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Runup estimations on a macrotidal sandy beach

J.-M. Cariolet [a,b,*], S. Suanez [a]

[a] GEOMER, UMR 6554 CNRS LETG, Institut Universitaire Européen de la Mer, Technopôle Brest-Iroise, Place Nicolas Copernic, 29285 Plouzané, France
[b] Department of Geography, University of Leicester, University Road, Leicester LE1 7RH, United Kingdom

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ABSTRACT

This paper presents a methodological approach to calculate runup from the analysis of morphodynamic conditions on a macrotidal sandy beach. The method is based on measurements of the elevation of high-tide deposits and on the analysis of morphological and hydrodynamic changes. A series of measurements has been carried out on the beach of Vougot (Brittany, France) under different wave conditions. This allowed to assess runup formula effectiveness on a macrotidal sandy beach and to determine the best slope parameters to estimate runup. The results suggest that on that macrotidal sandy beach the slope of the active section of the upper beach should be used instead of the entire slope of the foreshore, the latter resulting in an underestimation of runup elevations when used in predictive equations from the literature. Results obtained with widely used equations are relatively well correlated with observed values ($r^2 = 0.63$). An analysis of the relationship between observed runup elevations and various variables has enabled the establishment of a runup estimation formula with a relatively good fit to the study site ($r^2 = 0.86$).

1. Introduction

Runup, defined as the difference between discrete water elevation maxima and still water level, is a process that can generate extreme water levels (Bellomo et al., 1999; Benavente et al., 2006; Komar, 1998; Matias et al., 2012; Ruggiero et al., 2001). Runup is a key factor during coastal erosion processes, when swash reaches the toe of the dune (Erikson et al., 2007; Fisher and Overton, 1984; Larson et al., 2004; Van de Graaff, 1986) or barrier (Ruggiero et al., 2001; Sallenger, 2000; Stockdon et al., 2007). Wave overtopping over a barrier (Donnely et al., 2006; Orford et al., 1991; Sallenger, 2000) or a coastal structure (De Rouck et al., 2005; Van der Meer and Janssen, 1995) depends widely on runup processes too. Many studies based on laboratory and in-situ measurements of runup have shown that runup is a function of beach steepness ($tan\beta$) deep water wavelength (Lo) and significant wave height (H_{mo}), and thus Iribarren number (Battjes, 1974; Hunt, 1959). The first relation found by I.A. Hunt in 1959 was:

$$R = H_{mo}\xi_o \tag{1}$$

where R is the runup (in m) and ξ_o is the Iribarren number with

$$\xi o = tan\beta/(H_{mo}/Lo)^{1/2} \tag{2}$$

where H_{mo} is the significant wave height, Lo is the deep water wavelength and $tan\beta$ is the beach steepness.

A constant C has been added by Battjes, 1971. This constant varies according to the morphodynamic context, defined by Iribarren number (ξ_o):

$$R = CH_{mo}\xi_o. \tag{3}$$

From this basic relation, several equations have been proposed to estimate runup on different types of beaches. These studies have been carried out exclusively in micro or mesotidal environments (Table 1).

Many authors have taken into account runup process to estimate extreme water levels on macrotidal sandy beaches (Sabatier et al., 2009; Stéphan et al., 2010; Suanez, 2009; Suanez and Cariolet, 2010; Suanez and Stéphan, 2006). However, without any available in situ measurements in macrotidal sandy beaches, runup was estimated with equations parameterised in micro or mesotidal environment (Table 1).

As explained previously, runup is partially a function of beach slope (Komar, 1998). On a natural beach, the meaning of the term «beach slope» is fuzzy (Holman and Sallenger, 1985; Nielsen and Hanslow, 1991; Stockdon et al., 2006). For instance it is difficult to define a single slope value on concave beaches and beaches with sand bars (Stockdon et al., 2006). Some authors suggest using the slope of the surf zone (Holman and Sallenger, 1985; Nielsen and Hanslow, 1991). Nevertheless, the use of such parameter is not easy because breaking waves dynamic is still not completely known, especially where bathymetry is complex (Nielsen and Hanslow, 1991). For this reason, it is recommended to use the

* Corresponding author at: GEOMER, UMR 6554 CNRS LETG, Institut Universitaire Européen de la Mer, Technopôle Brest-Iroise, Place Nicolas Copernic, 29285 Plouzané, France.
E-mail address: carioletjm@yahoo.fr (J.-M. Cariolet).

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Table 1
List of the principal equations used to calculate runup, beach type for the use of each equation and tidal range of the study sites where equation were parameterised.

