. The equivalent d_{50} sediment sizes using the three grain size equivalence methods.

k (m/s)	d_{50} (mm) [Hazen-type]	d_{50} (mm) [Modified-Shepherd (1989)]	d_{50} (mm) [Kozeny-Carman]
0.0311	13.3388	24.3055	9.6208
0.105	24.5093	48.7152	17.6777
0.401	47.8969	104.7636	34.5464
0.00000001	0.0076	0.0047	0.0055

Wave Reflection Analyses

The wave reflection analyses were done for all wave conditions but a subset is presented in Table 3 for one bed permeability (0.105m/s) on the 11° beach slope. This data subset includes the wave condition for which the moving wave gauge experiment was conducted. Figure 6 illustrates graphically the data presented in tabular format.

It is evident from these results that there is little difference in the calculated reflection coefficient determined from the Lin and Huang (2004) and the MIKE WSWAT module. The moving wave gauge experiment was conducted on only one of these experiments and showed the same order of magnitude of the reflection coefficient.

The wave reflection coefficient was determined for all experiments performed using the Lin and Huang (2004) method. These reflection coefficient values (for the permeable beds) ranged from a minimum value of 0.0041 to a maximum value of 0.5299, with a median value of 0.0991. The correlation between the reflection coefficients and the parameters of permeability, beach slope, wave amplitude and wave frequency were assessed. The highest correlation was exhibited between the wave reflection coefficient and the wave frequency (R = -0.7). The two parameters were negatively correlated.

Table 3. Summary of Wave Reflection Analyses.

Experiment No.	Wave Amplitude (m)	Wave Frequency (Hz)	$K_{reflection}$ Lin and Huang (2004)	$K_{reflection}$ MIKE21 WSWAT	$K_{reflection}$ Moving Wave gauge
116	0.03	0.5	0.0736	0.0733	
117	0.04	0.5	0.0799	0.0819	
118	0.05	0.5	0.1051	0.1034	
119	0.06	0.5	0.1543	0.1492	
120	0.07	0.5	0.2238	0.2268	
121	0.03	0.7	0.0764	0.0578	
122	0.04	0.7	0.0664	0.0515	
123	0.05	0.7	0.0594	0.0479	
124	0.06	0.7	0.0480	0.0271	
125	0.07	0.7	0.0339	0.0312	
126	0.03	1.0	0.0251	0.0238	
127	0.04	1.0	0.0319	0.0344	
128	0.05	1.0	0.0724	0.0757	0.0981
129	0.06	1.0	0.1196	0.1222	
130	0.07	1.0	0.1202	0.1209	

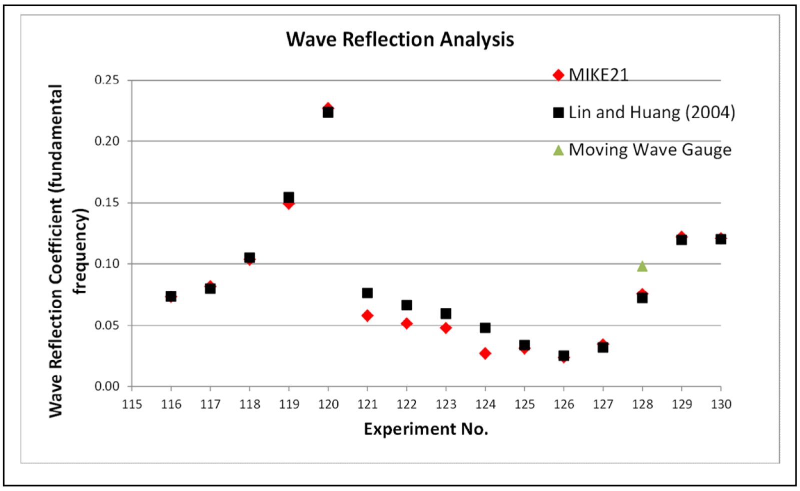

Figure 6. Wave Reflection Coefficients via three different methods.

Comparison with Parametric Wave Runup Formulations

The results of the comparison with the three wave runup predictive formulae will now be presented. The Stockdon et al. (2006), Ruggiero et al. (2001) and Douglass (1992) formulae are given in Equations 4, 5 and 6 respectively.

$$R_{u2\%} = 1.1\left(0.35\tan\beta\left(H_oL_o\right)^{1/2} + \frac{\left[H_oL_o\left(0.563\left(\tan\beta\right)^2 + 0.004\right)\right]^{1/2}}{2}\right) \qquad (4)$$

$$R_{u2\%} = 0.27\left(\tan\beta H_oL_o\right)^{1/2} \qquad (5)$$

$$R_{\max} = 0.12\left(\frac{H_{mo}}{\sqrt{\frac{H_{mo}}{L_o}}}\right) \tag{6}$$

where $tan\beta$ is the beach slope, L_o is the deep water wavelength, R_{max} is the maximum wave runup, $R_{u2\%}$ is the runup exceeded by 2% of incoming waves, H_o is the deep water wave height and H_{mo} is the spectral significant wave height.

