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FIELD OBSERVATIONS OF WAVE-INDUCED SET-UP ON THE FRENCH AQUITANIAN COAST

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ABSTRACT

We report and analyze extreme wave-induced set-up heights obtained during a large international field experiment on the Atlantic coast of France. The field experiment associated with a large storm with the maximum offshore wave height of more than 12 m, enabled us to record extreme set-up heights up to 2 m. Such extreme data which are necessary for developing further numerical and analytical studies in this field, were lacking in the literature. Our data agrees reasonably well with existing set-up data reported from other coasts in the world. A good correlation was observed between set-up and offshore wave height. Similar to other coasts, the setup-offshore wave height relationship was linear up to a value of about 1 m. Nonlinear behaviour was observed for higher set-up values. This study will help to further improve and validate the existing analytical and numerical solutions.

INTRODUCTION

Modelling of wave motion in the surf zone, where waves break, is among the most challenging topics in the field of ocean engineering. The study of surf zone processes including wave set-up/set-down, run-up, and near-shore currents, is necessary for many coastal applications.

Defined as the wave-induced increase in mean water level, set-up is responsible for considerable inundations of the beach during large storms and thus, needs to be predicted for beach planning purposes. However, this phenomenon cannot be observed easily as compared to other near-shore processes such as run-up [1], and perhaps this is the reason that much attention was not focused on it in the literature compared to the other surf zone phenomena.

In the last few decades, efforts have been made by some authors to understand and model wave set-up analytically [2], numerically [3], experimentally [4], as well as through field surveys [5 & 6]. However, still much remain to be done in this field. Literature review shows that enough field observations is lacking in the field of set-up which is a necessary tool to further understand the complex behaviour of this surf zone phenomenon. Especially, to our knowledge, little field data is available on the extreme set-up values during large storms. Similar to any other physical phenomenon, such extreme values are necessary for developing, improving and validating analytical and numerical studies in the field of set-up.

In this paper, we report and analyze extreme set-up data collected during an extensive international field experiment performed recently on the Atlantic coast of France. Due to the authors' previous experiences from field surveys in the same coast, the time of the experiment was chosen in a very high-energy wave period. The experiment was associated with two extremely large storms reaching a maximum offshore wave height of more than 12 m which enabled us to collect a unique wave set-up data. Our extreme set-up data will help to better understand and model the behaviour of wave induced set-up in the surf zone.

STUDY ATREA

The field data used in this study was part of the data collected during a 2-month international field experiment performed on the French Atlantic coast of Aquitanian in the period between February 25 and April 18, 2008. The field survey was one of the largest of its kind in Europe employing the most updated instruments, innovative methods, and including more than 100 researchers from 6 different countries [7].