Study	Equation	Beach type	Tidal range of the study site(s)
Holman (1986) and Nielsen and Hanslow (1991)	$R_{2\%}=0.92\ H_{mo}\xi_o$ (4)	$0.026<tan\beta<0.14$	Microtidal
	$R_{max}=1.07\ H_{mo}\xi_o$ (5)		
Mase (1989)	$R_{2\%}=1.86\ \xi^{0,71}H_{mo}$ (6)	$0.03<tan\beta<0.2$	Microtidal
Ruggiero et al. (2001)	$R_{2\%}=0.27(tan\beta H_{mo}L_o)^{½}$ (7)	$0.005<tan\beta<0.025$	Mesotidal
Stockdon et al. (2006)	$R_{2\%}=0.043(H_{mo}L_o)^{½}$ (8)	$\xi_o<0.3$	Microtidal and mesotidal
	$R_{2\%}=1.1\left(0.35\beta(H_{mo}L_o)^{1/2}+\frac{\left[H_{mo}L_o\left(0.563\beta_f+0.004\right)^{1/2}\right]}{2}\right)$ (9)	$0.3<\xi_o<1.25$	
	$R_{2\%}=0.73tan\beta(H_{mo}L_o)^{1/2}$ (10)	$1.25<\xi_o$	

foreshore slope, that is to say the slope of the intertidal zone (Nielsen, 2009; Nielsen and Hanslow, 1991; Stockdon et al., 2006).

In macrotidal environment, the calculation of the foreshore slope is problematic because the intertidal zone is often vast and rarely homogeneous. Macrotidal foreshores are characterised by an overall concave-upward profile with a steep upper profile and a low-gradient dissipative low tide terrace. It appears that morpho-dynamic model or index such as the model of Masselink and Short (1993) or the Iribarren number (ξ_o) is unadapted for macrotidal beaches, the upper beach and the low tide terrace having different morpho-dynamic behaviours (Anthony et al., 2004; Masselink and Hegge, 1995; Sedrati and Anthony, 2007; Wright et al., 1982). Indeed the average foreshore slope does not reflect reality since it may vary greatly from the lower to the upper beach in macrotidal environment (Fig. 1). Runup values can thus be greatly modified.

A previous study on the macrotidal sandy beach of Porsmillin (Brittany, France) has been conducted (Cariolet, 2011). The foreshore of this cove beach is 200 m wide and composed of mid sands (median = 320 μm). With a maximal tidal range of 7.2 m, the mean foreshore slope has a value of $tan\beta=0.037$. This sandy beach may be considered, on morphodynamic grounds, as an intermediate type with a reflective upper beach ($0.05<tan\beta<0.08$) and a dissipative low tide terrace ($0.02<tan\beta<0.035$). This beach is characterised by the seasonal presence of a berm and intertidal bars (Dehouck et al., 2009). The active section of the beach – section where greatest altitudinal variability is observed – is located between the toe of the dune and a slope break sited at around 90 m from the dune toe. During the field campaign, H_{mo} calculation has varied from 0.2 m to 3.1 m (average = 1.21 m), for a period between 6 and 16 s (mean period = 12.5 s.). The study has shown that runup values calculated with the foreshore slope underestimate reality. Calculation of runup using the slope of the active section of the beach resulted in more reliable results when compared with observed values. The results also show that on Porsmilin beach, $H_{mo}\xi_o$ is the best correlated morphodynamic variable with runup using the slope of the most mobile section of the beach ($r^2=0.72$). A new equation $R_{max}=1.09\ H_{mo}\xi_o$ has been calibrated for the beach of Porsmillin and gives better results than classic equations, with a mean deviation of −0.04 m, a root-mean-square error of 26 cm and a coefficient of determination that is equal to 0.72 (Cariolet, 2011).

The aim of the present study is to verify these first results with additional measurements on another macrotidal sandy beach. Another objective is to validate the method based on the study of statistical relationships between runup and morphodynamic variables. This method could help to better characterise this process on macrotidal sandy beaches and thus to propose adapted equations. For this study, a series of morphologic and water level in-situ measurements has been carried out on the macrotidal sandy beach of Vougot (Brittany, France).

2. Study site: morphologic characteristics

The beach of Vougot is located in the district of Guisseny (North coast of Brittany, France) and stretches over about 2 km facing north-west (Fig. 2). The foreshore is composed of mid sands (250 to 315 μm) and is bordered by a 13 m high dune (Suanez et al., 2012). During spring tides, the beach is 300 m wide and the maximal tidal range is 9 m. The morphological dynamic of the beach has been studied since 2004, with a monthly monitoring along a transect (Suanez and Cariolet, 2010).

