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Bore collapse and wave run-up on a sandy beach

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Abstract

Wave run-up on beaches and coastal structures is initiated and driven by collapsing incident bores, this process is often considered to define the seaward limit of the swash zone. It is hence a key feature in nearshore wave processes as extreme run-up can lead to structure overtopping and coastal inundation during storm conditions. In addition, the turbulent nature of incident bores and their collapse suspends and advects sediment, resulting in a highly morphologically dynamic swash zone. The cross shore bore collapse location varies from wave to wave and the process is very limited in both spatial and temporal extent, making direct measurement problematic. This paper presents high spatial-temporal resolution LiDAR field measurements of the evolving free-surface in the surf and swash zone which enable the bore collapse detection for 166 waves. These measurements are used to investigate the link between broken wave properties at bore collapse and wave run-up. Incident bores are identified at the seaward boundary of the LiDAR profiles and tracked through the inner surf and swash zones to the run-up limit. It is found that the vertical run-up height exceeds that which would be expected for a perfect conversion of potential to kinetic

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energy during bore collapse for 24% of the bores measured. By returning to an existing ballistic-type model to describe the run-up of individual waves, we show that wave run-up can be divided into three components: the bore collapse, terminal bore celerity and their non-linear interaction. For the present dataset, the contribution of the bore collapse and terminal bore celerity is 26% and 27% respectively, while non-linear interactions between the two dominates and account for 47% of the measured run-up. By including the terminal bore celerity, the ability to predict run-up is increased by 30% with the determination coefficient r increasing from 0.573 to 0.785. Likewise, the RMS-error for the wave run-up shows an approximately 10% reduction from 0.325 to 0.295 m.

Keywords: Bore collapse, Swash zone, Run-up, Swash-swash interaction.

1. Introduction

Incident waves dissipate their energy as they break and propagate in the surf zone as bores. As bores reach the shoreline, the wave form compresses as the wave decelerates and eventually collapses leading to wave run-up on beaches or coastal protection structures. The swash zone is recognized as a highly turbulent region with unsteady, non-uniform flows [14]. The turbulent flows suspend sediment into the water column leading to sediment transport [13] and relatively rapid morphological change on sandy [30, 25] and gravel beaches [3]. Consequently, new insight into processes at the boundary between inner and swash zones are valuable to enhance understanding of beach hydro and morphodynamics. In this work we focus on the shallowest part of the inner-surf zone, the bore collapse and associated vertical run-up. Furthermore, interaction between consecutive swash events is discussed.

Incident bores in relation to run-up have been studied in scaled laboratories with single bores running up a slope, e.g. [9, 17]. Field measurements of the swash zone have tended to focus on maximum run-up and the statistical distribution of swash excursions using cameras or run-up wires e.g. [18, 20, 35]. More recent field studies [26, 10] have investigated more detailed swash hydro

19 and morphodynamics using a variety of techniques in response to the recom-
20 mendations of Puleo and Butt [31] and Puleo and Torres-Freyermuth [33] who
21 suggested that measurements of swash on a wave-by-wave basis was key to en-
22 hancing understanding.

23 Whitham [38] describes bore collapse and run-up on a wave-by-wave basis
24 by applying an analytical mathematical solution of a propagating bore in non-
25 uniform water depth. This analytical solution shows that as bores propagate to
26 shore, they reach a maximum finite velocity (U_0) proportional to the local water
27 depth. This velocity is often applied as the starting point for run-up models of
28 individual bores such as the ballistic model of Shen and Meyer [34]. Yeh et al.
29 [40] calculated U_0 through a classical dam-break problem assuming a perfect
30 conversion of potential to kinetic energy. In the same work it is shown through
31 laboratory experiments that the theoretical value overestimates the measured
32 finite velocity for a single fully developed incident bore, while for undular bores
33 there seems to be a better match between theory and measurements. Baldock
34 and Holmes [8] recognized that the conversion efficiency varies with the type of
35 bore collapse (undular bores, uniform bores or waves breaking on the beach),
36 assuming that the theory of Whitham [38] is valid for the different types of bore
37 collapse or wave breaking. In order to take imperfect energy conversion into
38 account, Baldock and Holmes [8] introduced an energy conversion coefficient C .

39 The approaches above do not consider direct bore-bore interactions although
40 sediment transport in the swash zone is thought to be greatly affected by the
41 interaction between consecutive swash events [21, 26]. Capturing the complex-
42 ity of such interactions is a major challenge to existing hydrodynamic modelling
43 approaches and introduces significant uncertainty into sediment transport pre-
44 dictions [10]. Few existing studies have directly addressed this phenomenon,
45 though Hegge and Eliot [18] classified swash-swash interaction into 5 categories;
46 free, over-taking, over-riding, suppressed or composite. Over-taking represents
47 a bore that rides on top of the previous bore. Over-riding and suppressed
48 swash-swash interaction modes are linked through the strength of the backwash.
49 The composite mode consists of more than one of the other modes. Baldock

50 and Holmes [8] used their swash model to incorporate swash-swash interaction,
51 however in their study the effect of interactions was to translate the location of
52 bore collapse and the actual interaction between consecutive swashes was not
53 explicitly considered. More specific bore interaction-focussed laboratory exper-
54 iments investigated the interaction of two successive bores [29, 14] in which the
55 former showed that the degree of swash-swash interaction relates to the soli-
56 tary wave slope parameter [15]. Bore-bore interactions influence the cross shore
57 location of the bore collapse, bore height and advection of sediment into the
58 swash zone, which in turn affect swash-morphodynamics [5]. In line with this
59 observation, Alsina and Cáceres [4] showed that for saturated surf-zones the
60 amount of suspended sediment at the inner-surf, swash zone boundary is inde-
61 pendent of offshore wave height, but caused by the combined action of incident
62 swell and swell related long-period water oscillations, for example modulation
63 of wave-wave interaction due to the wave group frequency [6].

64 This paper focuses on swash run-up observed in the field using a 2D LiDAR.
65 A novel technique to capture and extract the bore collapse and incoming bore
66 celerity from the data is presented and applied to investigate the nature of bore
67 collapse and its importance to wave run-up.