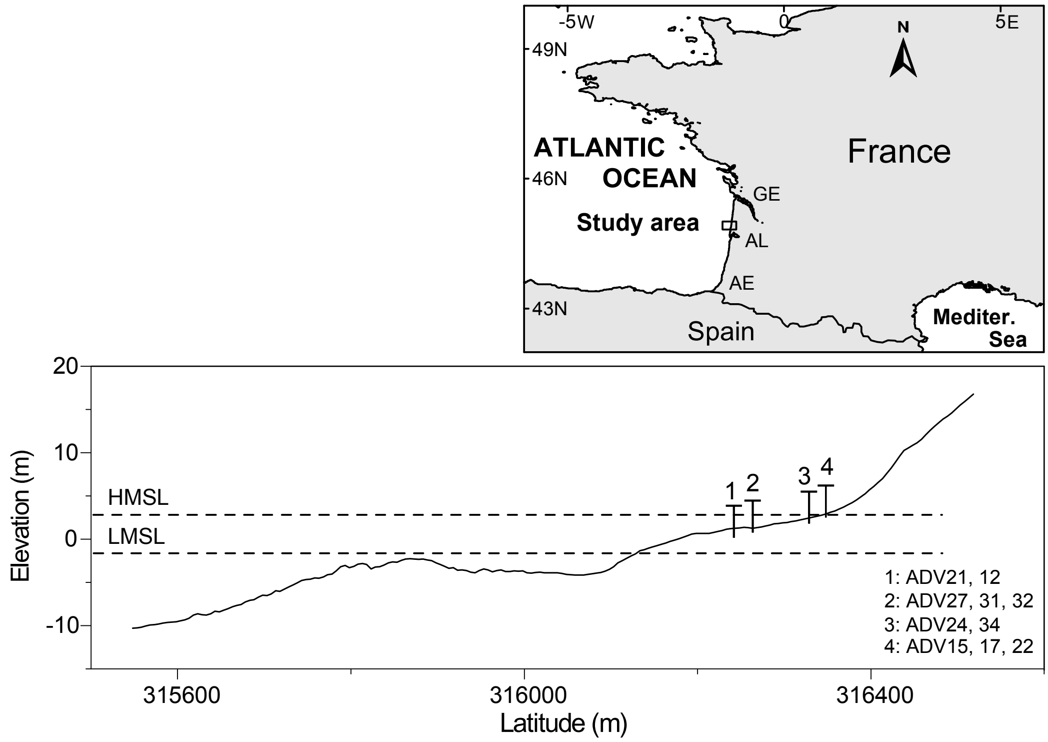


Figure 1. Map showing the study area at the Atlantic coast of France. A cross section of the ocean bathymetry showing the location of the instruments used in this study are shown. Abbreviations: GE, Gironde Estuary; AE, Adour Estuary; AL, Arcachon lagoon; ADV, acoustic Doppler velocimeter; HMSL, high mean sea level; LMSL, low mean sea level

The Aquitanian coast is a high energy meso-macrotidal straight coast extending north from the Adour Estuary (AE) to near Gironde Estuary (GE) with the length of about 250 km (Fig. 1) [8]. The experiments were performed at the Truc Vert beach, a double barred beach situated north of the Arcachon Lagoon (AL) (Fig. 1). The site is characterized by a Transverse Bar and Rip systems in the intertidal domain [9].

The Truc Vert beach is exposed to almost continuous high energy swell originating mainly from the west-northwest. The wave climate is typically oceanic, with a mean period and mean significant wave height of 12 s and 1.55 m, respectively during winter and those values of 7 s and 0.9 m during summer. The high meso-macrotidal range along with the relatively broad inter-tidal region (around 200 m), allows instruments to be deployed and recovered safely at low tide while measurements can be obtained at high tide.

INSTRUMENTS

Various instruments and methods were employed during the field work [7]. However, here we only discuss part of the data concerning our study of wave set-up, mostly wave records inside of the surf zone. Inside the surf zone, a combination of acoustic Doppler velocimeters (ADV Vector, Nortek) and pressure sensors (Keller) were employed to record the wave height and current velocity at different sample rates of 4, 8, and 16 Hz. Here we used the data acquired at the sample rate of 8 and 16 Hz: ADV24, ADV27, ADV31, ADV32 and ADV34 at 8 Hz and ADV12, ADV21, ADV15, ADV22 and ADV17 at 16 Hz (Fig. 1). The first digit in the name of an ADV shows the device's number and the second one represents the deployment number. Also, two offshore wave buoys were employed at the deep water depths of 20 and 55 m to record the offshore wave characteristics. The offshore wave characteristics will help to better analyze the processes inside the surf zone. Figure 2 shows the time histories of offshore wave height and period recorded at the offshore buoys, the tide evolution during the field experiment, and also the time period in which every ADV was deployed.