The average foreshore slope is low ($tan\beta=0.016$) (Suanez et al., 2007). Along the studied transect, morphological changes decrease from the upper to the lower section of the beach (Fig. 3a and b). It

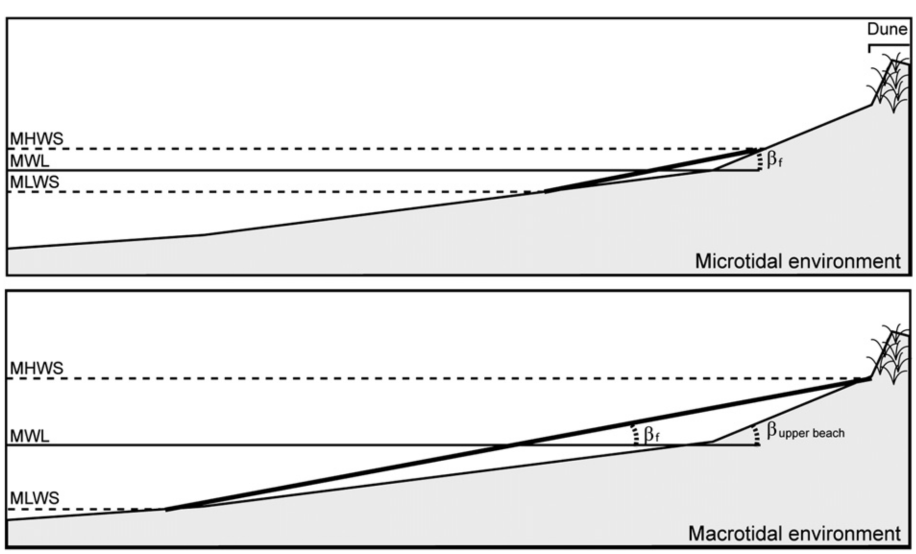

Fig. 1. Diagram representing the different types of slope on a beach regarding the tidal range. In microtidal environment, the foreshore slope (β_f) is calculated on a shorter distance than in macrotidal environment.

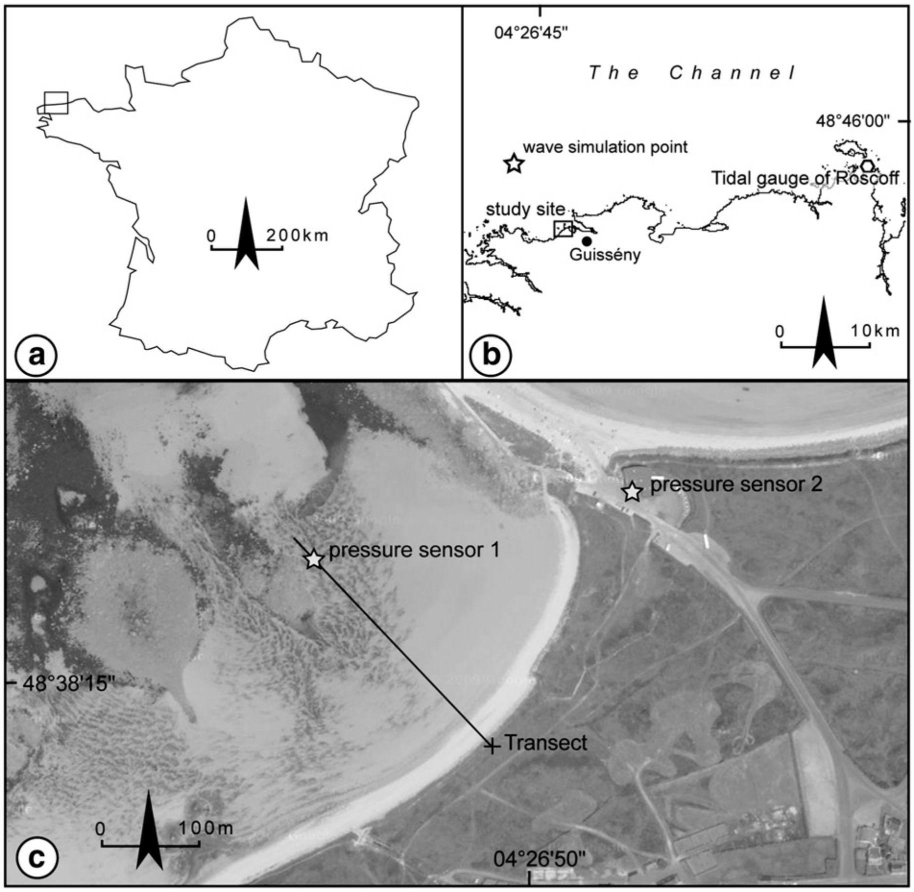

Fig. 2. Location of the study site (a), the Roscoff tidal gauge and the point where significant wave data (H_{mo} et T_{pic}) have been simulated (b). Aerial photography of the beach of Vougot, location of the transect and the two pressure sensors (c).