Figures 7, 8 and 9 provide the graphical comparisons between the experimental runup maxima and the parametric formulations described in Equations 4, 5 and 6 above. In these figures, the experimental data points are plotted as red squares, and a linear trendline with y-intercept at the origin is fitted through these data points. The thin black line on the graphs illustrates this linear trendline. A thick black line is drawn to delineate where the measured and predicted values are exactly equal.

The plots in Figures 7, 8 and 9 above show the experimental runup maxima versus the predicted runup based on the respective parametric equations. These plots use all the experimental data and therefore include all bed permeabilities.

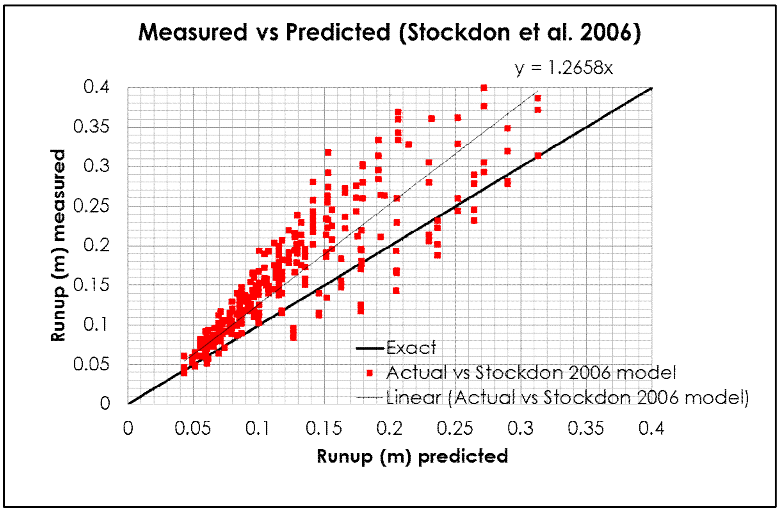

Figure 7. Experimental Data Comparison with Stockdon et al. (2006) parametric runup equation.

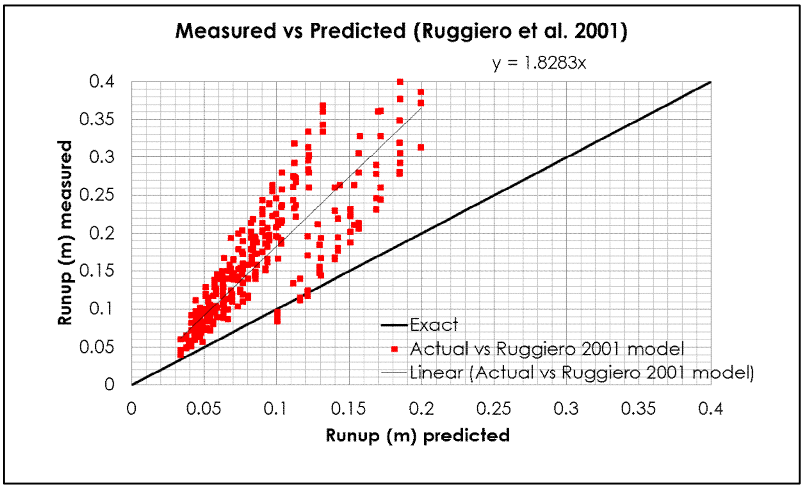

Figure 8. Experimental Data Comparison with Ruggiero et al. (2001) parametric runup equation.

