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Comparison between different wave runup level prediction formulas based on the wave breaking type

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ABSTRACT

In this study, the performance of some models for predicting the wave runup level is investigated. To do so, they are compared with each other over a database of 1390 field and laboratory data points. This comparison has actually two aims: The first one is to investigate the models using all data points and the second one is to consider the influence of wave breaking type on the accuracy of the formulas. The latter goal is achieved by dividing the data points based on the type of wave breaking using the Iribarren number. It is also important to mention that most of the models used here for comparison have been optimized by Power et al. in 2019 so that more accurate outcomes would be obtained by them. These models depend on certain wave and beach parameters, including wave height, wave length, wave period, and seabed slope. The results of the comparison have been demonstrated using several statistical characteristics (e.g. RMSE, R^2, etc.) so that a good understanding could be obtained from the behavior of each formula. At first, when the type of wave breaking is not considered in the comparison and all data points are used, the optimized formula derived from both studies of Holman and Atkins et al. seems to be the most accurate one with the least prediction error. Then, when the data points are divided into groups based on the wave breaking type (i.e. spilling and plunging), different outcomes are achieved. The optimized formula proposed by Poate et al. has almost the best performance in the case of spilling type and the formula of Power et al. is the most accurate one when considering the plunging type, showing that the type of wave breaking plays an important role in the accuracy of wave runup level prediction formulas.

1. Introduction

The landward propagation of waves contains several stages and wave runup is the final one. In other words, the final landward position a wave can reach before changing its movement to a seaward direction can be determined by runup. This process is actually a combination of swash and wave generated setup [1]. Therefore, the runup region is considered as an important area due to the fact that several processes such as coastal erosion, sediment exchange near shorelines and overtopping from coastal structures are directly affected by the runup level.

In order to express the runup level (i.e. the maximum elevation of water-surface measured from the still-water level (SWL) in a vertical manner [2]), several statistical measures exist in the literature [3]. The most common ones are R_{max} (which indicates the maximum elevation achieved by a single runup level during a specific period of time) and $R_{2\%}$ (which indicates an elevation exceeded by 2% of all runup events during a specific period of time) [4].

During the previous decades, several empirical models have been proposed for predicting the wave runup level [4]. These models are based on similar parameters related to wave and beach conditions such as wave height, wave length, wave period, and seabed slope. Moreover, wave breaking conditions are among the factors that have influence on the complexity of wave runup [5]. There exists a parameter by which the type of breaking waves (e.g. spilling, plunging, etc.) can be determined. This parameter is called the surf similarity parameter [6] (also known as the Iribarren number) and is denoted by ξ_o, which is:

$$\xi_o = \frac{\tan\beta}{\sqrt{H_o/L_o}} \tag{1}$$

where, $\tan\beta$ indicates the seafloor slope, H_o denotes the offshore wave height and L_o is the offshore wave length. It is worthwhile to mention here that when waves break, a significant amount of energy is released which affects the runup level [5].

In this paper, it is tried to investigate the accuracy of some wave runup level prediction models using a large field and laboratory wave database. These models have been mentioned as accurate ones for predicting $R_{2\%}$ in the literature and most of them have been optimized by Power et al. in 2019 [4] so that their accuracy would be increased further. The database used here has been divided based on the type of wave breaking and comparisons are carried out between the results of different prediction models using all data points as well as data points related to certain breaking types, so that the accuracy of these formulas in predicting wave runup level based on the breaking type has also been examined.

2. Materials and methods

The wave runup prediction models that have been investigated here are among the most accurate ones compared to other formulas, according to the literature [4]. These models have been obtained by different researchers, including Holman [1], Vousdoukas et al. [7], Poate et al. [8], Atkinson et al. [3], Power et al. [4] and Van der Meer and Stam [9]. It should be mentioned that in the study of Power et al. [4], along with proposing a new model for predicting wave runup level, some other relationships (which are also used in this paper) have been modified with optimized parameters to improve their accuracy. In Table 1, all of the relationships that are used in this study are provided.