is possible to locate the active section by analysing the standard deviation of the elevation. It appears that the active section is located between the toe of the dune and a slope break sited at around 25 m from the dune toe, that is to say between MHWS and MWL (Fig. 3). This section of the beach where the greatest morphological changes are observed corresponds to the swash zone (Fig. 3b). The active section is steeper than the lower section of the beach which spread from MWL to MLWS.

3. Method

Measurements of runup are based on the hypothesis that high tide deposit altitude is equal to the maximum level reached by the swash theoretically during the previous high tide. High tide deposit is thus a good geoindicator of runup if we know the still water level which is equal to the observed high tide level (Bush et al., 2001; FEMA, 2006; Fletcher et al., 1995; Moore et al., 2006). This relation can be expressed as:

$$\text{Altitude}_{\text{high tide deposit}} = \text{Altitude}_{\text{observed high tide}} + R_{max} \tag{11}$$

where R_{max} is the maximum runup.

3.1. Measurements of high tide deposit elevation

The method consists of measuring with a DGPS the limit between dry and wet sands, which is located at the same level as the high tide deposit (Fig. 4). This limit has been measured along the transect. Thirteen measurements have been realised between April 2008 and June 2010. DGPS measurements have been georeferenced using the geodesic

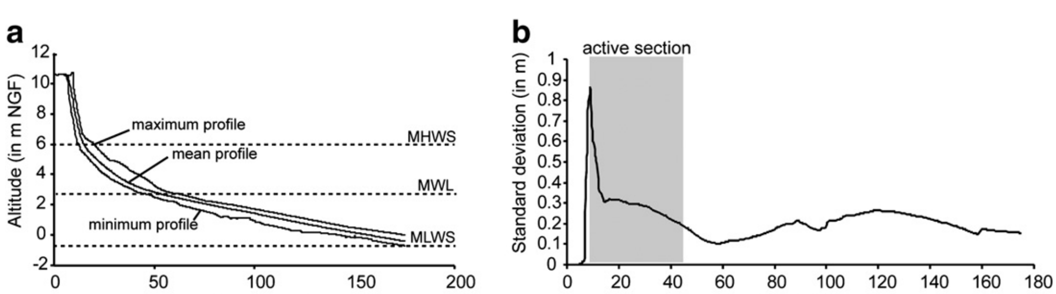

Fig. 3. a. Mean, minimum and maximum profiles of the Beach of Vougot. b. Standard deviation of the transect elevation.

Fig. 4. Measurement with DGPS of the limit reached by the maximum swash during the previous high tide. The limit between dry and wet sands at the level of high tide deposit shows the level reached by the swash during the previous high tide.

marker from the French datum and the geodesic network provided by the IGN (Institut Géographique National) sited about 2 km from the study site. The margin of error, estimated with the measurement of five control points, is 1 cm for the altitude. That is much lower than the one engendered by video technics (between 2 and 15 cm) usually employed to observe runup processes (Salmon et al., 2007; Stockdon et al., 2006).

3.2. Water level

In order to deduce runup values from high tide deposit measurements, data of observed high tide levels were needed. The closest tidal gauge (Roscoff) being located 30 km far from the study site, observed that tide data have been mainly obtained from a pressure sensor set up down the transect (Figs. 2c and 5). The sensor HOBO U20 Water Level Logger-Onset® measures the pressure exerted by the column of water and the column or air above it, with a measure every 2 min. A second pressure senor has been set up (Fig. 2c) behind the dune to measure atmospheric pressure. It was then possible to calculate the pressure exerted by the water column and thus to calculate the height of the latter with the following expression:

$$H = \left(P_{sensor-}P_{atmosphere}\right)/\rho.g \tag{12}$$

where H is the height of the water column (in m), P_{sensor} is the pressure measured by the sensor (in Pa), $P_{atmosphere}$ is the atmospheric pressure (in Pa), ρ is the density of water (=1025 kg/m^3) and g is the acceleration of gravity (=9.81 m s^{-2}).

