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Empirical Parameterization of Wave Runup and Dune Erosion during Storm Conditions on a Natural Macrotidal Beach

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ABSTRACT

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An experimental study based on field measurements for runup parameterization was conducted on a high energy macrotidal beach located on North Brittany (Vougot Beach). The approach was based on morphological and hydrodynamic high frequency monitoring collected between 2008 and 2013. The aim was to quantify in-situ environmental conditions and dimensional swash parameters for the best calibration of Battjes (1971) runup formula. In addition, an empirical equation based on observed tidal water level and offshore wave height was produced to estimate extreme water levels defined as the sum of (*i*) astronomic tide, (*ii*) storm surge, and (*iii*) vertical wave runup. A good correlation between this empirical equation ($1.01H_{mo}\xi_o$) and field runup measurements (R_{max}) was obtained (R^2 85%). The goodness of fit given by the RMSE was about 0.29 m. Extreme water levels were then used to explain dune erosion processes that occured during the winter storms 2013-2014. A good relationship was noted between dune erosion and high water levels when they exceed the dune foot elevation.

ADDITIONAL INDEX WORDS: *Macrotidal beach, runup, storm, dune, erosion, extreme water level.*

INTRODUCTION

Runup corresponds to the time fluctuating vertical position of the wash limit on the upper part of the beach. It is defined as the difference between discrete water elevation maxima and still water level corresponding generally to observed tide level (Holman, 1986; Hunt, 1959; Stockdon *et al.*, 2006). Runup is one of the most important components that can generate extreme water levels, especially during storm condition. Therefore, it is a key factor during coastal erosion processes, when extreme water levels reach the toe of the dune (Hesp, 2002; Kriebel, 1986; Pye and Neal, 1994; Ruggiero *et al.*, 2001; Sallenger, 2000; Vellinga, 1982). Estimation of wave runup is a complicated issue because of the complex processes driving the swash zone related to incident band wave energy transferred to both higher and lower frequencies through the surf zone (Longuet-Higgins and Stewart, 1962; Stockdon *et al.*, 2006). Therefore, wave runup is largely dependent on environmental conditions such as the local beach slope (synthesized through dissipative to reflective context generally given by Iribarren number, see Battjes, 1974) and the infragravity-to-incident offshore wave energy which dominates the inner-surf zone (Guza and Thornton, 1982; Holman and Sallenger, 1985; Ruessink *et al.*, 1998; Ruggiero and Holman, 2004). A simple formula was first proposed by Hunt (1959) showing that runup (R) was proportional to significant wave height (H_s) and slope (S).

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Battjes (1971) has shown that runup was better related to a morphodynamic component defined by a dimensionless surf similarity parameter called the Iribarren number, expressed by the following equation:

$$\frac{R}{H_s} = C\xi_o \tag{1}$$

where C is a constant, and ξ_o is the Iribarren number given by Battjes (1974):

$$\xi_o = \frac{\tan\beta}{(H_o/L_o)^{1/2}} \tag{2}$$

where $tan\beta$ is the beach slope, H_o corresponds to significant offshore wave (equivalent to H_s in deep water), and L_o is deep water wavelength.

Following this approach, Holman (1986) found a clear relationship between the 2% exceedence value of runup normalized by H_s and ξ_o, and fit this equation on a natural intermediate-to-reflective beach ($0.07 < tan\beta < 0.2$). Based on the laboratory tests, Mase (1989) developed a predictive on uniform impermeable slopes ($0.03 < tan\beta < 0.2$). He found that the runup was approximately twice as large as values measured in the field by Holman (1986), and explained this discrepancy by the effect of beach profile geometry. Nielsen and Hanslow (1991) indicated proportionality between the best-fit of runup elevation distribution and the beach slope for a steeper beach ($tan\beta \geq 0.10$). For the flatter beaches ($tan\beta \leq 0.10$), the slope became largely unimportant and the vertical scale of the runup distribution was scaled directly with $(H_oL_o)^{0.5}$. Ruessink *et al.* (1998) came to the same conclusion under highly dissipative conditions ($0.01 < tan\beta < 0.03$) and found that the significant infragravity swash height (R_{ig}) was about 30% of the offshore wave height H_0, and that the slope in the linear H_0 dependance of R_{ig} amounted to only 0.18. More recently, Stockdon *et al.* (2006) indicated that in an infragravity-dominated dissipative context, the magnitude of swash elevation $R_{2\%}$ was dependent only on offshore wave height and wavelength while in intermediate and reflective context with complex foreshore morphology, beach slope was on the contrary much more important. Therefore, the authors have elaborated different runup equations according to the beach morphodynamic context from a dissipated state ($\xi_o < 0.3$), to an intermediate state ($0.3 < \xi_o < 1.25$), to a reflective state ($\xi_o > 1.25$).