68 **2. Method**

69 *2.1. Study site and data collection*

70 In-situ 2D LiDAR data was collected at Nha Trang beach, on the East coast
71 of Vietnam (Figure 1) during a 9-day field experiment from 26 November to 4
72 December 2015. The sandy beach of Nha Trang is situated in a semi-enclosed
73 bay, protected by a group of islands at the Southern part of the bay. The 5 km
74 long stretch of beach is therefore mostly exposed to North-Easterly swell. The
75 East-Vietnam coast experiences a wave climate that is primarily governed by two
76 monsoon seasons; the North East and South West monsoon. The former (latter)
77 is characterized by strong (mild) winds and energetic (moderate) waves. In addi-
78 tion to monsoons, the region experiences occasional tropical storms (typhoons)

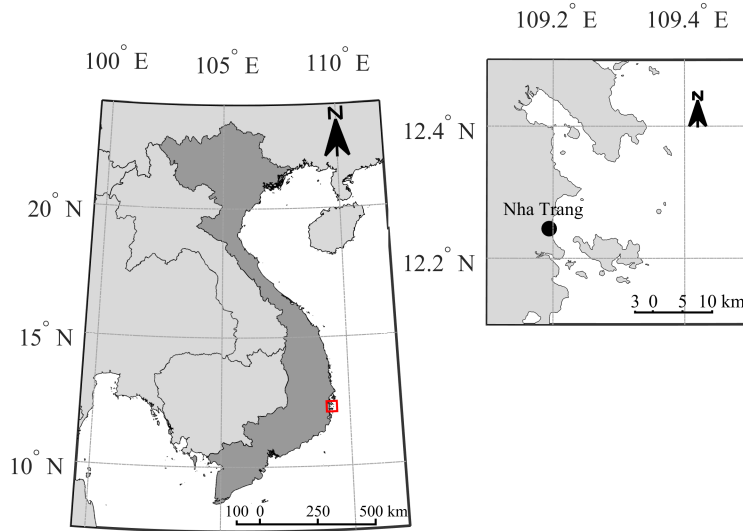


Figure 1: Left-hand map highlights Vietnam (darker area) and the red square indicates the zoomed area for the right-hand map. The right-hand map shows the location of Nha Trang.

79 leading to rapid erosion at Nha Trang bay [37, 1]. During the time-frame of
 80 the experiment, the average significant wave height (H_s) was 1.07 m, with a
 81 corresponding peak period of 11 seconds. The micro-tidal regime at Nha Trang
 82 (maximum tidal range = 1.5 m) consists of a mix of diurnal and semi-diurnal
 83 tides [27]. The upper beach slope was 0.1 while the inter-tidal terrace has a
 84 slope of 0.01. The sediment sizes varies within Nha Trang bay from $D_{50} = 900$
 85 μm (coarse) in the North to 400 μm (medium-coarse) in the South [2]. During
 86 the experiments, almost no wind was present, but this was not measured.

87 During the field campaign a range of instruments were deployed, an off-
 88 shore Acoustic Doppler Current Profiler (ADCP), near-shore ADV (Acoustic
 89 Doppler Velocimeter), shore mounted video cameras, a swash pole camera, pres-
 90 sure transducers and a 2D LiDAR (for details see Almeida et al. [2]). This paper
 91 will focus on data only from the 2D LiDAR which was deployed on a 4 m tall
 92 tower above the high tide limit as shown in Figure 2. LiDAR data was collected
 93 at 25 Hz and was typically able to obtain beach profile and free surface data

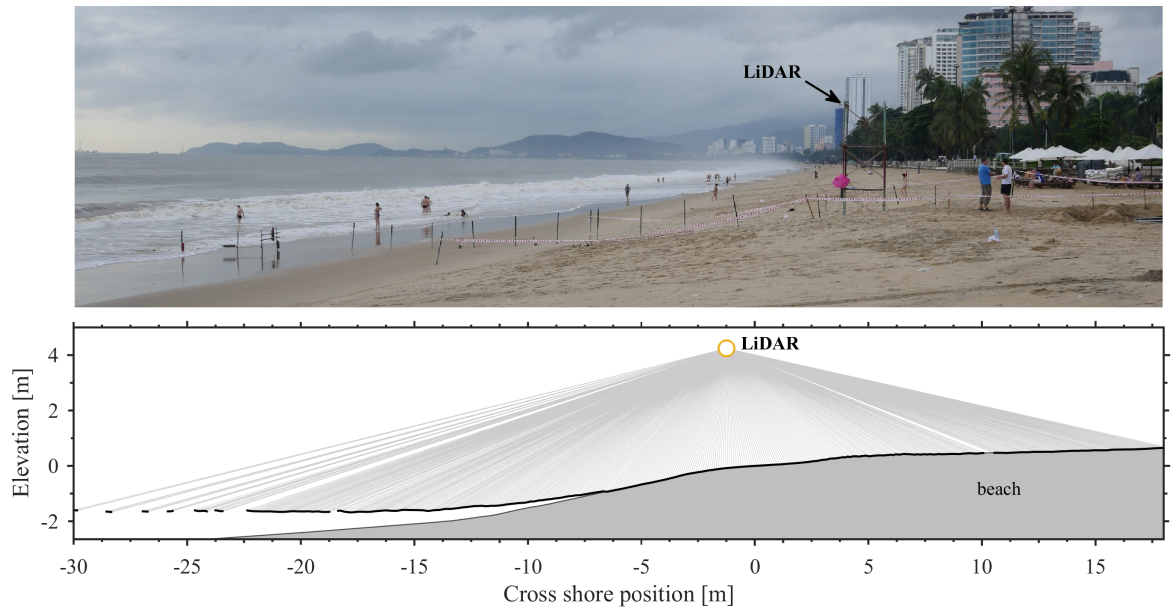


Figure 2: The upper plot shows a photograph of the setup at low-tide at Nha Trang beach during the field experiment. The arrow in the top plot indicates the position of the 2D LiDAR. The bottom plot shows a snapshot of obtained and processed LiDAR data (beach and free surface - black line) at Nha Trang through a schematic representation of the LiDAR position and laser beams.