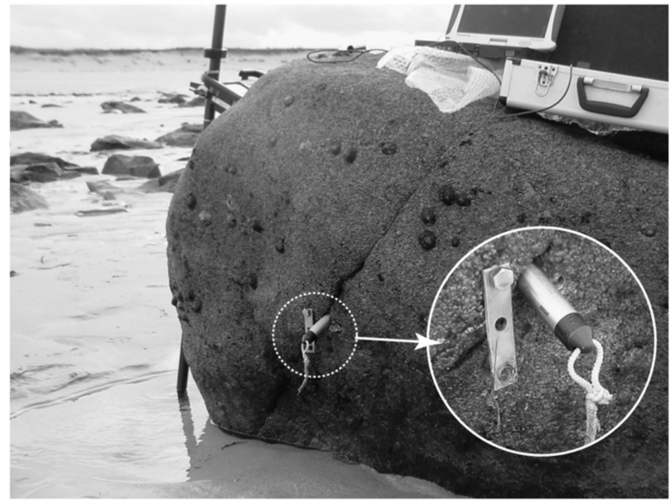

Fig. 5. Pressure sensor set up down the transect at the beach of Vougot.

The altitude of the water level above the sensor (in m NGF) has been obtained adding the altitude of the sensor (−1.11 m NGF) with the calculated height of the water column. The data have been smoothed to a moving average of 20 min to filter out deformations of the water surface related to wave action. For each high tide deposit measurement, the maximum of this moving average corresponds to the level of observed tide (astronomic tide and atmospheric effects) during the deposit of the high tide mark. In order to validate this approach, the maximum daily water level was extracted for each of the two series from the Roscoff tide gauge station and the HOBO sensor. High tide levels measured on Vougot beach and in Roscoff are well correlated ($r^2=0.99$) and show a difference of 13±2 cm (Fig. 6). The value of 0.13 m was taken to correct the tidal data from Roscoff, recorded for the entire observation period (April 2008 to July 2010). In order to deduce runup values, levels of observed tide have been subtracted from high tide mark levels (Fig. 7).

3.3. Representative beach slope

Twenty-two morphological measurements have been realised with DGPS along the transect between April 2008 and June 2010. Two slopes have been calculated for each measurement. The slope of the active section is calculated on a profile-by-profile basis from the high tide deposit to the slope break separating the upper beach to the lower beach and the foreshore slope is calculated on a distance of 300 m from high tide deposits.

3.4. Wave conditions

Simulated significant wave data are used to calculate runup values from literature equations. The offshore wave data were acquired by modelling using the digital model WAVEWATCH III™ (Ardhuin et al., 2009, 2010), at the calculation point 4°29′24″ W, 48°40′12″ N in 18.3 m water depth. These simulated data have been used to calculate runup values from literature equations using different values of slopes. During watermark measurements, H_{mo} calculated at high tide has varied from 0.7 m to 5.31 m (average=2.01 m), for a period between 6 and 16 s (mean period=11 s.).

4. Results

4.1. Beach slope variation

During the campaign, the foreshore slope has varied between 0.021 and 0.035. The greatest morphological changes have been observed for

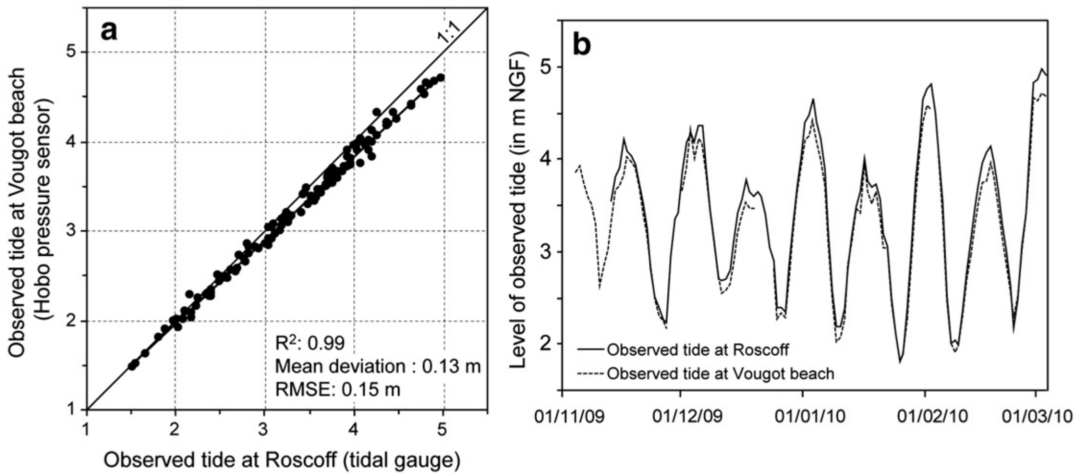

Fig. 6. Comparison between daily high tide water levels observed at Vougot beach using the Hobo data logger and at Roscoff tidal gauge.

the active section, with a slope varying between 0.039 and 0.184 (Table 2).