Table 1: Empirical wave runup level prediction relationships based on the optimized parameters (except for the formula proposed by Van der Meer and Stam [9]) proposed in Ref. [4]

Authors	Relationships
Holman (1986) [1] / Atkinson et al. (2017) [3]	$0.50\tan\beta\sqrt{H_s L_p} + 0.70H_s$
Van der Meer and Stam [9]	$0.96H_s\xi_o \cdots \text{for } \xi_o \le 1.5$ $1.17H_s(\xi_o)^{0.46} \cdots \text{for } \xi_o > 1.5$
Vousdoukas et al. (2014) [7]	$0.005\beta\sqrt{H_s L_p} + 4.563\tan\beta H_s + 0.458$
Poate et al. (2016) [8]	$0.309\tan\beta^{0.48} T_p H_s$
Power et al. (2019) [4]	See the Appendix

As seen in Table 1, the models depend on different parameters, which are $\tan\beta$ (seabed slope), H_s (wave height), L_p (peak wave length), T_p (peak wave period) and *r* (hydraulic roughness length). It should be noted that the wave length considered here is actually the offshore wave length and it can be obtained using the Airy theory, in which the relation for calculating the offshore wave length is $gT_p/2\pi$, where *g* denotes the gravitational constant. There are also other wave runup level prediction formulas that use further parameters, such as D_{50} (grain size), but they are not investigated in this study. The hydraulic roughness length can be obtained using the grain size for the field data and there are some standard tables to find the value of this parameter when investigating the laboratory data (more information is available in Ref. [4]). Moreover, after carrying out the optimization process by Power et al. [4] and modifying the models, the formulas proposed by Holman [1] and Atkinson et al. [3] have become a single formula with optimized constants, as shown in this Table 1.

The wave runup data base used in in this study contains 1390 field and laboratory data points (Refs. [3, 8, 10-14]). These data points were gathered from different studies, which are given in Table 2, along with the range of the desired parameters in each study.

Table 2: The available compiled field and laboratory data

Dataset	H_s(m)	$\tan\beta$	T_p(s)	Data points
Field				
Stockdon et al. (2006) [10]	0.350-4.080	0.009-0.160	3.70-17.00	491
Poate et al. (2016) [8]	1.040-7.170	0.088-0.290	4.80-23.70	663
Atkinson et al. (2017) [3]	0.550-1.190	0.051-0.190	6.40-9.30	71
Nicolae Lerma et al. (2017) [11]	3.090-6.070	0.060-0.081	13.30-16.30	17
Laboratory				
Mase (1989) [12]	0.026-0.110	0.033-0.200	0.81-2.50	120
Baldock and Huntley (2002) [13]	0.019-0.066	0.100	1.03-1.98	16
Howe (2016) [14]	0.820-0.910	0.167	9.80-13.70	12

In order to divide the data points based on the wave breaking type, the criterion proposed by Battjes [6] has been applied. This criterion is based on the Iribarren number and using this number, the breaking type can be categorized as spilling, plunging, surging, or collapsing. In the following equation, different ranges of the Iribarren number for each wave breaking type are given:

$$\begin{cases} \text{spilling} & \text{if } \xi_o \le 0.5 \\ \text{plunging} & \text{if } 0.5 < \xi_o \le 3.3 \\ \text{surging/collapsing} & \text{if } \xi_o > 3.3 \end{cases} \tag{2}$$

In order to investigate the accuracy of different models shown in Table 1 in predicting the wave runup level, the calculated level ($R_{2\%(c)}$) is compared with the observed one ($R_{2\%(o)}$) based on the dataset shown in Table 2. The statistical characteristics shown in Table 3 are used for examining the results of this comparison. For more information about these characteristics and their concept, the interested reader may refer to Ref. [15]. It should be noted that in this table, $\bar{R}$ refers to the average value.