94 along a transect extending approximately 30 m seaward of the LiDAR position.

95 The obtained LiDAR data was post-processed using the methodology de-
 96 scribed by Almeida et al. [3] and Martins et al. [24] and interpolated onto a 1D
 97 grid with $\Delta x = 10$ cm. The lower panel in Figure 2 shows a snapshot of the cap-
 98 tured water surface elevation and beach profile data. Here, a 40 minute subset
 99 of the total collected dataset between 22:21 to 23:01 on the 27th of November
 100 2015 containing 166 bores is analysed. During this time a significant wave height
 101 of 1.2 m and peak period of 12 seconds was measured offshore.

102 2.2. Bore collapse and vertical run-up

103 The seaward boundary of the swash zone is characterized by a rapid steepen-
 104 ing of the incoming bore and ultimately, as the water depth in front of the bore
 105 approaches zero, the bore collapses, driving swash up-rush [39, 20]. As briefly

106 discussed above, previous analytical work by Whitham [38] suggests that a fi-
 107 nite velocity U_0 proportional to the local water depth $\propto \sqrt{h}$ is reached. It is
 108 noted that the empirical approach presented here takes no account of several
 109 processes known to influence swash flows, including friction swash-groundwater
 110 interactions and porosity e.g. [32, 22, 12]. Yeh et al. [40] used the classic bore
 111 collapse theory to calculate the finite velocity at collapse, assuming a perfect
 112 conversion of potential to kinetic energy during the bore collapse process e.g.
 113 [8, 11, 36]. This initial shoreline velocity can then be used in to estimate swash
 114 trajectory via a ballistic-type model e.g. [34]. Hence vertical run-up (R) can be
 115 approximated as a function of the initial shoreline velocity U_0 :

$$R = \frac{U_0^2}{2g} \quad (1)$$

116 In which g is the acceleration due to gravity. The maximum velocity in the
 117 case where no energy is lost during the transformation of potential to kinetic
 118 energy is approximated as a function of the bore height at collapse following
 119 $U_0 = 2\sqrt{gH_{b,c}}$ [40]. Baldock and Holmes [8] replaced the factor of 2 (perfect
 120 conversion) by an empirical bore collapse efficiency coefficient C to approximate
 121 the initial velocity which, in theory, is in the range 1 to 2:

$$U_0 = C\sqrt{gH_{b,c}} \quad (2)$$

122 where $H_{b,c}$ is the bore height at collapse in which according to Shen and
 123 Meyer [34], the bore height must be taken in slope-normal direction. Following
 124 (2), the vertical run-up from the bore collapse location can now be calculated
 125 as:

$$R = \frac{C^2 H_{b,c}}{2} \quad (3)$$

126 *2.3. Detection of bore collapse*

127 The high spatial and temporal resolution of the LiDAR data collected en-
 128 ables individual incident bores to be tracked through the near shore. Track-
 129 ing of individual bores allows evolving bore characteristics such as bore shape,

130 height, period and the bore collapse process to be captured. The bore track-
 131 ing methodology is similar to that used in the surf zone by Martins et al. [24],
 132 though instead of tracking peaks in the surface elevation, peaks in its spatial
 133 derivative are tracked instead. The tracking was initiated at the cross-shore po-
 134 sition $x = -18$ m. Then, individual bores are subsequently tracked inshore for
 135 every Δx by identifying the maximum surface gradient around the previously
 136 detected peak. An example of this process is shown in Figure 3.

137 Inshore of the breakpoint, the bore front gradient varies considerably in the
 138 surf zone with the breaking intensity [23]. As the bores approach the boundary
 139 between inner surf and swash, the front steepens, reaching a local maximum
 140 gradient just before the bore collapses (red dot in the bottom plot of Figure 3).
 141 The LiDAR is able to detect this and here we define bore collapse as the point
 142 at which the local maximum bore front steepness occurs, before the bore front
 143 suddenly and rapidly flattens as observed in Figure 3. Thus the location of bore
 144 collapse is defined as the location of the local maximum bore front gradient in
 145 time:

$$\text{Bore Collapse} = \max \left(\left| \frac{\Delta \eta_{bf}}{\Delta x} \right| \right)_t \quad (4)$$

146 In which η_{bf} is the free surface elevation of the bore front which is defined
 147 between a seaward and landward limit taken here as:

$$\text{Fitting Limits } \eta_{bf} = \left| \frac{\Delta \eta}{\Delta x} \right| < \frac{1}{8} \max \left(\left| \frac{\Delta \eta}{\Delta x} \right| \right)_t \quad (5)$$

148 where η is the free surface elevation. In Figure 4, a dot-dashed line is drawn
 149 connecting the points defined by (5) to indicate the bore front slope at collapse.
 150 A second line is fitted at the moment of bore collapse to the free surface elevation
 151 0.5 metres seaward of the seaward-limit of (5) as illustrated in Figure 4. The
 152 fitting limits are illustrated by the grey vertical dashed lines in Figure 4. The
 153 intersection of the two lines is taken as the bore head point; indicated by the blue
 154 circle in Figure 4. The bore height is ultimately determined at the bore head
 155 point as the vertical distance from the bore head to the bed. The fitting limits