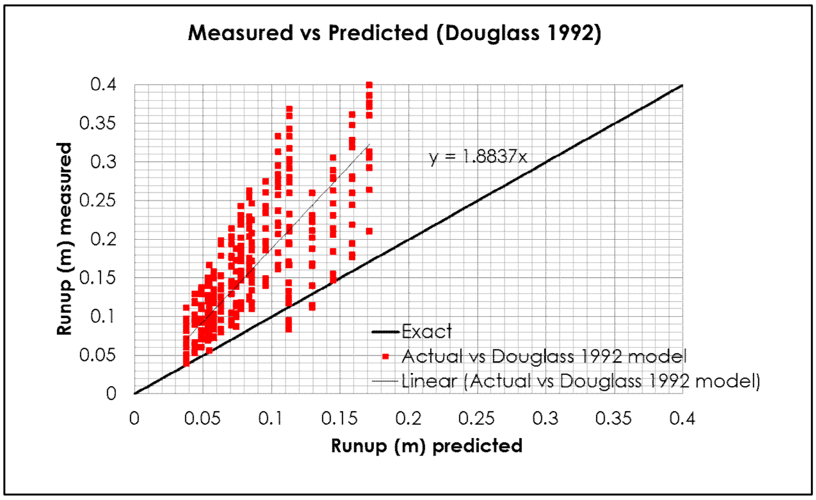

Figure 9. Experimental Data Comparison with Douglass (1992) parametric runup equation.

Parameter Correlation

The most significant correlation between combinations of dependent and independent parameters was obtained with the non-dimensional form of the maximum wave runup (R_{max}/H_o) and the surf similarity parameter (ξ_o, or Irribarren number). The Pearson correlation parameter, R, was determined as 0.87 for this pair of non-dimensional parameter groups. This inevitably results in a Hunt-type formulation for the description of the maximum wave runup. The final form of the parametric formulation that best suited these experimental results is given in equation 7 below, where C_{perm} is a non-dimensional permeability coefficient that is initially set to 1 (unity) in the analyses for data comparison. C_{perm} is inserted to assess the effect of bed permeability on the runup maxima.

$$\frac{R_{max}}{H_o} = C_{perm}\left(\frac{\tan\beta}{\sqrt{\frac{H_o}{L_o}}}\right) \tag{7}$$

A comparison plot (similar to those in Figures 7 to 9) is also generated using equation 7 and all the experimental data. This plot is shown in Figure 10 below.

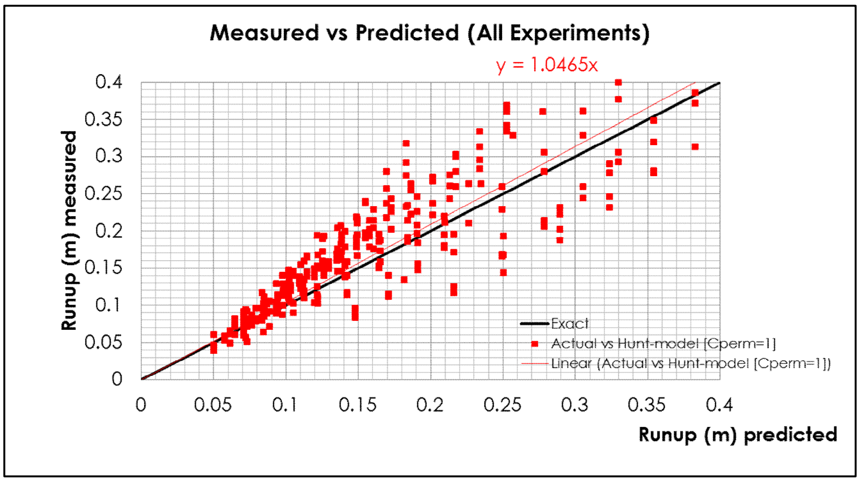

Figure 10. Experimental Data Comparison with Hunt-type parametric runup equation.

In figures 7 to 10 above, the thick solid black line represents where the measured and predicted values are exactly equal. Where experimental data points lie above this line, the predicted values underestimated the measured data. Conversely, where experimental data points lie below this line, the predicted values overestimated the measured data. The linear trendline plotted in these comparisons has its y-intercept set to zero and the gradients of these trendlines are shown on each plot. The trendlines are thin black lines in Figures 7 to 9 and a red line in Figure 10. A gradient of unity of this trendline indicates that the predicted formula generally fits with the experimental data. Where the slope of the trendline is greater than one, the predictive formula generally underestimates the maximum runup, using this experimental data set.

As is usual for these types of plots, the scatter seen across the plotted data points indicates the precision of the predictive formula. To assess the degree of scatter in the data presented, the percentage relative error ($\%E_{rel}$) may be determined for each data point. This % relative error is given in equation 8 below as:

$$\%E_{rel} = \frac{R_{meas} - R_{pred}}{R_{meas}} x100 \tag{8}$$

where R_{meas} and R_{pred} are the measured and predicted runup values respectively.