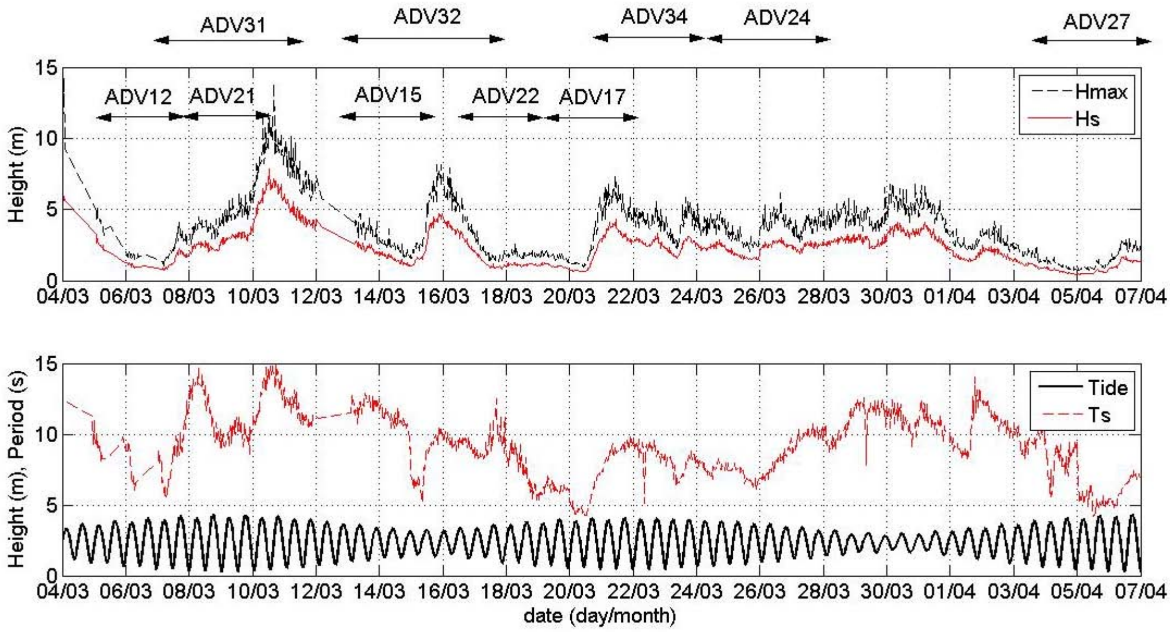


Figure 2. Time histories of offshore maximum and significant wave height (top panel), the tide record at the offshore region and offshore wave period (bottom panel). Double arrows show the time periods of each ADV deployments. Ts, Hs, and Hmax represent the significant wave period, significant wave height, and maximum wave height, respectively.

An extremely large storm can be observed in Fig. 2 (top panel) which happened between 9th and 12th of March reaching a maximum wave height of about 12 m. This reveals that the wave field was extremely energetic during the experiment. Another storm also occurred on March 16 with the maximum wave height of about 8 m. As shown in Fig. 2 (bottom panel), the French coast of Aquitanian experiences a semi-diurnal tidal regime with a mean range of 1.5 m and 4.5 m for neap and spring tides, respectively. The offshore significant wave period is ranging between 5 and 15 seconds having an average value of about 10 s.

DEFINITION AND THE PRESENT METHOD

It is long known that wave set-up and set-down are generated by variation in the radiation stresses across the surf zone due to wave breaking. The radiation stress is the depth-integrated mean excess flux of momentum due to the presence of the waves [10]. In the surf zone, where there is a significant dissipation, the radiation stress decreases in the shoreward direction and the mean water level increases creating set-up (Fig. 3) [11]. As it is expected from the mass continuity, offshore of the breaker zone where dissipation is negligible, set-down occurs due to an increase in the radiation stress (Fig. 3). Therefore, set-up (η) which is the super-elevation of the mean water level (MWL) above the still water level (SWL), can be measured using the following equation:

$$\eta(x) = MWL(x) - SWL(x) \tag{1}$$

Figure 3 schematically shows the method used in this study to measure wave-induced set-up. The mean water level in deep water often is used as the still water level (SWL) for calculation of set-up (e.g., [11 & 12]). As shown, while the offshore wave gauge shows the SWL, the surf zone gauge measures an increase in the SWL, i.e., set-up. Hence, here we compared the wave height recorded at the surf zone gauge with that of the offshore gauge at the same time to obtain the set-up heights.

ENERGY SPECTRAL ANALYSIS

As set-up is a direct manifestation of wave action and its energy, the energy behaviour of the wave is studied for a better understanding of the wave environment during the experiment. Our energy spectral analysis was performed using Fourier transform and by breaking the entire records to 1800-second segments and by considering overlapping. The analysis was performed for wave height records for the instruments used during the experiment. However, here we only report the results obtained for ADV31 and ADV27 which represent two extreme conditions during our experiment: ADV31 for extremely large waves and ADV27 for the smallest waves.

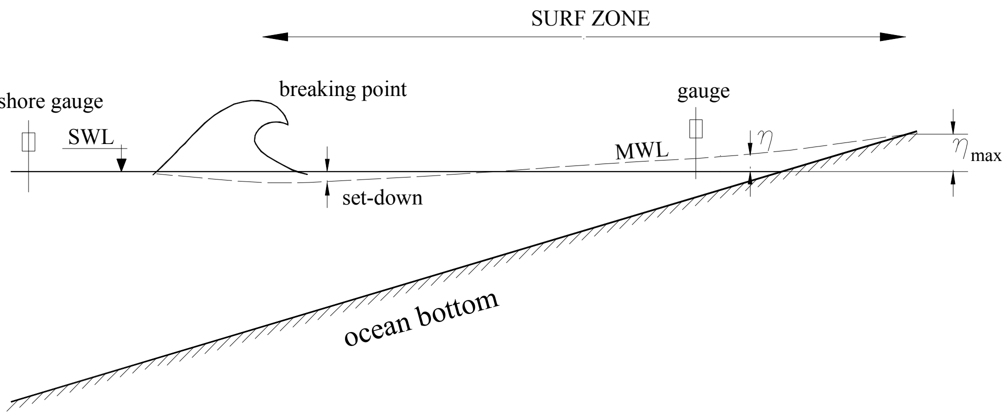


Figure 3. Definition sketch showing wave set-up and set-down in the surf zone.

Out of numerous energy spectra, six of them are presented in Fig. 4 which we believed contain more useful information. In this figure, the 3 top panels are from the records of VEC31 and the remaining are from those of the VEC27. As the instruments were out of water during low tide, our data lack wave records during low tide and hence, the analysis is done only on mid-tide and high-tide conditions.