4.2. Comparison between observed and simulated runup values

For each watermark measurement, runup has been calculated with simulated wave data and slope values using literature's equations. Calculations have been realised using the slope of the foreshore and the slope of the active section. Obtained runup values have been compared with observed runup values (we call observed runup values the values deduced from in situ measurements). It appears that runup values calculated with the foreshore slope underestimate reality, with a mean deviation between −0.73 m and −0.20 m (Table 3). In the other hand, results are closer to the observed values when using the active slope of the beach in calculation, but an overestimation is observed. The equation of Ruggiero et al. (2001) gives the best results, with a mean deviation of +0.29 m and a root-mean-square error (RMSE) of 57 cm (Table 3).

4.3. Calibration of the runup formula

Statistical relations between observed runup values and morphodynamic variables have been analysed in order to characterise runup processes on the beach of Vougot. It appears that $H_{mo}\xi_o$ is the variable which is best correlated with runup, especially when using the slope of the active section (Table 4).

Considering the slope of the active section, the relation between runup and $H_{mo}\xi_o$ can be expressed as:

$$R_{max} = 0.67 H_{mo} \xi_o. \tag{13}$$

This expression better fits with reality, with a mean deviation of −0.01 m, a root-mean-square error of 25 cm and a coefficient of determination that is equal to 0.86 (Fig. 8). We observe that two points at the end of the range may distort the relation. However, when removing those two points, the relation is relatively similar with a constant C equal to 0.69. As they express extreme phenomena, we consider that these two points need to be taken into account.

5. Discussion

None of the previous studies based on runup measurements have been carried out on macrotidal sandy beaches. Moreover, the definition of the morphologic parameter ($tan\beta$), used in runup calculation, has always been relatively fuzzy in these earlier works. From in situ measurements, this study shows that the computation of runup with the slope of the active profile as defined in the paper gives better agreement with measured runup values on the macrotidal sandy beach of Vougot. The same result was found at the macrotidal sandy beach of Porsmillin. On that beach, the use of the foreshore slope also lead to an underestimation of runup values (from 0.33 to 0.62 m), while the use of the slope of the active section better fits with reality (mean deviation from −0.02 to 0.17 m; Cariolet, 2011). Regarding the use of the equations from literature, mean deviation and root-mean-square error are lower when using the slope of the active section of the beach in both studies. This result can be explained by analysing the relative part of the two components of the runup, meaning setup and swash. Observations of Raubenheimer et al. (1996) show that setup increases strongly near the shoreline. Setup process is probably highly dependent on the upper section of the beach. Runup being the sum of both setup and swash, is logically influenced by the slope of the active section of the

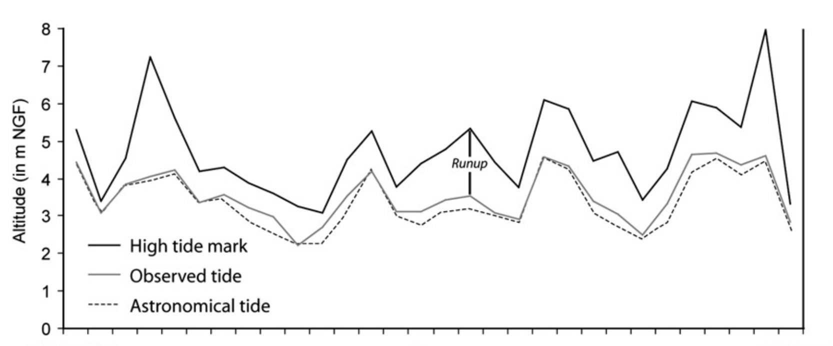

Fig. 7. High tide water mark levels, observed tide levels and astronomical tide levels (in m NGF) used in this study at the beach of Vougot.

Table 2
Values of slopes ($tan\beta$) measured during the campaign along the transect at the beach of Vougot.