Table 3: The statistical characteristics used for comparing the results of this study

Characteristics	Relationships
Root mean square error (RMSE)	$\sqrt{\frac{\sum_{i=1}^{N}\left(R_{2\%(c),i}-R_{2\%(o),i}\right)^2}{N}}$
Coefficient of determination (R^2)	$\left[\frac{\sum_{i=1}^{N}\left(R_{2\%(c),i}-\bar{R}_{2\%(c)}\right)\left(R_{2\%(o),i}-\bar{R}_{2\%(o)}\right)}{\sqrt{\sum_{i=1}^{N}\left(R_{2\%(c),i}-\bar{R}_{2\%(c)}\right)^2}\sqrt{\sum_{i=1}^{N}\left(R_{2\%(o),i}-\bar{R}_{2\%(o)}\right)^2}}\right]^2$
Bias (B)	$\frac{\sum_{i=1}^{N}R_{2\%(c),i}-R_{2\%(o),i}}{N}$
Percentage relative error (E_{rel})	$\left\lvert\frac{\bar{R}_{2\%(c)}-\bar{R}_{2\%(o)}}{\bar{R}_{2\%(c)}}\right\rvert\times 100$
Absolute error (E)	$\left\lvert\bar{R}_{2\%(c)}-\bar{R}_{2\%(o)}\right\rvert$
Scatter index (SI)	$\frac{\text{RMSE}}{\frac{1}{N}\sum_{i=1}^{N}R_{2\%(b),i}}\times 100$

3. Results and discussion

In Tables 4-6, the results of comparing different wave runup prediction models (i.e. the ones optimized by Power et al. [4] as well as the model proposed in their study) in three cases of using all, spilling and plunging data points are provided. As it is understood from Table 4, the optimized formula derived from both studies of Holman [1] and Atkinson et al. [3] seems to be the most accurate one (RMSE=0.854m, B=0.005m, R^2=0.769, E_{rel}=0.233%, E=0.005m and SI=36.838%) when the type of wave breaking is ignored in the comparison and all data points are considered for the comparison. However, the results are different when considering the breaking type. In other words, for the case of spilling breaking type, the optimized formula of Poate et al. [8] seems to have the least error and almost acceptable performance (RMSE=0.585m, B=0.064m, R^2=0.665, E_{rel}=10.101%, E=0.064m and SI=101.965%) compared to the other formulas and when considering the plunging breaking type, the formula proposed by Power et al. [4] has the best performance (RMSE=0.779m, B=0.014m, R^2=0.804, E_{rel}=0.544%, E=0.014m and SI=31.184%). Therefore, it seems that the performance of these accurate models changes when the data points relating to specific breaking type are investigated, rather than a general group of data points in which the type of breaking is ignored. This issue complies with the concept of wave breaking as well. In other words, a significant amount of energy is released along with the wave breaking phenomena. Apart from several other factors, this amount is related to the type of breaking as well. Therefore, the runup level, which is influenced by the amount of the released energy, can be affected by the type of breaking waves.

In order to show a better picture of the performance of the models when predicting the wave runup level, the scatter diagram of the observed vs. calculated value of the runup level of all models for the three cases (all, spilling, and plunging data points) are shown in Figures 1-3.

4. Conclusions

The level of wave runup plays a major role in many coastal issues (e.g. sediment transport, overtopping form structures, erosion, etc.) and being able to predict its value as accurate as possible is of significant importance. In this study, the performance of several wave runup level prediction models that have been optimized by other researchers and are considered as accurate formulas in this regard have been investigated. A database containing 1390 different field and laboratory data points was used here to apply a comparison between the models. In this comparison, two questions have been investigated; one, what is the general performance of each model when considering the whole database? and two, what is the effect of wave breaking type on the accuracy of each model? As for the answer of the first question, the optimized formula derived from the studies of Holman and Atkinson et al. was the most accurate one with the least error.

However, when the data points were divided based on the wave breaking type, different models became the almost most accurate ones (i.e. the optimized formula of Poate et al. for the case of spilling breaking type and the formula of Power et al. for the case of plunging one). Therefore, it is clear that the type of wave breaking has a direct influence on the accuracy of wave runup level prediction models and proposing different formulas based on the type of wave breaking seems to be a reasonable idea.