For the records of ADV31 (Fig. 4- top panels), the peak wave energy frequencies are about 0.014, 0.023, and 0.009 for the records of March 10 mid-tide, March 10 high-tide and March 11 mid-tide, respectively. Based on these frequencies, all of them are categorized as infragravity waves. The situation in ADV27 is different. In this case, the peak wave energy frequencies are at 0.10, 0.09, and 0.12 for the three panels from left to right, respectively, revealing that the swell wave is dominating. Since the area under the energy-frequency curve represents the total wave energy, Fig. 4 also reveals that most of the wave energy is due to infragravity waves for the records of ADV31. Likewise, swell wave is responsible for most of the wave energy in the case of ADV27.

A clear difference between energy spectrum of high-tide condition and that of mid-tide condition can be distinguished. As shown, the total energy contained in mid-tide spectrum is larger than that of the high tide spectrum for both ADV31 and ADV27. It can be observed that the energy spectrum is narrower in high tide conditions resulting in less total energy. Based on the comparison of energy spectra, it is evident that the wave field is far more energetic during the deployment of ADV31 than that of ADV27.

RESULTS AND DISCUSSION

The results of set-up calculations are shown in Figs. 5–9. In Fig. 5, the time histories of wave records at some of the surf zone gauges are shown along with the corresponding offshore gauge record. By comparing the two records, the wave-induced set-up heights were obtained. As can be seen, the records of the surf zone gauges are not continuous because the instruments were out of water during low tide, and thus no wave records were available. Therefore, we report set-up data obtained during only high and mid stages of tide. The values shown in Fig. 5 are set-up values at the location of the instruments. Based on Fig. 3, the maximum set-up occurs at the zero water depth.

It is long known that wave-induced set-up increases with increasing offshore wave heights and decreasing water depth. In addition, set-up increases with increasing wave period up to a certain value [13]. Our results are in agreement with the aforesaid facts. The highest measured set-up value of about 1.7 m (Fig.5, ADV31) was observed during the largest offshore wave height, and the lowest value (Fig. 5, ADV27) also was obtained during the smallest offshore wave height.

For the records of ADV27, very small set-up values and sometimes negative values were obtained which perhaps represent set-down as the offshore wave field was very small during the deployment of this instrument. As shown in Fig. 3, it is evident that set-down occurs around the breaking point, outside of the surf zone. As the ADV27 was employed during a very small offshore wave height (Fig. 2, top panel), it is likely that the width of the surf zone was relatively short during this period and thus, the instrument was located at the breaking point or outside of the surf zone. However, to make sure if it was outside of the surf zone or not, we used index of γ, defined as the significant wave height over the water depth which according to Fredsoe and Deigaard (1995) [14], ranges between 0.5 and 0.8 for waves inside the surf zone.