Date	Slope of the active section	Slope of the foreshore
08/04/2008	0.127	0.027
29/08/2008	0.048	0.022
29/09/2008	0.094	0.025
12/01/2009	0.110	0.034
13/02/2009	0.090	0.028
29/04/2009	0.091	0.024
17/12/2009	0.071	0.024
22/12/2009	0.065	0.023
23/12/2009	0.066	0.023
27/12/2009	0.066	0.023
28/12/2009	0.056	0.025
30/12/2009	0.066	0.025
04/01/2010	0.092	0.027
07/01/2010	0.081	0.023
13/01/2010	0.069	0.025
14/01/2010	0.082	0.025
16/01/2010	0.088	0.027
21/01/2010	0.084	0.025
28/01/2010	0.079	0.023
01/02/2010	0.141	0.030
03/02/2010	0.128	0.029
05/02/2010	0.054	0.021
05/02/2010	0.054	0.021
06/02/2010	0.039	0.023
26/02/2010	0.078	0.025
28/02/2010	0.122	0.030
03/03/2010	0.118	0.029
29/03/2010	0.088	0.028
31/03/2010	0.184	0.035
10/06/2010	0.069	0.022

beach which has its own morpho-dynamic behaviour, and which is located near the shoreline when no sandy bar is present. On macrotidal gravel barriers, Matias et al. (2012) used a slope calculated between mean water level and the base of the barrier crest to estimate runup from several literature equations. The authors obtained good estimations using this slope especially with the equation of Stockdon et al. (2006). This study shows that the use of the slope of the upper profile in runup calculation seems to give better results not only on macrotidal sandy beaches but also on macrotidal gravel barriers.

The analysis of the relation between observed runup values and morpho-dynamic variables confirms the role of the slope of the active section. The constant C of the equation of Battjes (1971) has been adjusted for the beach of Vougot (with $C=0.67$). At the beach of Porsmillin, where a similar analysis had been realised, the constant C has been adjusted to 1.09 (Cariolet, 2011). The difference between the 2 sandy beaches can be explained by the respective morphologic and hydrodynamic characteristics of the 2 beaches (Table 5). The low tide terrace is longer and has a weaker slope at the beach of Vougot. The active section is shorter at the beach of Vougot but its slope is greater. Regarding hydrodynamic conditions, the cove beach of Porsmillin is more sheltered with smaller waves than the beach of

Table 3
Coefficient of determination (r^2), mean deviation and root-mean-square error (RMSE) between observed runup values and calculated runup values, depending on slope.

Slope		Komar R2%	Komar R_{max}	Ruggiero R2%	Holman R2%	Stockdon R2%
Foreshore	r^2	0.59	0.59	0.59	0.59	0.13
	Mean deviation	−0.73	−0.65	−0.36	−0.57	−0.20
	RMSE	0.88	0.80	0.60	0.76	0.73
Active section	r^2	0.63	0.63	0.63	0.63	0.49
	Mean deviation	0.30	0.54	0.29	0.36	1.78
	RMSE	0.56	0.81	0.57	0.53	2.15

Table 4
Statistical relations between observed runup values and morpho-dynamic variables, using the two different slopes.

Observed runup/Variable	Coefficient of determination (r^2)	Equation of the regression line
R/H_{mo}	0.55	y = 1.62×
$R/(H_{mo}L_o)^{½}$	0.17	y = 13.63×
Slope of the foreshore		
$R/(tan\beta\ H_oL_o)^{½}$	0.42	y = 0.43×
$R/H_{mo}\xi_o$	0.60	y = 0.4×
Slope of the active section		
$R/(tan\beta\ H_oL_o)^{½}$	0.66	y = 4.5×
$R/H_{mo}\xi_o$	0.86	y = 0.67×

Vougot. This explains that the constant C is greater at the beach of Vougot.

Several studies following this approach are required on other macrotidal beaches. But if these first results are confirmed with additional in situ measurements, they would question many studies carried out in macrotidal environment. Indeed, some studies may have underestimated water levels using the slope of the foreshore in the calculation of runup (Sabatier et al., 2009; Suanez, 2009; Suanez and Cariolet, 2010).