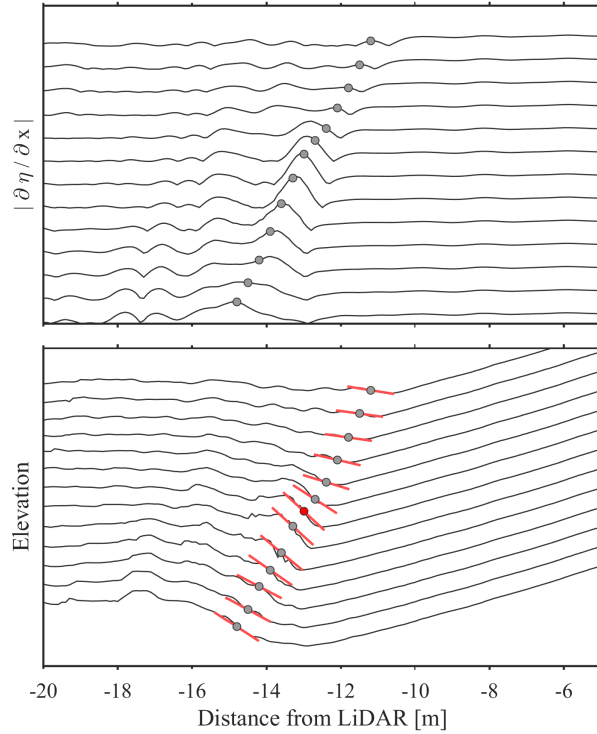


Figure 3: A schematic representation of bore tracking using the LiDAR data. In both plots, the time between every line is 3 time steps ($\Delta t = 25$ Hz). The upper plot shows the gradient of the measured free surface. The dots represent the tracked bore positions. The dots are the local maximum gradient determined for every gridded cross shore point in time. The lower plot shows the measured free surface elevation and the grey dots are the positions as derived from the upper plot. The red-lines represent the bore front gradient and the red-dot indicates the bore collapse (maximum bore front gradient in time).

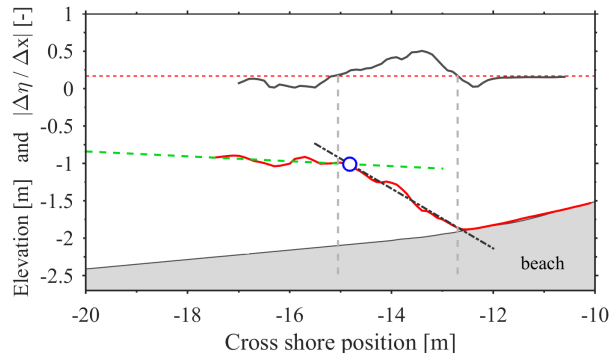


Figure 4: Schematic representation of the bore collapse detection. The solid red line represents the measured free surface elevation, the dash-dotted (-.) line is the slope of the bore front, the dashed green line represents the slope of the free surface elevation on the seaward side of the bore head. In the upper part of the plot, the black solid line represents the absolute derivative of the surface elevation and the dashed red line indicates the fitting limit. The grey dashed lines give the used fitting boundaries.

156 used here are calibrated for the current Nha Trang dataset and are therefore
 157 site-specific. Nonetheless, considering bore self-similarity, it is expected that
 158 similar thresholds are likely to be valid for other datasets with differing site and
 159 wave conditions. The same method was used successfully to define surf zone
 160 bores by Martins et al. [23].

161 The bore height is estimated at every cross-shore location using the surface
 162 elevation data. Tracking the incident bores through the surf zone allows for an
 163 estimation of the bore celerity. Until bore collapse, changes in the bore shape
 164 are minimal, leading to a robust celerity estimate. After collapse, the earlier
 165 bore features such as the steep front appear less distinct and as such the celerity
 166 estimate is equivalent to the shoreline velocity. At bore collapse, a local bore
 167 related Froude number (similar to that presented by Yeh et al. [40], Zhang and
 168 Liu [41]) based on the bore celerity ($c_{b,c}$) and bore height ($H_{b,c}$) is defined:

$$\text{Fr}_{b,c} = \frac{c_{b,c}}{\sqrt{gH_{b,c}}} \quad (6)$$

169 *2.4. Determination of run-up (R) from LiDAR data*

170 The run-up of every wave is defined as the distance (horizontal and vertical)
171 between the toe of the bore at collapse and the most landward shoreline position.
172 In order to calculate the vertical run-up (R), the shoreline is extracted from the
173 LiDAR data using the 3 cm water depth contours which is tracked throughout
174 the up-rush/backwash cycle.

175 **3. Results**

176 *3.1. Bore collapse signature from LiDAR*

177 To date, the bore collapse process has predominantly been observed in lab-
178 oratory experiments and modelled with numerical models (e.g. [40, 28]). The
179 LiDAR data provides the opportunity to observe the nature of the bore collapse
180 process on a wave-by-wave basis in the field. An example observation of the
181 most commonly occurring bore collapse sequence is shown in Figure 5. Figure
182 5a shows a bore approaching the shoreline which reaches a maximum steepness
183 at the point of collapse (Figure 5b). The bore collapse process initiates the
184 swash up-rush (Figure 5c-d), following flow reversal (Figure 5e) the backwash
185 flow is then observed to interact with the proceeding bore (Figure 5f).

186 By tracking the bore properties, the spatial development of the bore front
187 gradient can be investigated. Figure 6 shows the spatial variations of the bore
188 front gradient in the vicinity of bore collapse. At $x = 0$, the gradient of the
189 bore front is at its maximum which indicates bore collapse, following (4). The
190 grey lines represent a subset of individual bores from the collected dataset and
191 show the variation in pre/post collapse bore front gradient.

192 In Figure 6, the solid blue line shows a relatively stable incoming bore with
193 a bore height of 0.63 m, a terminal bore celerity 1.41 m/s and a Froude number,
194 $Fr_{b,c} = 0.57$. The bore front slope at $x = 0$ m is approximately 17 degrees, 70%
195 of the maximum steepness at bore collapse. Steepening of the bore front occurs
196 until the bore collapses at $x = 0$ when the maximum slope (~ 25 degrees) is
197 reached. Here, the terminal bore front slope angle is in the range of 12 to 35