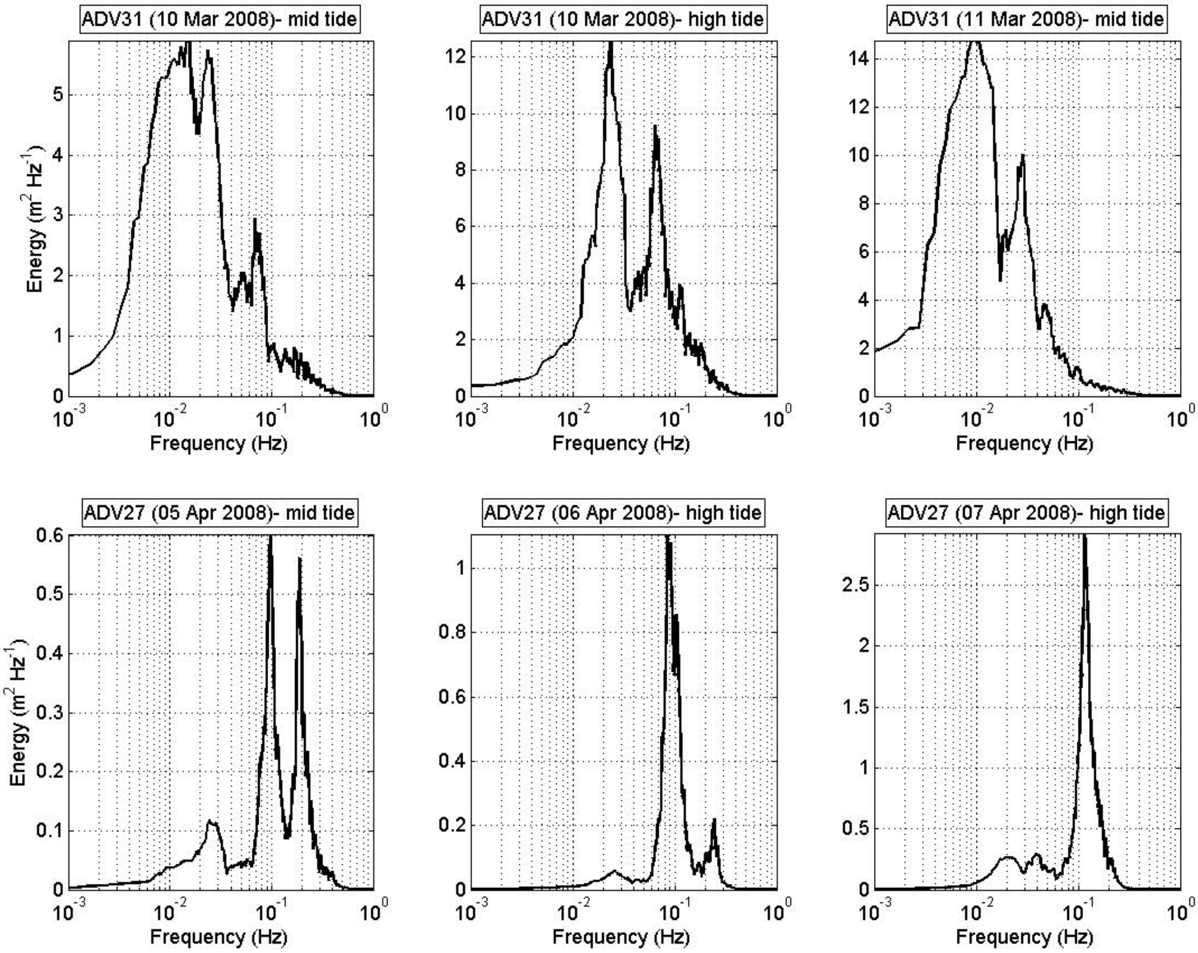


Figure 4. Examples of energy spectrums obtained from wave-height time histories at different times for VEC31 (top panels) and VEC27 (bottom panels).

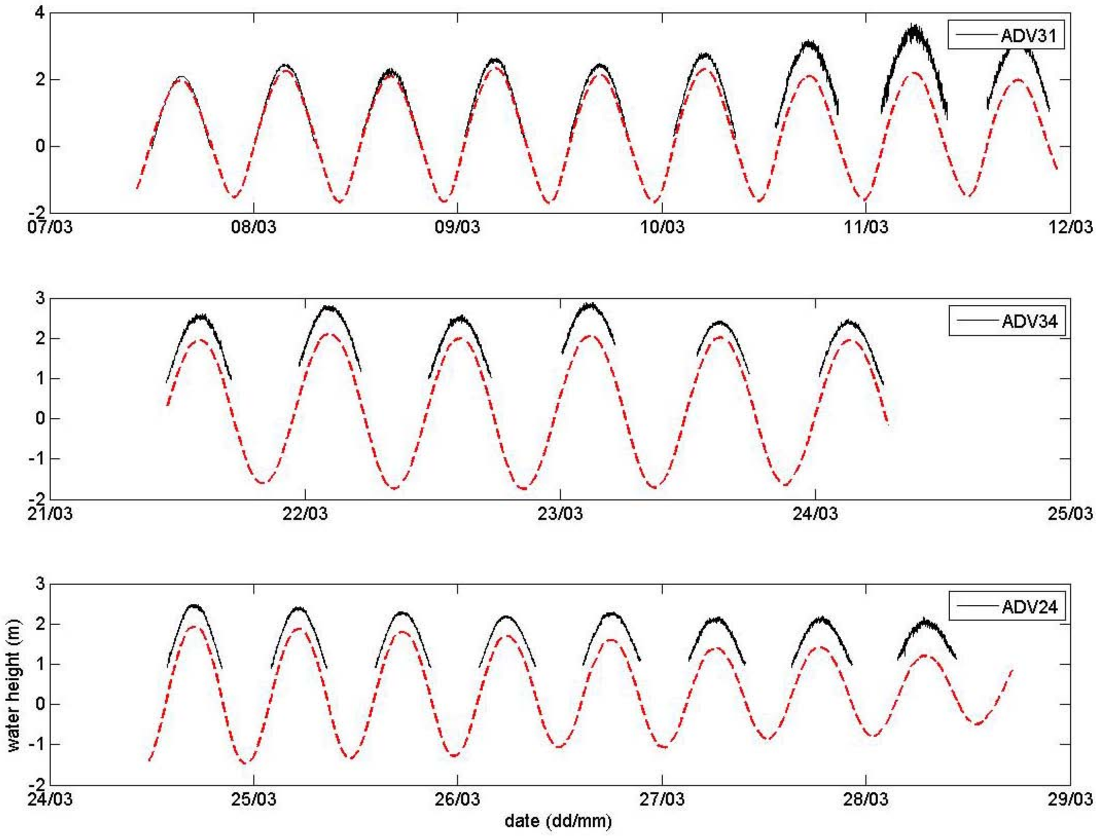
Figure 6 shows the variation of γ during the deployment of ADV27 and compares it with those of the ADV34. As shown, γ always remains around 0.3 or less for the ADV27 verifying our suggestion that the instrument was located at the breaking point or outside of the surf zone.