Some inherent limitations have to be highlighted. Some of the differences observed between measurements and calculations can be explained by some issues which step in during data creation and treatment. Firstly, the use of simulated wave data can be a source of error. It is for instance difficult to simulate the parameter T_{pic}. It would be interesting to use the mean period (T_{m02} or $T_{m0\text{-}1}$) of which simulation is more reliable than T_{pic} (Krogstad et al., 1999; Munthe-Kaas and Krogstad, 1985). Secondly, wind can directly and locally “push” or “slow down” the swash. This process has not been taken into account in this study. Lastly, the method is based on non-contiguous measurements of maximal runup (R_{max}) and does not measure $R_{2\%}$ values. Comparison between observed R_{max} values and calculated $R_{2\%}$ values is thus

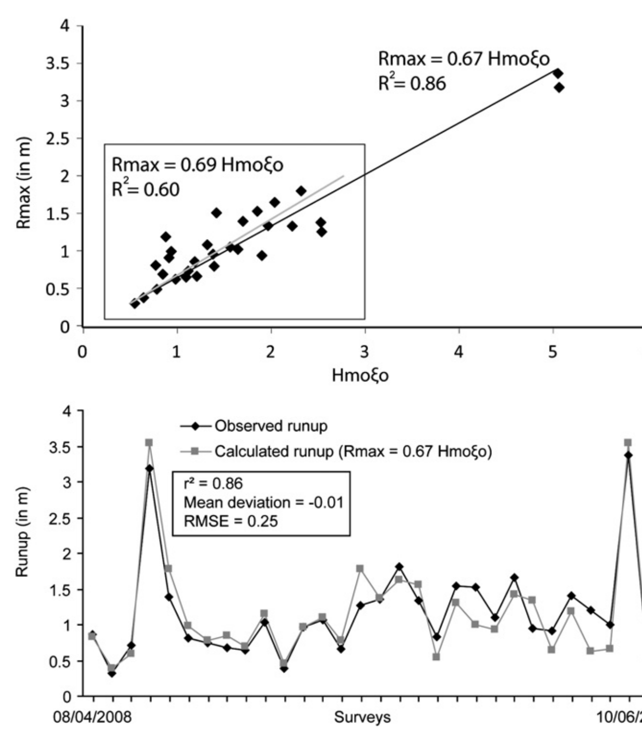

Fig. 8. Comparison between observed runup values and $H_{mo}\xi_o$, and between observed runup values and values calculated with the equation $R_{max}=0.67\ H_{mo}\xi_o$. Runup values have been calculated using the slope of the active section.

Table 5
Morphologic and hydrodynamic characteristics of the beaches of Porsmillin and Vougot.

Beach	Mean foreshore slope	Low tide terrace slope	Low tide terrace length (m)	Active section slope	Active section length (m)	Mean H_{mo} (m)	Mean T_{pic} (s)	Constant C
Porsmillin	0.037	$0.02<tan\beta<0.035$	110	$0.05<tan\beta<0.08$	90	1.21	12.5	1.09
Vougot	0.016	$0.013<tan\beta<0.017$	250	$0.039<tan\beta<0.18$	25	2.01	11	0.67

debatable. Moreover, we consider in this method that the maximal runup is reached during high tide, which is not every time the case. For instance, different wave conditions could induce a higher maximal runup before or later than high tide. All these potential sources of error have to be considered in the interpretation of the results.

It would be interesting to integer this method in existing morphologic monitoring which already use transects survey (Lacey and Peck, 1998; Larson and Kraus, 1994; Reeve et al., 2007; Southgate, 2008; Suanez et al., 2012). This kind of monitoring would help to better simulate runup and thus water levels and would support decision-making regarding the dimension of coastal structures and low-lying coastal zones planning.

6. Conclusion

Runup process is relatively unknown in macrotidal environments and this paper represents the first analysis of runup processes on macrotidal sandy beaches from in situ measurement. This study reveals a number of key points relating to runup processes on macrotidal sandy beaches:

- The methodological approach developed in this study, which differ from classic video measurements, is practical and relatively easy to carry out to measure in situ runup in this kind of environment.
- Results highlight the importance of the choice of the slope when using equations on macrotidal sandy beaches.
- The study confirms that the use of the slope of the active section of the beach gives better results than the use of the foreshore slope which underestimates runup values.
- Using the slope of the active section of the beach, the constant C of the equation of Battjes (1971) has been adjusted to 0.67 at the beach of Vougot. The constant C was found to be 1.09 at the beach of Porsmillin during a previous study (Cariolet, 2011). This difference can be explained by the particular hydrodynamic and morphologic characteristics of both sites.
- If these results are confirmed with further measurements, extreme water level would be recalculated on macrotidal sandy beaches. This study has allowed calculating runup values at the beach of Vougot for a recent study about dune erosion and recovery processes (Suanez et al., 2012).

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