In a previous study already on the Vougot beach, a first methodological approach for calibrating runup equation suggested that on the macrotidal beach, the slope of the active section of the upper beach should be used to obtain the most relevant estimation of observed runup elevations (Cariolet and Suanez, 2013). The aim this study was to improve this simple parameterization approach for calculation of maximum runup elevation in order to estimate extreme water levels. Based on the Sallenger (2000) and/or Ruggiero *et al.* (2001) models, the aim was then to understand processes of the erosion of the dune of Vougot beach that occurred during the stormy winter 2013-2014.

STUDY SITE

The Vougot beach is located on the North coast of Finistère in Brittany (France) (Figure 1). It is formed by a massive foredune, anchored on the Zorn abandoned cliff, that stretches over about 2 km in a southwest to northeast direction. It culminates at an altitude of 13 m above sea level – asl.

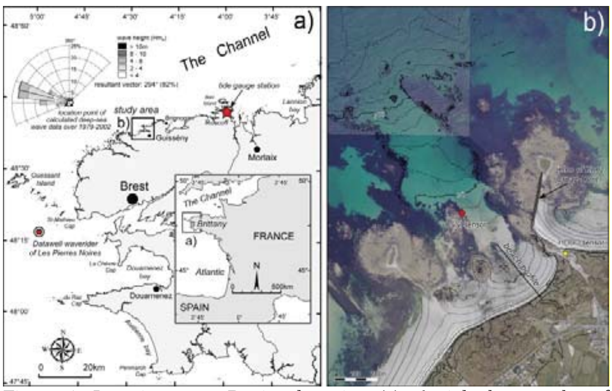

Figure 1. Location map. Regional setting (a). Aerial photography of Vougot beach showing the beach/dune profile location and both wave/water level and atmospheric pressure sensors (b).

Over the last decades, the eastern part of the dune has experienced erosion reaching about -0.6 m/yr between 1952 to 2014. This rate has increased to -1.5 m/yr over the last decade (from 2000 to 2009) due to the impact of a major storm on 10th March 2008 (Suanez *et al.*, 2010). Erosion was caused by the construction of the Enez Croas Hent jetty in 1974 (Figure 1b), which completely modified the hydrodynamics and interrupted the westward sand drift. However, from spring 2008 to summer 2013, almost 5 years of dune recovery occured inducing a maximum progradation of dune front reaching +12 m (Suanez *et al.*, 2012).

Incident waves come mostly from the west-north-west direction (242°) (Figure 1a). The most frequent wave height (H_{m0}) is between 1.5 and 3 m (average of 2.2 m), and the most frequent period (T_{pic}) is between 9 and 11 s (average of 10.6 s). The maximum wave height and period related to storm events reached respectively 14 m and 20 s. Macrotidal range is reaching about 7 m between MHWS and MLWS. The beach profile is characterized by different morphodynamic environments according to the composite slope and concave beach (Figure 2). The lower part of the tidal beach, between MHWN and MLWN, is characterized by dissipative context with a very gentle slope ($\xi_0 \leq 0.3$ and $0.034 < tan\beta < 0.014$). In contrast, the upper beach up to MHWN, is characterized by intermediate to moderately reflective conditions ($0.72 < \xi_0 < 1.6$ and $0.081 < tan\beta < 0.18$). Therefore, depending on the tide's water level, waves break on different morphodynamic environments. This is important because runup process differs between dissipative to reflective conditions (Senechal *et al.*, 2011; Stockdon *et al.*, 2006).

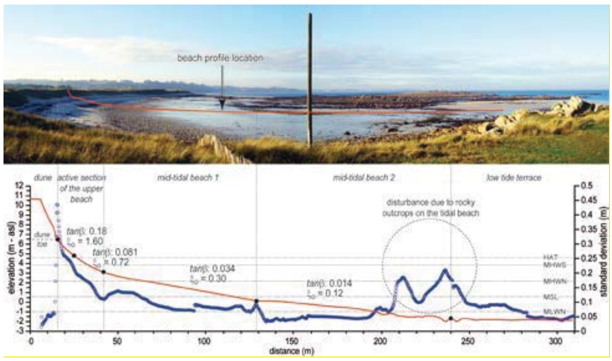

Figure 2. Mean cross-shore profile of the surveyed Vougot beach section (red line). Morphodynamic conditions (dissipative to reflective conditions) have been analyzed along the concave beach profile using Iribarren value.