All the data were grouped into the different bed permeabilities regardless of bed slope. In these analyses, the optimal value for the C_{perm} parameter was fitted to the data for each different bed permeability. The results of this C_{perm} fitting are shown in Table 4 below. In addition, the C_{perm} values are plotted against the actual bed permeability in order to extract the best trendline from the limited data. This regression should provide the best description of the C_{perm} parameter given the bed permeability, k. This plot is shown in Figure 11 below and the trendline equation is given by equation 9. The Pearson correlation, R, for this trendline fitting was determined as 0.98.

$$C_{perm} = 2.9737k^2 - 1.6772k + 1.1408 \tag{9}$$

where k is the bed permeability.

Table 4. Summary of C_{perm} Parameter with range of experimental bed permeability

Bed Permeability (m/s)	C_{perm}
0.401	0.9470
0.105	0.9875
0.0311	1.1187
0.00000001	1.1232

Equation 9 was used to describe the C_{perm} parameter in order to yield an adjusted Hunt-type model for wave runup which can include the bed permeability. A plot of the original Hunt model with C_{perm} value set to unity and the adjusted Hunt model using equation 6 is shown in Figure 12.

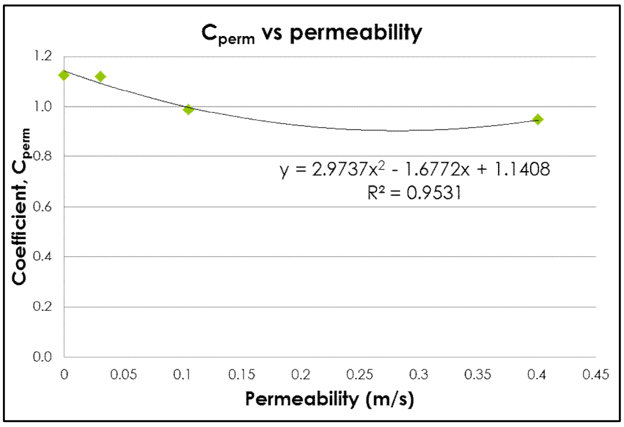

Figure 11. A plot of the best-fit C_{perm} value for each permeability versus the bed permeability.

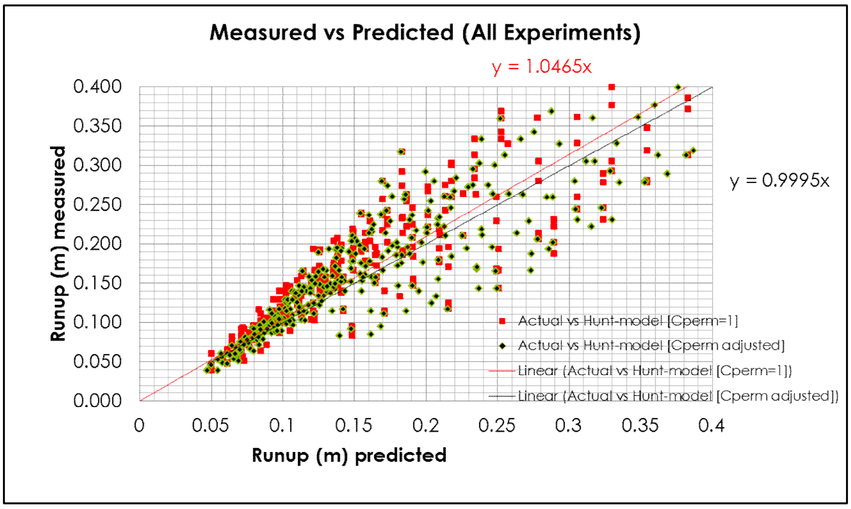

Figure 12. Experimental Data Comparison with Hunt-type equation and adjusted Hunt model.

To assess the scatter between the Hunt-type model and the one adjusted for bed permeability, the average of the $\%E_{rel}$ was obtained for each beach slope and each bed permeability. These results are presented in Table 5 below for the Hunt-type formulation and the adjusted Hunt model.

The average percentage relative error ($\%E_{rel}$) is a useful indicator as it illustrates whether the parametric model is under-predicting or over-predicting the measured values. If the $\%E_{rel}$ is negative, then the parametric model is producing an over-estimate at that condition, based on the measured value.