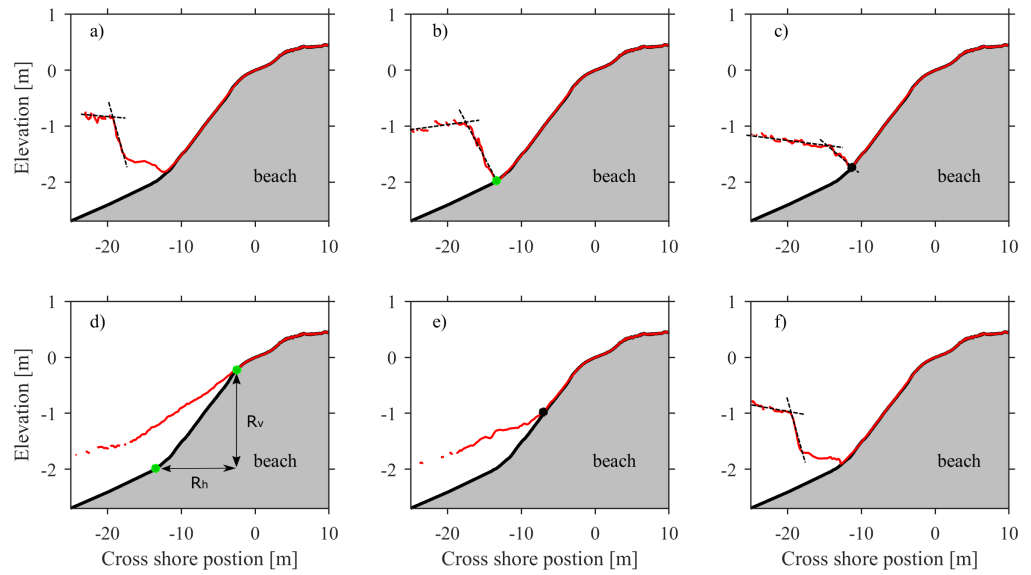


Figure 5: Example of a swash event highlighting the bore collapse process/sequence observed at Nha Trang beach. The sequence shows: a) the incoming bore and the retreating toe of the previous bore 1 second prior to collapse, b) the bore at collapse, c) the initiation of swash motion following bore collapse 1 second post collapse, d) 4 seconds after the collapse flow divergence between the upper and lower parts of the swash flow, e) latter stages of backwash and f) the arrival of the subsequent bore, 10.5 seconds after a). The black and green dots indicate the shoreline tracking and the lines the calculated slopes during the collapsing process. Our detection here, mainly focusses on the b)-d) in which the green dots are used to determine the run-down limit at collapse in b) and maximum run-up as the upper green dot in d).

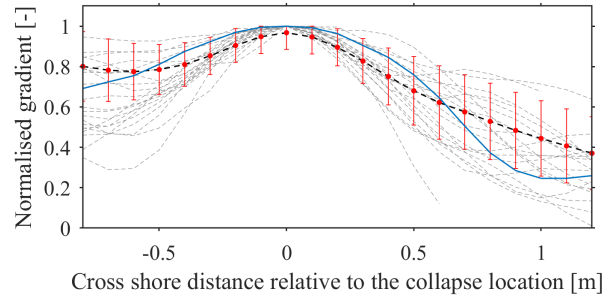


Figure 6: Cross-shore variation of normalised bore front gradient. The grey lines represent the bore front gradient for an arbitrary set of bores. The blue line shows a representative bore discussed in the text. $x = 0$ is the point of bore collapse. The dashed black line is the mean gradient in space of all observed bores within this dataset and the error bars indicate the associated standard deviation.

198 degrees which is much flatter than previously observed in the laboratory [40]
 199 or in a numerical test case [28] which indicated a near-vertical bore front at
 200 collapse. After the moment the bore collapses, the collapsing bore slope reduces
 201 at a higher rate compared to the steepening observed prior to collapsing. The
 202 mean bore front gradient shows that the steepening typically occurs within
 203 the last half metre before the bore collapse. This rapid process highlights the
 204 need for high spatio-temporal resolution measurements to fully capture bore
 205 collapse. The individual bore collapse signatures shown in Figure 6 highlight
 206 the variability of this process.

207 3.2. Observed bore celerity

208 Bore celerity through the surf and swash zone can be estimated through
 209 the bore tracking methodology. Detection and magnitude of the bore celerity
 210 is influenced by changes in bore shape, front slope changes and instabilities.
 211 Tracking the bore-head typically over-estimates the celerity as the front steep-
 212 ens. Likewise, tracking the bore toe leads to an underestimate. It was found
 213 that the most stable results were obtained by tracking the bore's maximum
 214 gradient. Figure 7 represents the celerity corresponding to the same bores as
 215 shown in Figure 6.

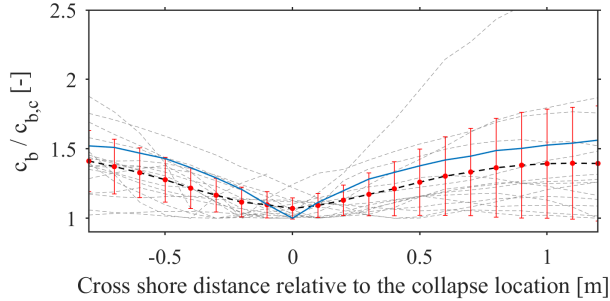


Figure 7: Cross-shore variation of normalised bore celerity (before collapse) and normalised shoreline velocity (after bore collapse). The grey lines represent bore celerity/shoreline velocity for the same bores as in Figure 6. The blue line shows a representative bore. The dashed black line is the mean bore celerity in space of all observed bores for this dataset and the error bars indicate the associated standard deviation

216 The bore celerity in Figure 7 is normalized by the minimum bore celerity for
 217 each detected wave. Minimum bore celerities are therefore indicated by a value
 218 of 1. The blue solid line indicates the estimated celerity for the same bore as
 219 highlighted in Figure 6. Prior to bore collapse, a reduction of the bore celerity
 220 can be observed as the bore approaches zero depth. Minimum bore celerity is
 221 reached at the point of bore collapse ($x = 0$), where the absolute bore celerity is
 222 1.41 m/s for the highlighted bore. Immediately following bore collapse, a rapid
 223 acceleration occurs as the swash flow is initiated [19]. The average bore celerity
 224 (black dashed line) shows a very similar behaviour with a deceleration prior
 225 to the minimum value at bore collapse and subsequent acceleration following
 226 the collapse process. The significantly larger error bars after collapse can be
 227 explained by the fact that the swash tip is significantly harder to detect due to
 228 the flattening of the front (swash-tip) slope and small flow depths.