Table 4: Comparison between the calculated runup level and the observed one for all data points

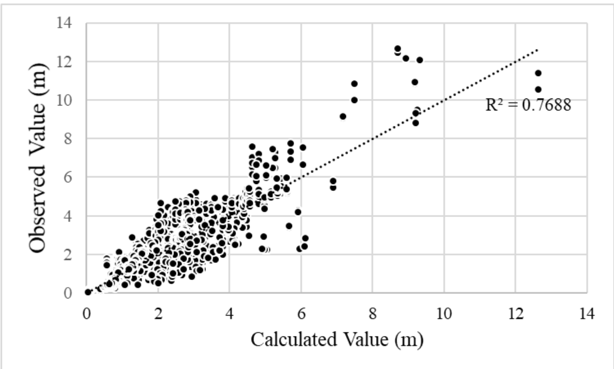
Formula	$\bar{R}_{2\%(o)}$ (m)	$\bar{R}_{2\%(c)}$ (m)	RMSE (m)	B (m)	R^2	E_{rel} (%)	E (m)	SI (%)
Holman [1] / Atkinson et al. [3]	2.319	2.324	0.854	0.005	0.769	0.233	0.005	36.838
Van der Meer and Stam [9]	2.319	1.791	1.154	-0.528	0.700	29.475	0.528	49.746
Vousdoukas et al. [7]	2.319	1.574	1.341	-0.745	0.686	47.327	0.745	57.843
Poate et al. [8]	2.319	2.178	1.098	-0.141	0.719	6.483	0.141	47.360
Power et al. [4]	2.319	2.347	0.755	0.029	0.820	1.214	0.029	32.545

Table 5: Comparison between the calculated runup level and the observed one for spilling data points

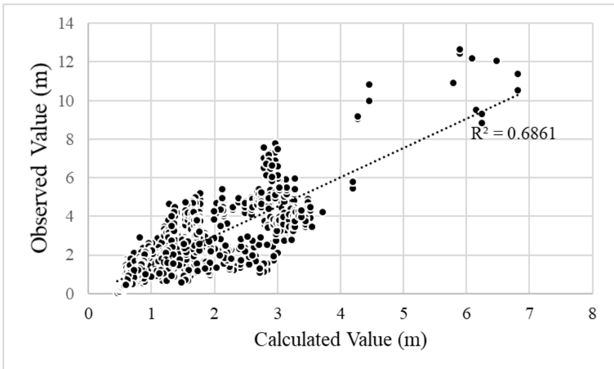
Formula	$\bar{R}_{2\%(o)}$ (m)	$\bar{R}_{2\%(c)}$ (m)	RMSE (m)	B (m)	R^2	E_{rel} (%)	E (m)	SI (%)
Holman [1] / Atkinson et al. [3]	0.574	0.947	0.700	0.372	0.774	39.354	0.372	122.032
Van der Meer and Stam [9]	0.574	0.328	0.423	-0.246	0.721	75.092	0.246	73.750
Vousdoukas et al. [7]	0.574	0.681	0.419	0.107	0.665	15.762	0.107	73.072
Poate et al. [8]	0.574	0.639	0.585	0.064	0.665	10.101	0.064	101.965
Power et al. [4]	0.574	0.747	0.454	0.173	0.797	23.138	0.173	79.019

Table 6: Comparison between the calculated runup level and the observed one for plunging data points

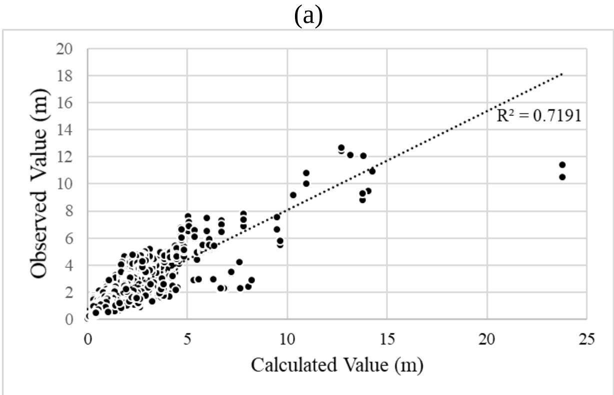
Formula	$\bar{R}_{2\%(o)}$ (m)	$\bar{R}_{2\%(c)}$ (m)	RMSE (m)	B (m)	R^2	E_{rel} (%)	E (m)	SI (%)
Holman [1] / Atkinson et al. [3]	2.497	2.465	0.868	-0.032	0.757	1.314	0.032	34.7621
Van der Meer and Stam [9]	2.497	1.941	1.203	-0.557	0.634	28.674	0.557	48.187
Vousdoukas et al. [7]	2.497	1.665	1.402	-0.832	0.658	49.980	0.832	56.127
Poate et al. [8]	2.497	2.335	1.138	-0.162	0.704	6.956	0.162	45.550
Power et al. [4]	2.497	2.511	0.779	0.014	0.804	0.544	0.014	31.184