Table 5. Summary of % Relative Error in the Hunt-type formulation

Beach Slope (degrees)	Bed Permeability (m/s)	$\%E_{rel}$ Hunt Model	$\%E_{rel}$ Adjusted Hunt Model
9	0.401	-11.042	-5.092
9	0.105	-3.575	-3.314
9	0.031	7.992	-0.428
9	0.000	5.246	-8.096
11	0.401	4.162	9.297
11	0.105	15.765	15.977
11	0.031	17.286	9.716
11	0.000	14.334	2.272
13	0.401	-11.063	-5.112
13	0.105	-5.502	-5.236
13	0.031	14.827	7.033
13	0.000	13.697	1.545
15	0.401	-4.168	1.414
15	0.105	1.167	1.416
15	0.031	10.507	2.317
15	0.000	11.615	-0.830

DISCUSSION OF RESULTS

The grain size equivalence based solely on bed permeability is very challenging and the results depicted in Table 2 reflect the fact that a simplified formulation such as those used in equations 1 to 3 can yield a broad range of possible grain sizes. There is a wide range in equivalent grain sizes obtained via the three methods, with the Hazen and the Kozeny-Carman formulations yielding values that are on the same order of magnitude. The Hazen and the modified-Shepherd only use a representative grain size to estimate permeability, whereas the Kozeny-Carman includes bed porosity and a grain size to estimate permeability. Since the bed porosity does affect the permeability and porosity can range approximately between 24% and 53% for granular materials, the Kozeny-Carman method is anticipated to yield more realistic estimates for the grain size estimate.

It is evident from Table 3 and Figure 6, that the wave reflection coefficients obtained by the three various methods were all the same order of magnitude. Therefore, there is confidence in the wave reflection coefficient obtained from the Lin and Huang (2004) method, which was only used in subsequent analyses. In certain wave conditions, the high value of the reflection coefficient will clearly have an impact on the incident wave energy in the flume. The reflected wave will interact with the incident wave as produced by the wave generator. Interaction may be constructive or destructive and either increase or decrease the incident wave energy that is experienced by the beach face. In any wave runup analysis, where the incident wave energy is used to predict the wave runup magnitude, it is imperative to use the incident wave energy that will realistically impact the beach and hence runup. In those cases where the reflection coefficient is high, this factor must be considered. The highest reflection coefficients were associated with the longest wave, which is the 0.3Hz (3.33s) wave condition, for all bed conditions. The largest percentage relative error ($\%E_{rel}$), is also associated with these wave conditions indicating that the extent of the reflection does impact on the predictive capability of the wave runup.

The three parametric formulations of Stockdon et al. (2006), Ruggiero et al. (2001) and Douglass (1992) consistently under-predict the measured values. While wave reflection may be a contributing factor in this discrepancy, other factors may contribute to the under-prediction of these parametric formulations which were all developed using field data. For example, there must be consideration given to the contribution by the infragravity component of the wave energy, the significance of the contribution of breaking, the extent of swash-swash interaction and non-breaking waves to the runup magnitude and the varying effect of regular and irregular waves on wave runup. Nonetheless, the Stockdon et al. (2006) formula was the best predictor of the three parametric equations used for comparison.

It was not surprising that the experiments yielded a Hunt-type expression as the most suitable for runup prediction. Without any adjustment for bed permeability, the Hunt formula still provides reasonable estimates for wave runup based on these experiments, providing generally an under-prediction of runup magnitude by about 4.65%, with considerable scatter. However, a clear relationship between bed permeability and wave runup does exist, as shown in Figure 11. As seen in Table 4, as the bed permeability decreases the C_{perm} parameter increases, which is the expected link between these two parameters.

However, the application of the permeability parameter in the adjusted Hunt formula improves the predictive capability of the formula in two distinct ways. Firstly, the trendline gradient is almost unity, indicating that generally the predictive and measured values are of the same magnitude (see Figure 12). Secondly, there is a reduction in the scatter of the data which is evident from Figure 12 and also Table 5. The average percentage relative error ($\%E_{rel}$) for each slope and bed permeability generally is on the same magnitude or reduced, with two notable exceptions: one at the highest permeability bed on the 11° slope and the other on the impermeable bed with a 9° slope.

One last point to note is that the presence of the metal plate should have reduced the absolute volume of water that infiltrated the bed, but this effect was expected to be the same across all experiments. Experiments conducted with the perforated plate should produce an increase in the maximum runup, when compared to a bed whose beach surface is 100% permeable. It was anticipated that the degree to which the metal plate affected the maximum runup was indistinguishable across the different experiments and therefore, should not affect the analyses conducted to assess the effect of bed permeability. However, this aspect will be subject to further investigation.

CONCLUSION

Analysis has identified a clear relationship between the runup and bed permeability. In this study, the effect of bed permeability was included via the inclusion of a non-dimensional coefficient. This non-dimensional coefficient was determined based on the bed permeability and was used to amend an existing formula. Only a Hunt-type model was explored for adjustment based on its suitability and compatibility to the nature of the experiments performed.

Further assessment of the permeability effect is required for beaches consisting of sand-sized to gravel-sized sediment to improve the mathematical expression for the C_{perm} parameter.

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