229 3.3. Wave run-up

230 As discussed in the Methods section, previous authors have suggested that
 231 the vertical run-up can be considered a function of the bore height at collapse
 232 using (3). Figure 8 shows the vertical run-up as a function of the terminal bore
 233 height where the lines indicate constant values of the coefficient C . It can be

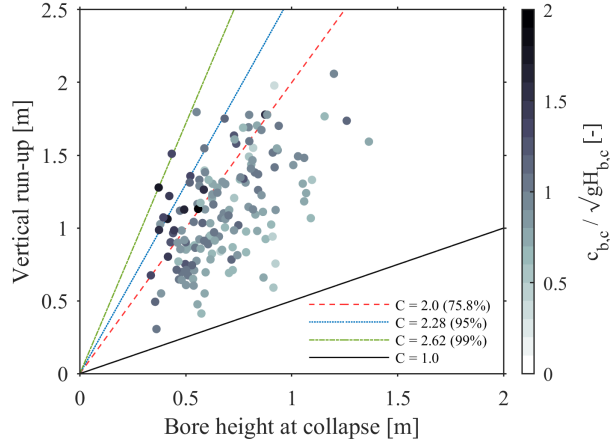


Figure 8: Bore height versus vertical run-up per detected bore collapse. The colour indicates the local bore related Froude number following (6). The lines represent C thresholds, the red dashed line is $C = 2$ (perfect conversion), 95% threshold is represented by blue line and the solid green line indicates the 99% interval of the scatter and the theoretical minimum C ($C = 1$) is represented by the dark black line.

234 observed that the variability of C is much greater in the current field dataset
 235 compared to the large flume experiments described by Blenkinsopp et al. [11]
 236 where values of C were between 1.95 and 2.25 for monochromatic waves. The
 237 average value of C for the current data is 1.79 with a standard deviation of 0.265,
 238 compared to a mean \bar{C} of 2.09 and standard deviation of 0.08 in Blenkinsopp
 239 et al. [11]. Here, we find the majority (75.2%) of the bores have a C -value
 240 indicating an imperfect conversion form potential to kinetic energy ($C < 2$)
 241 while a significant portion of the bores experience greater run-up than predicted
 242 by equation (3) assuming a perfect conversion ($C = 2$). It is suggested that while
 243 the bore collapse process is the primary factor in determining initial swash
 244 velocity, other processes including swash-swash interaction and terminal bore
 245 celerity seem to contribute. Note that C -values greater than 2 have previously
 246 been observed in laboratory experiments with fully developed [7] and solitary
 247 bores [16].

248 The dots in Figure 8 are coloured according to the Froude number at bore

249 collapse defined in (6). It is observed that relatively small values of $Fr_{b,c}$ tend
 250 to correspond to lower values of C implying that bores arriving with a rela-
 251 tively low celerity tend to generate smaller than expected run-up. Observations
 252 suggest that such events typically feature strong interaction between the pre-
 253 ceding backwash flow and the incoming bore which acts to retard wave run-up.
 254 Conversely, relatively large values of $Fr_{b,c}$ tend to correspond with the higher C -
 255 values, indicating larger than expected run-up for a given bore collapse height.
 256 In this case, observations indicate that such events correspond to overtaking
 257 swash events according to the definitions of Hegge and Eliot [18] which act
 258 to enhance wave run-up. Over the total dataset 50.3% of the bores are free
 259 swashes without bore-bore interaction. 19.3% of the bores are overtaken by
 260 the subsequent incident bore (6.2% of the dataset consists of the subsequent
 261 bores). Overriding and suppressed bores collectively comprise 16.8% of the
 262 total dataset and the remaining 7.4% corresponds to composite swash-swash
 263 interactions. While there is clear scatter in measured values of the coefficient
 264 C , if the average measured value (1.79 as found above) is taken to calculate the
 265 run-up for each swash event in the dataset using (3), the RMS error is 0.325 m.

266 The LiDAR data and tracking routines allow individual incident bores and
 267 bore-pairs to be tracked, which enables an analysis of bore-bore interactions.
 268 Figure 9 shows 3 example cases with increasing swash duration (hence reducing
 269 swash saturation as described in (6)) from left to right: overtaking (a), (par-
 270 tially) suppressing (b) and a free bore (c). In all of the presented cases, the bore
 271 heights of two consecutive bores are of similar order at -17.5 m cross shore (sea-
 272 ward of all collapse locations for the presented bores). The maximum difference
 273 is 6 cm, which corresponds to 5% of the maximum height of the two consecutive
 274 bores. Figure 9d-f shows the variation in the time between the two consecutive
 275 bores as they progress shoreward, and these demonstrate a characteristic be-
 276 haviour for the different types of bore-bore interaction. For the overtaking case
 277 (Figure 9 a and d), the second bore propagates before the flow reversal of the
 278 preceding bore, thus it travels in a greater depth, the bore is partially-advected
 279 by the uprush flow and it collapses further landward. As a result, the time