METHODS

Two set of data collected along a transect situated on the eastern part of the beach (see Figure 1b) were used concerning the survey of beach profile and maximum swash elevation (runup) R_{max}. The first one concerns the data acquired between between 2008 and 2010 and already published in a previous study (see Cariolet and Suanez, 2013). The second one corresponding to the current data was collected between June 2012 and 2013 following the same approach as Cariolet and Suanez (2013). In total, a set of 90 morphological and runup measurements was used in this study. The maximum swash elevation was determined by the wrack deposit and/or the limit of the water mark (Figure 3). We assume that this limit corresponded to the highest level reached by the runup during the previous high tide. Therefore, it corresponds to R_{max} (maximum runup) instead of the generally used random variable $R_{2\%}$ that corresponds to vertical runup distance exceeded by 2 percent of wave runups. Measurements were carried out using a Differential GPS in RTK mode. Measurements were calibrated using the geodesic marker from the French datum.

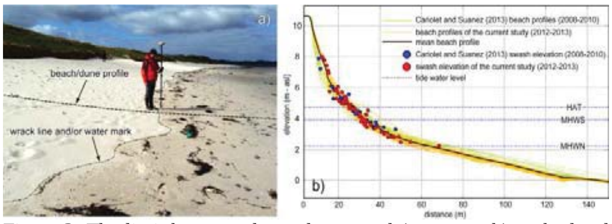

Figure 3. The limit between dry and wet sand (water mark) at the level of high tide deposit (wrack line) shows the level reached by the swash processes (a). Beach/dune profile measurements and the runup elevation R_{max} reached during the previous high tide (b).

Offshore wave analysis was based on data acquired from the WAVEWATCH III model (WW3) which reproduced the offshore wave conditions at the calculation point 4°29'24"W, 48°40'12"N at a water depth of 18.3 m. Wave parameters such as wave height (H_{m0}) and period ($T_{m0,-1}$) were extracted for the time periods corresponding to the high tide level.

Analysis of water levels was based on records achieved between June 2012 and 2013 on the intertidal zone using a pressure sensor deployed along the beach transect mentioned above (see Figure 1b). It was computed taking into account atmospheric pressure measured on the site. The data was smoothed to a moving average of 10 min to filter out wave deformations of the water surface, and water levels corresponding to both daily high tides were extracted (Figure 4a).

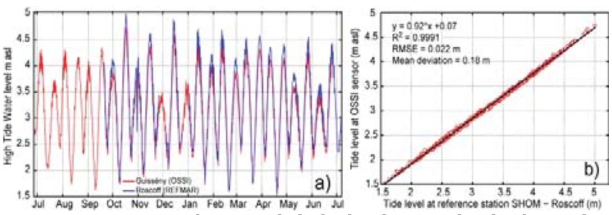

Figure 4. Comparison between daily high tide water levels observed at Vougot beach, using the OSSI-010-003C sensor, and at the permanent Roscoff tidal gauge station.

A similar calculation was done using data recorded at a permanent tide gauge station of Roscoff located at about 30 km east of the study site (Figure 1). Both the time series were used to estimate the differences in high tide water level between the two sites reaching 18 cm mean deviation (Figure 4b).

RESULTS

The results show the parameterization of a runup equation, and the use of this calibrated equation to analyze the dune erosion processes during the winter 2013-2014.

Runup parameterization

First, calibration of Battjes (1971) runup formula was achieved following the same methodological approach as the one used by Cariolet and Suanez (2013). Morphodynamic parameters such as $H_{m0}\xi_o$ and slope of the beach active section were used to estimate maximum runup elevation R_{max} (Figure 5). The correlation between observed runup and $H_{m0}\xi_o$ can be expressed as:

$$R_{max} = 0.68H_{m0}\xi_o \quad (3)$$

It gives the same result as the previous Cariolet and Suanez (2013) study with a constant equal to 0.68 (95% confidence intervals [0.65; 0.71]).