(a)



(b)



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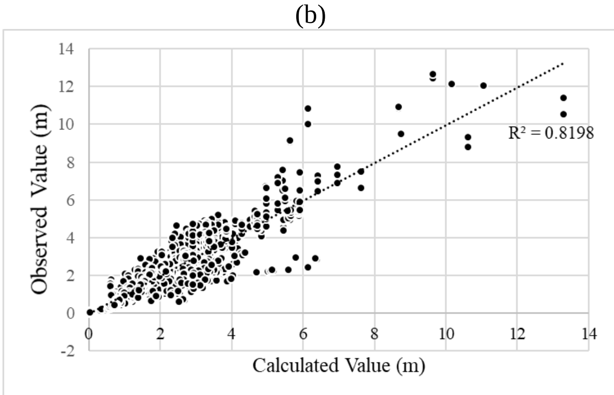

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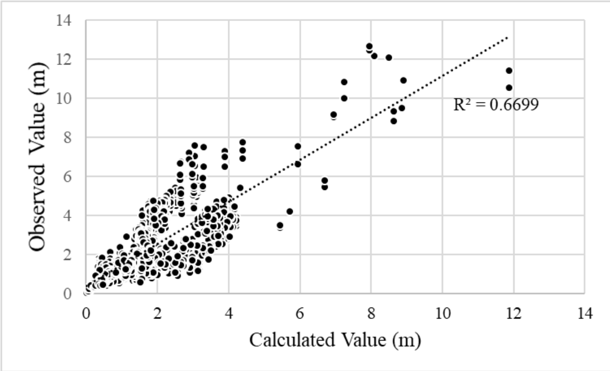
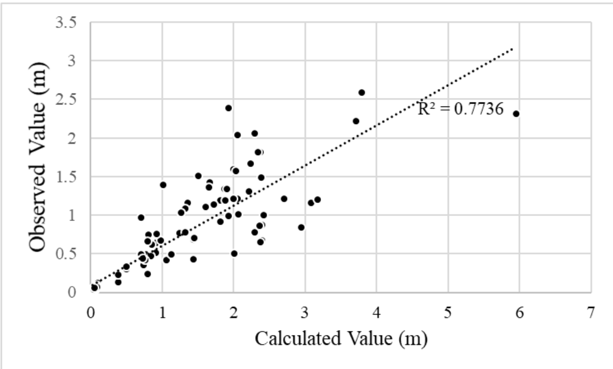
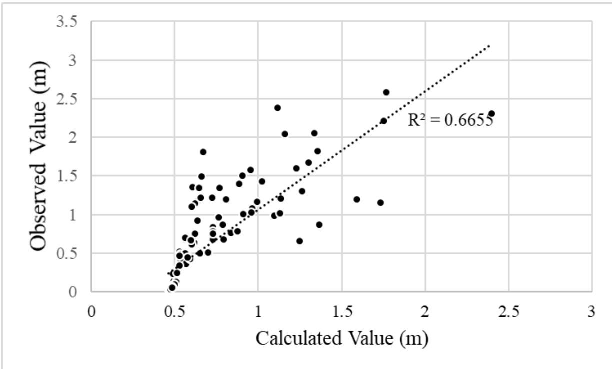


(e)