To estimate the maximum set-up heights, in Fig. 7 the variation of set-up versus normalized water depth, i.e. $1-d/d_b$ in which d and d_b are local and breakpoint water depths respectively, is shown. As the maximum set-up occurs at the zero water depth, the extrapolated set-up at the normalized water depth of 1 can give an estimate of $\eta_{\max}$. In general, Fig. 3 shows that set-up increases by decreasing water depth. However, the correlation between water depth and set-up is not always strong which can be attributed to the variation of offshore wave height during the deployment of the instruments. We know that offshore wave height is the main factor influencing set-up height. For example, when the offshore wave field is nearly constant (e.g., ADV24 or ADV22), stronger correlation between set-up and normalized depth is observed.

Also, the weak correlation between set-up and normalized depth for the ADV31 is due to the strong variation of offshore wave height during the deployment of this instrument. According to Fig 7, the maximum setup can be estimated as 1.5–2, 1.25, and 1.1 m for ADV31, ADV32, and ADV24 respectively.

Two distinct curves can be observed in Fig. 7 for the data of ADV31, ADV32 and ADV24. This behaviour is due to the effect of offshore wave height on set-up. In other words, at the same normalized depth, the larger offshore wave height, the larger set-up height that is produced.

Figure 8 presents set-up values versus offshore wave height (H_0) for all of the instruments. Unlike the correlation between set-up and normalized depth, a relatively strong correlation between offshore wave height and set-up can be observed in Fig. 8.



Figue 5. Results of set-up calculations for some of the ADVs without modifying for $\eta_{\max}$. Dashed line shows the offshore gauge record while the solid one represents the surf zone records.

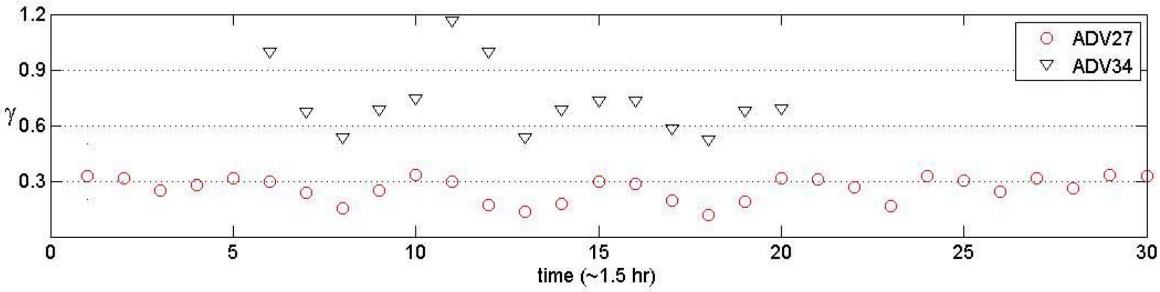


Figure 6. Variations of γ during the ADV deployment for ADV27 and ADV34.

The maximum set-up value was about 1.5–2 m which was observed in March 11 when the offshore maximum and significant wave height were about 7 and 12 m, respectively. Such extreme set-up heights can cause considerable inundation of about several 10 meters during severe storms.

Based on Fig. 3 and as the beach slope is about 0.03 in the region, the maximum set-up can cause up to about 60 m of inundation on the Aquitanian coast. To the authors' knowledge, such extreme set-up data have been rarely reported from a field experiment.

To investigate the possible nonlinear effects of shallow water on set-up behaviour, nonlinear regression was performed for the $\eta_{\max} - H_0$ relation as shown in Fig. 8 (dashed line). The resulting nonlinear fitting line approximately coincides with the linear one for both cases up to a set-up value of about 1 m, and after that, it diverges from the linear line and predicts smaller set-up values compared to the linear predictions.