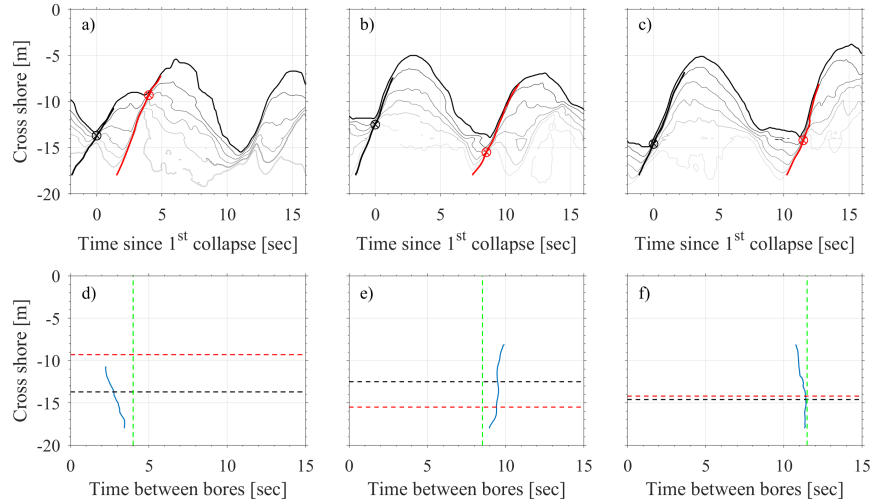


Figure 9: Examples of bore-bore interactions. a) represents an extended run-up due to overtaking, b) indicates a suppressing bore-interaction and c) shows a free swash movement. The black line shows the bore-track of the first incident bore and the red represents the second. The circles represent the detected bore collapse point. d)-f) show corresponding relative time between two consecutive bores as the bores propagate inshore. The black and red dashed lines correspond to the cross shore location of the bore collapse for the first (black) and second (red) bore. The green dashed line represents the time between two consecutive bore collapse events and the blue line shows the time between incident bores propagating inshore.

280 between consecutive bores reduces as they move landward, and the maximum
 281 run-up is much greater for the second bore despite the fact that the bores had
 282 the same height at $x = -17.5$ m. In the partially suppressing case (Figure 9 b and
 283 e), the second bore propagates on a seaward-directed backwash flow which holds
 284 the bore back prior to collapse, making the bore collapse further seaward and
 285 reducing the maximum run-up. The time between consecutive bores reduces in
 286 the landward direction due to both a lower terminal velocity and smaller bore
 287 collapse height of the second bore. Finally, in the free bore case (Figure 9 c
 288 and f) the bore collapse position of the second wave is almost unaffected by the
 289 preceding bore, and the run-up for both bores is very similar

290 **4. Discussion**

291 The results above show a majority of bores with a C-value smaller than
 292 2. However, $C > 2$ is found for a significant number of bores which can be
 293 important for extrema-analyses such as run-up predictions. C-values are often
 294 greater than predicted by a conversion of potential to kinetic energy during
 295 bore collapse and appear to be influenced by the local Froude number. If we
 296 assume that the terminal bore celerity $c_{b,c}$ contributes directly to the initial
 297 swash velocity U_0 , we can rewrite (2) as:

$$U_0 = c_{b,c} + \alpha \sqrt{gH_{b,c}} \quad (7)$$

298 by substituting U_0 using (7) instead of (2) in (1), the vertical run-up can be
 299 calculated in terms of the local bore related Froude number (8):

$$R = \frac{[c_{b,c} + \alpha \sqrt{gH_{b,c}}]^2}{2g} \iff R = \frac{[(Fr_{b,c} + \alpha) \sqrt{gH_{b,c}}]^2}{2g} \quad (8)$$

300 The term in parentheses in the right part of (8) effectively represents C ,
 301 which consists of the bore related Froude number and a new conversion coeffi-
 302 cient α , as presented in (9). Considering (9) and by rearranging (3), α is then
 303 related to the run-up and bore height as presented in (10).

$$C = Fr_{b,c} + \alpha \quad (9)$$

$$\alpha = \sqrt{\frac{2R}{H_{b,c}}} - Fr_{b,c} \quad (10)$$

304 Notably, the definition of C compared to Baldock and Holmes [8] has not
 305 changed other than that C is now defined by a celerity component and a conver-
 306 sion efficiency component α which in the case of a perfect conversion of potential
 307 to kinetic energy will take the value 2 as in the earlier formulation [40]. Also,
 308 the left hand side of (8) allows for a component expansion which suggests that
 309 R is a function of two physical components: terminal bore celerity and the con-
 310 version efficiency in the bore collapse process. In addition to these two distinct

311 physical processes, (11) and (12) also include a third term which incorporates
 312 non-linear interactions between them:

$$R = \frac{c_{b,c}^2}{2g} + \frac{c_{b,c}\alpha\sqrt{gH_{b,c}}}{g} + \frac{(\alpha\sqrt{gH_{b,c}})^2}{2g} \quad (11)$$

$$R = R_c + R_{\alpha,c} + R_\alpha \quad (12)$$

313 In (12), R_c is the run-up component related solely to the terminal bore
 314 celerity, R_α is the component related solely to bore collapse and $R_{\alpha,c}$ represents
 315 non-linear interaction between the terminal celerity and collapse. C and α are
 316 similar conversion coefficients respectively with and without a terminal bore
 317 celerity component. The upper plot in Figure 10 shows total vertical run-up
 318 as a function of the conversion coefficient C^2 . In the lower plot in Figure 10
 319 the component of the vertical run-up due to the terminal bore celerity R_c is
 320 subtracted from the total run-up, leaving the components of run-up that are
 321 related to the terminal bore height at collapse and this is shown as a function
 322 of α^2 .

323 From Figure 10 it is evident that by removing the component of run-up
 324 directly caused by the terminal bore celerity, the relationship between the re-
 325 maining components of run-up and the bore collapse height is strengthened,
 326 as indicated by the reduced scatter. Thus, the results in Figure 10b indicate
 327 the energy converted by the bore collapse process through α , and the scatter
 328 represents the non-linear interaction with the terminal bore celerity. To further
 329 highlight this, we present $R_{\alpha,c}$ and R_c as a function of α in Figure 11.