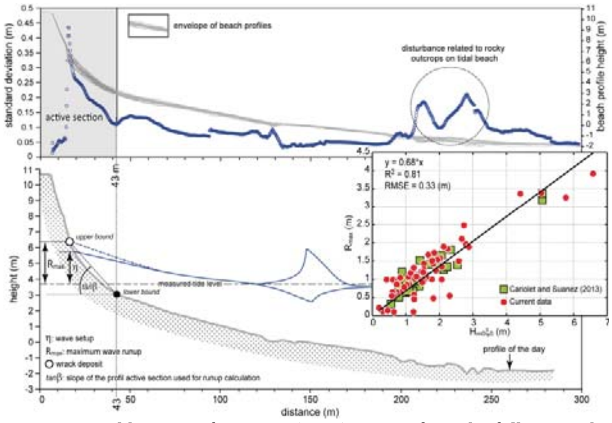

Figure 5. Calibration of Battjes (1971) runup formula following the method used by Cariolet and Suanez (2013) to calculate beach slope for the runup calculation. The lower bound corresponds to the limit of the profile section (called "active section") where changes of elevation are the most significant. This limit of 43 m has been defined by calculating the standard deviation of height changes of the beach profiles (gray lines). The upper bound corresponds to field measurements of the swash height given by the water mark limit or wrack line deposit.

Secondly, the parameterization of a general empirical equation of the runup was achieved using offshore wave and water level data. The slope was calculated using the observed high tide water level (*HTWL*) and a fraction of the offshore wave height (H_{m0}) from which the horizontal beach slope section (*HBSS*) was defined (Figure 6). Different correlation tests have shown that $1/4H_{m0}$ gives the best result in this case. Therefore, the upper and lower bounds of the beach slope profile width is calculated as follows:

$$Bound_{\text{up and low}} = HTWL \pm 1/4H_{m0} \quad (4)$$

Swash runup is in this case best parameterized with a best-fit R²: 0.85 and Root Mean Squared Error (RMSE): 0.29 m. The coefficient of the regression line is 1.01 with 95% confidence intervals [0.97; 1.05]. In this case, the relationship can be expressed as (Figure 6).

$$R_{max} = 1.01\ H_{m0}\xi_0 \qquad (6)$$

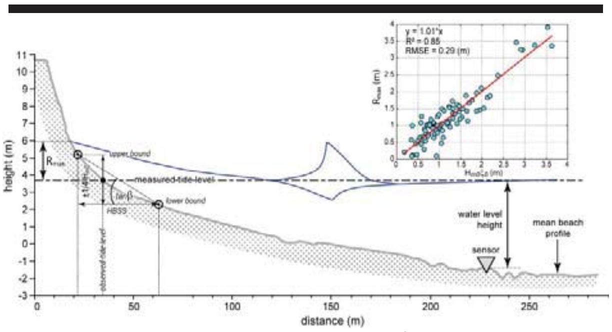

Figure 6. Method used to calculate beach slope for the runup calculation. It is based on measured tide level from which the beach section is defined. In contrast to the Cariolet and Suanez (2013) previous method, note that this approach is using the mean beach profile instead of daily beach profile.

Winter Storm 2013-2014 test case

Winter 2013-2014 (December 2013 to March 2014) was characterized by a series of about 12 storms that hit the Brittany coast (Blaise *et al.*, in press). It was in February that these storms were the most frequent and particularly virulent. The maximum wave heights measured off Finistère reached 23.5m during Petra storm of February 4-5 (Figure 7b). However, analysis of hydrodynamic conditions shows that only three episodes promoted extreme morphogenetic conditions because they were combined with high spring tide. The first one occurred on January 3-4, it was followed by events from February 1st to 3, and March 2-3 (Figure 7a).

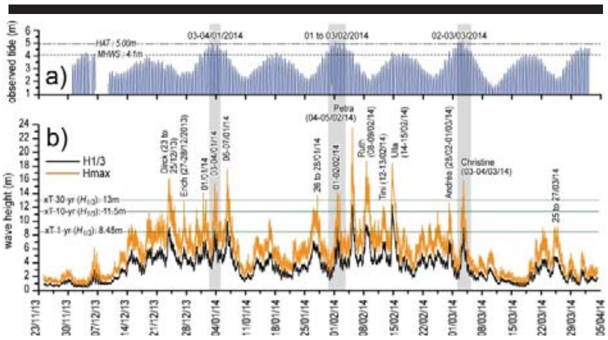

Figure 7. Wave conditions (a) and tide (b) recorded respectively by Datawell waverider off western Brittany peninsula at Les Pierres Noires and tide gauge at permanent Roscoff station (see Figure 1), during the winter 2013-2014. Grey lines show the three major storm events.