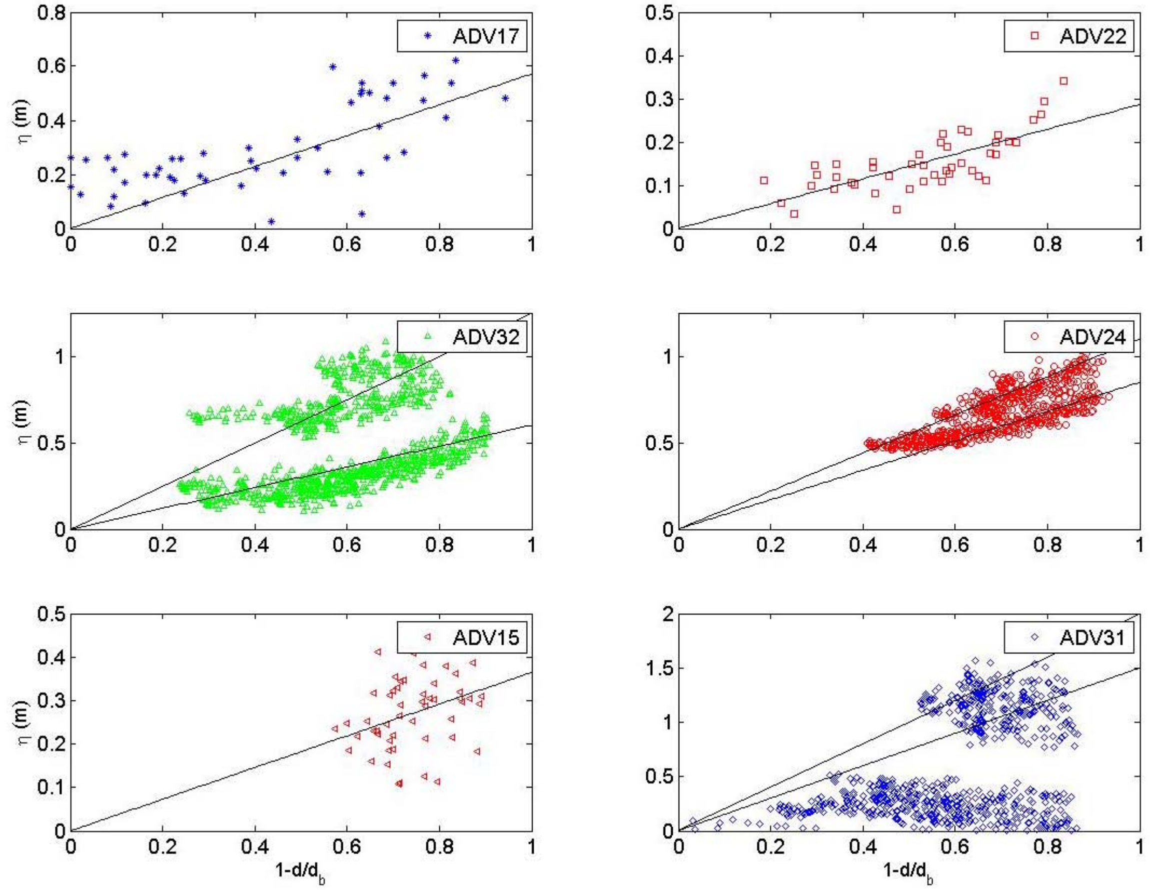


Figure 7. Set-up versus normalized water depth.

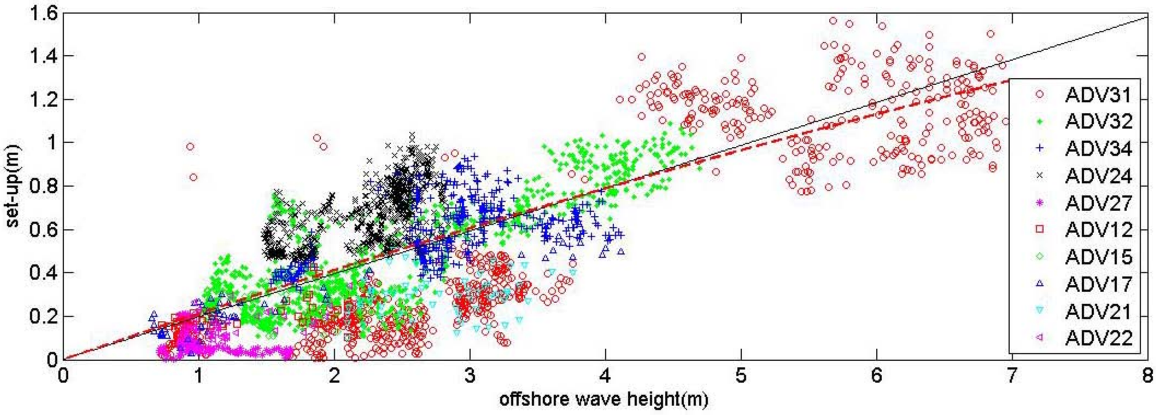


Figure 8. Set-up versus offshore wave height (H_0) for all of the instruments. The solid and dashed lines show the linear and nonlinear fitting lines, respectively.