330 Figure 11 shows that R_α is smaller than the non-linear interaction term $R_{\alpha,c}$
 331 for most range of α , until α exceeds a value of 1.5. The colouring suggests that
 332 even when the value of α is small, substantial vertical run-up can occur when
 333 there is a large value of the terminal bore celerity. It is also evident that the
 334 higher values of terminal bore celerity are typically related to low values of α and
 335 for high values of α , terminal bore celerity tends to be relatively small. For the
 336 lower (greater) values of α this suggests a larger (lower) relative contribution of

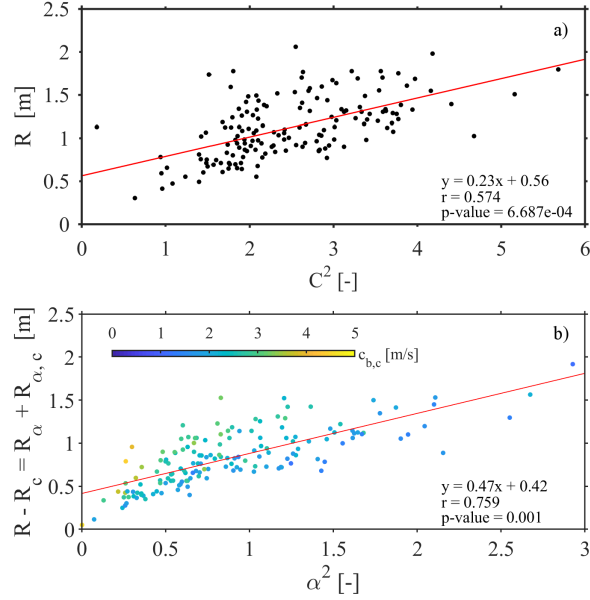


Figure 10: Scatter plots of run-up versus conversion coefficients C and α . a) presents the total run-up as a function of C^2 . b) shows the relation between α^2 and run-up without the terminal celerity component. The colour of the symbols represents the terminal bore celerity. The red lines in both plots represent the linear fit with details presented in the lower right corner of each panel.

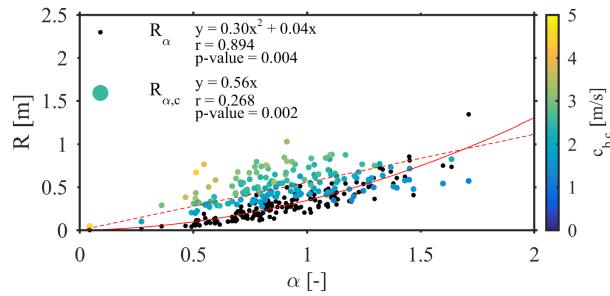


Figure 11: Scatter plot of α compared to run-up related to c_{bc} and α represented by the coloured dots $R_{\alpha,c}$, whereas the black dots show the run-up related to the energy conversion R_{α} . The red lines represent the quadratic fit with between α and R_{α} (solid) and the linear fit between α and $R_{\alpha,c}$ (dashed).

337 the terminal bore celerity to the total run-up in comparison to the terminal bore
 338 height for the $R_{\alpha,c}$ term. The solid red line in Figure 11 represents a quadratic
 339 fit to the R_{α} component which shows a good and significant correlation to α (r
 340 $= 0.894$ with an associated p-value of 0.004). Since the non-linear interaction
 341 term is also dependent on the terminal bore celerity and non-linear in nature,
 342 the correlation with α is weaker ($R = 0.268$ and a p-value of 0.002). On average,
 343 for all the bores within this dataset, the contribution to the total run-up from
 344 R_{α} 26%, the R_c term accounts for 27% while the contribution of $R_{\alpha,c}$ is 47%.
 345 This analysis indicates that while the collapse and terminal celerity mechanisms
 346 contribute equally to the total run-up, the non-linear interaction term clearly
 347 dominates. This highlights the significance of including celerity component to
 348 approximate run-up, suggesting that its direct and indirect impact on the run-
 349 up and bore collapse process should not be neglected. With the inclusion of
 350 bore front celerity, the run-up can be estimated more accurately from measured
 351 bore collapse parameters. Using (8) and the average observed α ($\overline{\alpha_{obs}} = 0.889$)
 352 the RMS error for the run-up is reduced by approximately 10% to 0.295 m.

353 In the previous model by Baldock and Holmes [8], C can be seen as a reposi-
 354 tory of all unknown processes and interactions that occur between the inner surf
 355 and swash zone [36]. A direct link between α and C with terminal bore celerity
 356 or other measured components was sought to enable improved prediction of in-
 357 dividual wave run-up based on measured bore properties. Attempts were made
 358 to relate C and α to the incident bore front slope, the slope of the free-surface
 359 behind the bore front (see green dashed line in Figure 4) and the relative angle
 360 between the two, but no significant relationship could be found other than a
 361 weak trend found between back angle and C . Landward-sloping free surfaces
 362 behind the bore front were found to be associated with greater C -values, while
 363 seaward-slope free surfaces behind the bore front tended to have lower C -values.

364 **5. Conclusion**

365 A 2D LiDAR scanner has been used to obtain high spatial and temporal
366 resolution water surface profiles illustrating the complex bore collapse process.
367 From the 2D LiDAR data, it is possible to accurately obtain the bore collapse
368 point in space and time and extract a range of parameters including bore celerity,
369 bore slope and bore height at collapse. It is observed that the terminal bore
370 celerity at collapse is consistently non-zero and the bore collapse front slope is
371 in the range 12-35 degrees to the horizontal.

372 In agreement with other studies, a clear relationship between wave run-up
373 and bore height at collapse was observed. However, the measurements obtained
374 by tracking incident bores using the LiDAR enabled further analysis of the
375 underlying mechanisms causing wave run-up. This indicates that terminal bore
376 celerity at the point of bore collapse contributes significantly to individual wave
377 run-up and is strongly influenced by bore-bore interactions in the inner surf
378 zone. Term-expansion of an existing ballistic-type model to describe the run-up
379 of individual waves in combination with the novel measurements showed that
380 the total run-up R could be separated into three different components: bore
381 collapse conversion efficiency, bore celerity and their non-linear interaction. In
382 the dataset presented here, the bore collapse and terminal bore celerity have an
383 equal contribution, while the non-linear interaction between the two dominates
384 the total run-up. This analysis of the driving mechanisms which cause wave
385 run-up, shows that the former conversion coefficient C can be separated into
386 three components: the bore collapse, terminal bore-celerity and their non-linear
387 interaction. Hence, including terminal celerity with collapsing bores cannot be
388 neglected when investigating or predicting wave run-up at sandy beaches.

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