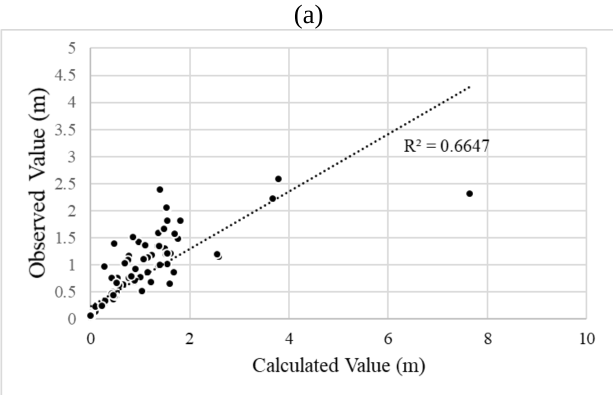
Figure 1. The scatter diagram of (a) Holman / Atkinson et al. formula (b) Vousdoukas et al. formula (c) Poate et al. formula (d) Power et al. formula (e) Van der Meer and Stam formula for all data points



(a)



(b)



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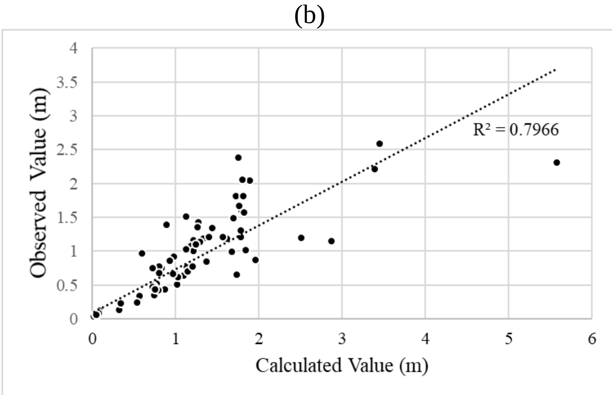

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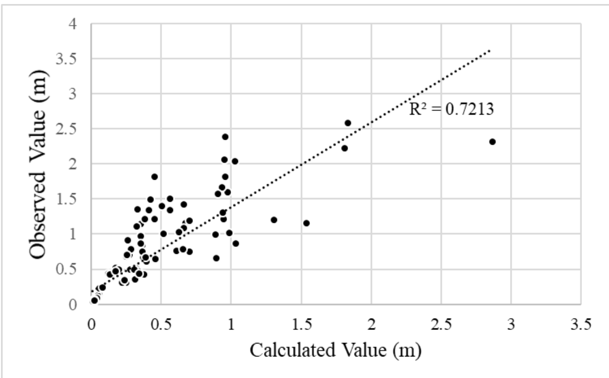

(e)

Figure 2. The scatter diagram of (a) Holman / Atkinson et al. formula (b) Vousdoukas et al. formula (c) Poate et al. formula (d) Power et al. formula (e) Van der Meer and Stam for spilling data points