This nonlinear effect was not discussed in the literature as the reported field-measured set-up heights were limited to around 1 m in the previous field investigations. In fact, one advantage of our field experiment was that it was associated with a large storm enabling us to record extreme set-up heights. However, again we believe that more experimental and field studies are necessary to further investigate and validate this nonlinear behaviour.

To further examine the accuracy of the results, we compared them with some of the available field data worldwide. In Fig. 9, the set-up results obtained for 9 different coasts around the world are shown along with our data. In general, good agreement can be observed between our set-up values and those of the other coasts. Especially, the linear part of our data (up to set-up value of 1 m) well coincides with the most part of the set-up data reported from other coasts. However, a careful look at Fig. 9 reveals that our data is slightly smaller than those of the Duke82 and Duke94 data, both obtained in Duck, North Carolina [15]. This small reduction of set-up height can be attributed to the type of the Aquitanian coast which shows a dissipative behaviour during high energy conditions in winter [8 & 16], while the Duck beach is an intermediate to reflective one. As it was reported by some authors (e.g., [17]), it is evident that set-up heights in a dissipative beach is lower than those of a reflective or intermediate one.

We were not able to compare and validate the high set-up heights (above 1 m) obtained in our study with similar data from other coasts as literature lacks such data. Since the first part of our data (up to set-up value of 1 m) is in good agreement with the data from other coasts, it may be an approval for the accuracy of the remaining part as both data (under and above 1 m) were obtained in the same experiment, under the same conditions and especially, using the same method. It is evident in Fig. 9 that if we remove high set-up values from our data, the dashed line will well coincides with the solid line. This shows that the behaviour of setup-offshore wave height is slightly different in the presence of high set-up values. The divergence of high set-up heights from linear prediction perhaps can be attributed to the effect of breaking which seems to be stronger for higher offshore wave heights.

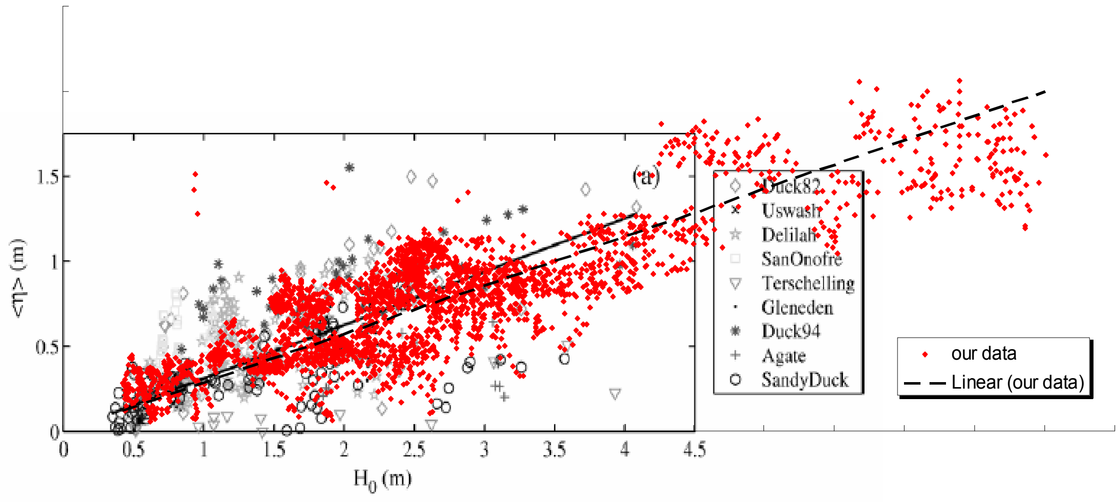


Figure 9 . Set-up versus offshore wave height for various coasts around the world [15] along with our set-up results (red points). The solid and dashed lines show the linear fit for other coasts and our data, respectively.

CONCLUSIONS

Extreme set-up heights were reported and analyzed obtained during a large international field experiment performed at the French Atlantic coast of Aquitanian. The main findings are:

(1) The maximum observed set-up height was about 1.5–2 m which was obtained during a large storm having a maximum offshore wave height of about 12 m.

(2) A good correlation was observed between set-up and offshore wave height.

(3) The setup-offshore wave height relationship was linear up to a set-up value of about 1 m as similar behaviour was reported from many other coasts.

(4) A slightly nonlinear setup-offshore wave height relationship was observed for set-up heights larger than 1 m which tends to predict smaller heights compared to those of linear prediction.

(5) Further numerical and experimental studies are necessary to better understand the behaviour of extreme set-up heights in the surf zone.

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