During these three extreme events the observed tide levels were above highest astronomical tide level (HAT) with maximum surge level up to 1m during Ulla storm of February 14-15.

Dune survey achieved during this winter period showed a retreat reaching about -7 m (Figure 8a). This erosion induced a net loss of sediment of about -20 m^3/l.m that occurred into three stages (Figure 8b). The first one is related to the January 3-4 storm event that generated extreme water levels reaching more than 9 m asl (Figure 8c). Nevertheless the erosion has not been not so important because the altitude of the dune foot was high at that period (about 8.25 m asl). The second storm event of the beginning of February generated a very significant dune érosion. It was associated to high extreme water levels reaching 9 m asl whereas the altitude of dune foot was considerably reduced due to the impact of the previous storm (6.7 m asl). The last storm event of March 2-3 has produced very few impact on dune erosion because a short phase of dune recovery occurred just after the 1-2 February storm event (see beach measurement of 16/02/2014 in Figure 8). Therefore, the altitude of the foot of the dune was higher due to accretion whereas the extreme water levels were lower (about 8.3 m asl).

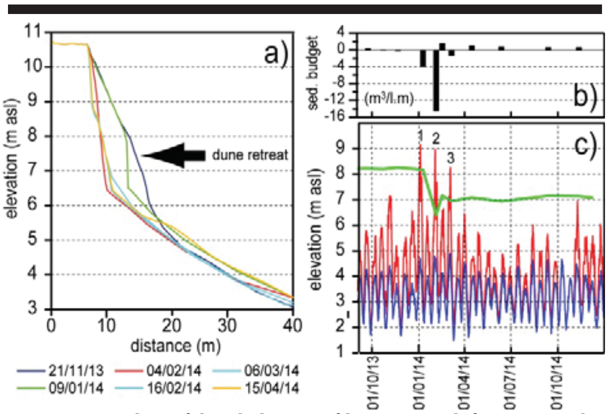

Figure 8. Envelop of beach/dune profiles measured from November 2013 to April 2014 (a). Dune sediment budget in m^3/l.m (b). Altitude of the dune foot (green line) related to observed tide level (bleu line) and extreme water level (observed tide level + runup elevation; red line) (c). 1, 2, and 3 indicate the three major storm events of the beginning of January, February, and March.

DISCUSSION AND CONCLUSIONS

Following the previous study of Cariolet and Suanez (2013) this experiment has more deeply examined new parameterization of the runup formula for predicting total swash elevation in the extreme water level calculation. The new set of data used in this study has confirmed the complexity of defining the best slope when the beach exhibits composite-slope and/or a concave profile in macrotidal environment. A best-fit was obtained when beach slope was calculated using observed water level (R^2: 85%; RMSE of 29 cm). This approach, based on sea level changes due to tides and/or storm surges, allows for better consideration of beach slope variations in the context of a concave beach profile. As already indicated by Mayer and Kriebel (1994) the use of fixed bounds (upper or lower bounds) or an averaged planar slope for the calculation of beach steepness is therefore inappropriate when beaches exhibit complex morphology with a composite-slope, especially in a macrotidal environmental context. If we take into consideration the steep slope face of the upper concave beach (0.08 > tanβ > 1.8), this experiment also confirms the findings of Nielsen and Hanslow (1991), attesting that the best-fit distribution is proportional to the surf similarity parameter (ξ_o) on intermediate to reflective beaches in agreement with Hunt's formula for runup of regular waves on steep slopes.

Validation of this equation to calculate the runup during the stormy winter 2013-2014 shows very good applicability of this approach. The three significant morphogenetic events of the beginning of January, February and March are very well identified from the extreme water levels and explain very relevant way retreating of the dune. Refering to the Sallenger's model (2000), the type process controling the dune erosion corresponds to the collision regime. In this context, as R_{high} increases, runup collides with the base of the dune inducing erosion. The eroded sand is generally transported out of the system (offshore or longshore transfer) and does not return to recover the dune. In addition to the net erosion of the dune, the upper part of the tidal beach also experiences erosion. Nevertheless, depending on the post-storm weather conditions, eroded sand may be returned to the beach as a post-storm-recovery processes.

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