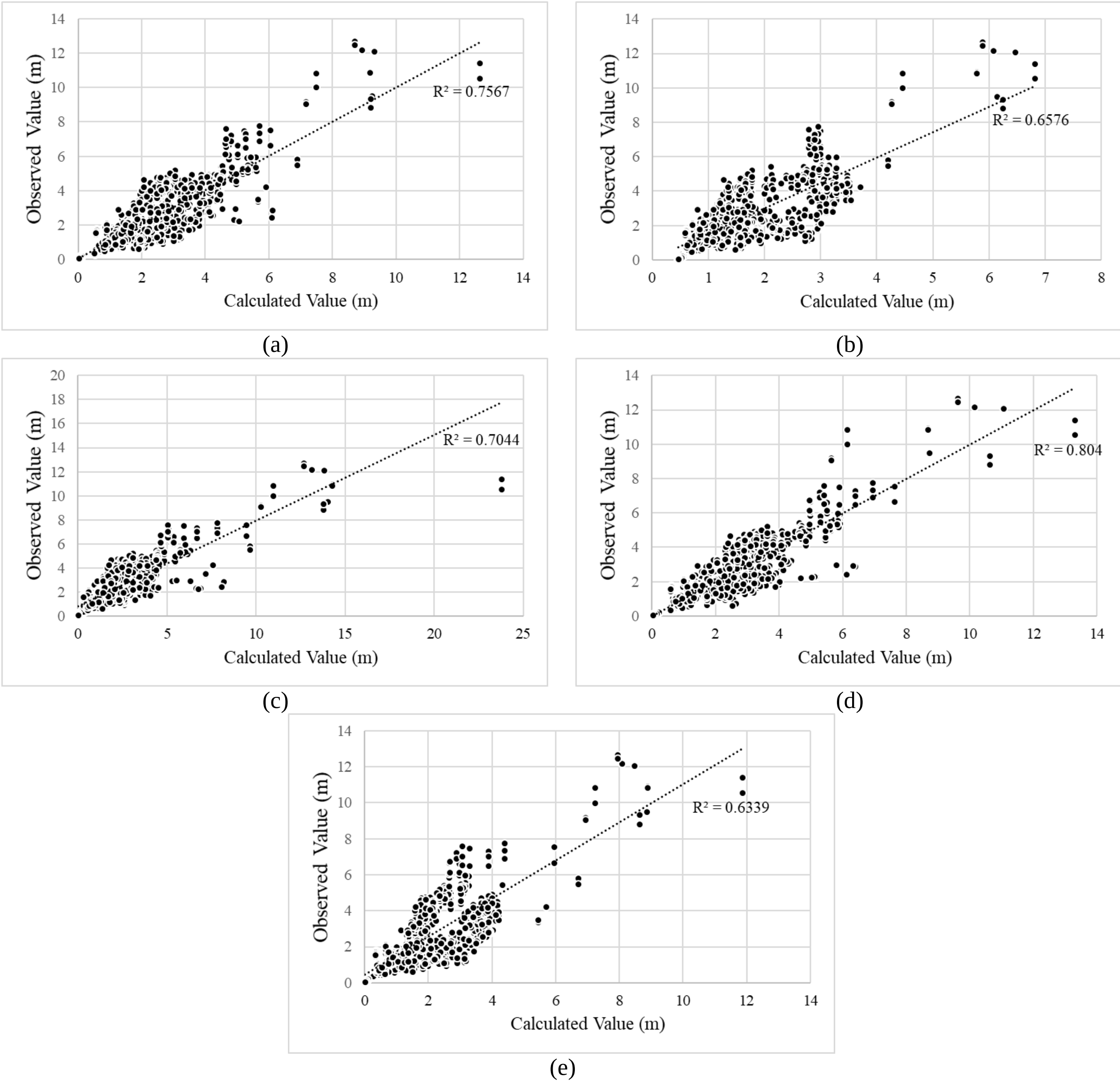

Figure 3. The scatter diagram of (a) Holman / Atkinson et al. formula (b) Vousdoukas et al. formula (c) Poate et al. formula (d) Power et al. formula (e) Van der Meer and Stam for plunging data points

5. Acknowledgment

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6. References

[1] Holman, R.A., (1986), Extreme value statistics for wave run-up on a natural beach, Coastal Engineering, Vol.9(6), p.527-544.

[2] Burcharth, H.F., Hughes A.S., (2003), Fundamentals of Design, In Coastal Engineering Manual, Coastal Engineering Research Center, Vol.6, p.VI-5-i - VI-5-316.

[3] Atkinson, A.L., Power, H.E., Moura, T., Hammond, T., Callaghan, D.P., Baldock, T.E., (2017) Assessment of runup predictions by empirical models on non-truncated beaches on the south-east Australian coast, Coastal Engineering, Vol.119, p.15-31.

[4] Power, H.E., Gharabaghi, B., Bonakdari, H., Robertson, B., Atkinson, A.L., Baldock, T.E., (2019), Prediction of wave runup on beaches using Gene-Expression Programming and empirical relationships, Coastal Engineering, Vol.144, p.47-61.

[5] Khoury, A., Jarno, A., Marin, F., (2019), Experimental study of runup for sandy beaches under waves and tide, Coastal Engineering, Vol.144, p.33-46.

[6] Battjes, J., (1974), Surf similarity, Proceedings of the 14th International Conference on Coastal Engineering (Copenhagen, Denmark, ASCE), p. 1050–1061.

[7] Vousdoukas, M.I., Wziatek, D., Almeida, L.P., (2012), Coastal vulnerability assessment based on video wave run-up observations at a mesotidal, steep-sloped beach, Ocean Dynamics, Vol.62(1), p.123-137.

[8] Poate, T.G., McCall, R.T., Masselink, G., (2016), *A new parameterisation for runup on gravel beaches*, Coastal Engineering, Vol.117, p.176-190.

[9] Van der Meer, J.W., Stam, C.J., (1992) *Wave runup on smooth and rock slopes of coastal structures*, Journal of Waterway, Port, Coastal, and Ocean Engineering, Vol.118(5), p.534-550.

[10] Stockdon, H.F., Holman, R.A., Howd, P.A., Sallenger Jr, A.H., (2006), *Empirical parameterization of setup, swash, and runup*, Coastal engineering, Vol.53(7), p.573-588.

[11] Lerma, A.N., Pedreros, R., Robinet, A., Sénéchal, N., (2017), *Simulating wave setup and runup during storm conditions on a complex barred beach*, Coastal Engineering, Vol.123, p.29-41.

[12] Mase, H., (1989) *Random wave runup height on gentle slope*, Journal of Waterway, Port, Coastal, and Ocean Engineering, Vol.115(5), p.649-661.

[13] Baldock, T.E., Huntley, D.A., (2002), *Long–wave forcing by the breaking of random gravity waves on a beach*, Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, Vol.458(2025), p.2177-2201.

[14] Howe, D., (2016), *Bed shear stress under wave runup on steep slopes*, Doctoral dissertation, Ph. D. Thesis, University of New South Wales, Sydney, Australia.

[15] Tadayon, B., Dehghani, H., Ershadi, C., (2019), *Recent Wave Breaking Prediction Formulas Evaluation Based On Compiled Laboratory Data*, International Journal of Coastal and Offshore Engineering, Vol.3(1), p.41-6.

Appendix

The wave runup level prediction model proposed by Power et al. [4] has been developed using gene expression programming (GEP). The relationship of this model is given below:

$R_{2\%} / H_s$ = (x2+(((x3.*3)/exp(-
5)).*((3.*x3).*x3))) + ((((x1+x3)-2)-(x3-
x2))+((x2-x1)-x3)) + (((x3.^x1)-
(x3.^(1.0/3.0)))-(exp(x2).^(x1.*3))) +
sqrt((((x3+x1)-x2)-(x2+log10(x3)))) +
((((x2.^2)./(x1.^(1.0/3.0))).^(x1.^(1.0/3.0)))-
sqrt(x3)) +
((x2+((x3./x1).^(1.0/3.0)))+(log(2)-
(1./(1+exp(-(x2+x3)))))) + ((sqrt(x3)-
(((3.^2)+3).*(x2.^2))).^2) + ((((x3.*-
5).^2).^2)+(((x3+x3).*x1)./(x2.^2))) +
log((sqrt(((x2.^2)+(x3.^(1.0/3.0))))+((x2+3).
^(1.0/3.0)))) + ((((x1./x3).*(-
5.^2)).*(x3.^2))-log10((1./(1+exp(-
(x2+x3)))))) + (x1.^x3) + exp(-
((((x3./x1).^exp(4))+(exp(x3).^3)).^2))+
exp((log((x2-x3))-log(exp(-((-1+x1).^2)))))
+ ((sqrt(4).*(((x3./x2)-x2)-(0-x1))).^2) +
(2.*((((-5.*x3)+x1).*(2-x3))-2)) +
((sqrt(4).*(((x3./x2)-x2)-(0-x1))).^2) + ((((-
5+x1)-x2).*(x2-x3)).*((x1-x2)-(-4.^-5)))+
(exp(-((x2+(-5-x1)).^2))+((x2--5).*(x3.^2)))
+ sqrt(1./(1+exp(-((exp(x1)-exp(-
((x3+x3).^2)))+((x1.^x3)-(x3.*4)))))) +
((exp(-((((exp(-(((sqrt(x3).*4)+(1./(1+exp(-
(x2+2)))))).^2))).^2)+x1).^2))).^3)   (A.1)

where, x_1, x_2, and x_3 represent H_s / L_p, $\tan\beta$ and r / H_s, respectively.