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Billson, O

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Article

# Storm Waves at the Shoreline: When and Where Are Infragravity Waves Important?

Oliver Billson <sup>1,2,\*</sup>, Paul Russell <sup>1</sup> and Mark Davidson <sup>1</sup>

<sup>1</sup> Coastal Process Research Group, University of Plymouth, Drakes Circus, Plymouth, PL4 8AA, UK; P.Russell@plymouth.ac.uk (P.R.); M.Davidson@plymouth.ac.uk (M.D.)

<sup>2</sup> School of Geography and Planning, University of Liverpool, Brownlow Hill, Liverpool, L69 3BX, UK

\* Correspondence: Oliver.Billson@Liverpool.ac.uk

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**Abstract:** Infragravity waves (frequency,  $f = 0.005\text{--}0.05$  Hz) are known to dominate hydrodynamic and sediment transport processes close to the shoreline on low sloping sandy beaches, especially when incident waves are large. However, in storm wave conditions, how their importance varies on different beach types, and with different mixes of swell and wind-waves, is largely unknown. Here, a new dataset, comprised of shoreline video observations from five contrasting sites (one low-sloping sandy beach, two steep gravel beaches and two compound/mixed sand and gravel beaches), under storm wave conditions (deep water wave height,  $H_0$  up to 6.6 m and peak period,  $T_p$  up to 18.2 s), are used to assess: how the importance and dominance of infragravity waves varies at the shoreline? In this previously unstudied combination of wave and morphological conditions, significant infragravity swash heights ( $S_{ig}$ ) at the shoreline in excess of 0.5 m were consistently observed on all five contrasting beaches. The largest infragravity swash heights were observed on a steep gravel beach, followed by the low-sloping sandy beach and lowest on the compound/mixed sites. Due to contrasting short wave breaking and dissipation processes, infragravity frequencies were observed to be most dominant over gravity frequencies on the low-sloping sandy beach, occasionally dominant on the gravel beaches and rarely dominant on the compound/mixed beaches. Existing empirical predictive relationships were shown to parametrise  $S_{ig}$  skillfully on the sand and gravel beaches separately. Deep water wave power was found to accurately predict  $S_{ig}$  on *both* the sand and gravel beaches, demonstrating that, under storm wave conditions, the wave heights and periods are the main drivers of infragravity oscillations at the shoreline, with the beach morphology playing a secondary role. The exception to this were the compound/mixed beach sites where shoreline infragravity energy remained low.

**Keywords:** infragravity; swash; storm; gravel beach; parameter space; field observations

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## 1. Introduction

### 1.1. Background and Literature

Infragravity (IG) waves (frequency  $f = 0.005\text{--}0.05$  Hz) are known to play a crucial role in storm impacts such as overwashing and inundation [1], dune erosion and barrier breaching [2] and beach face erosion [3], becoming increasingly dominant toward the shoreline [4,5]. As such, gaining an understanding of their influence on hydrodynamics [6–8] and sediment transport is vitally important to sustaining coastal infrastructure.

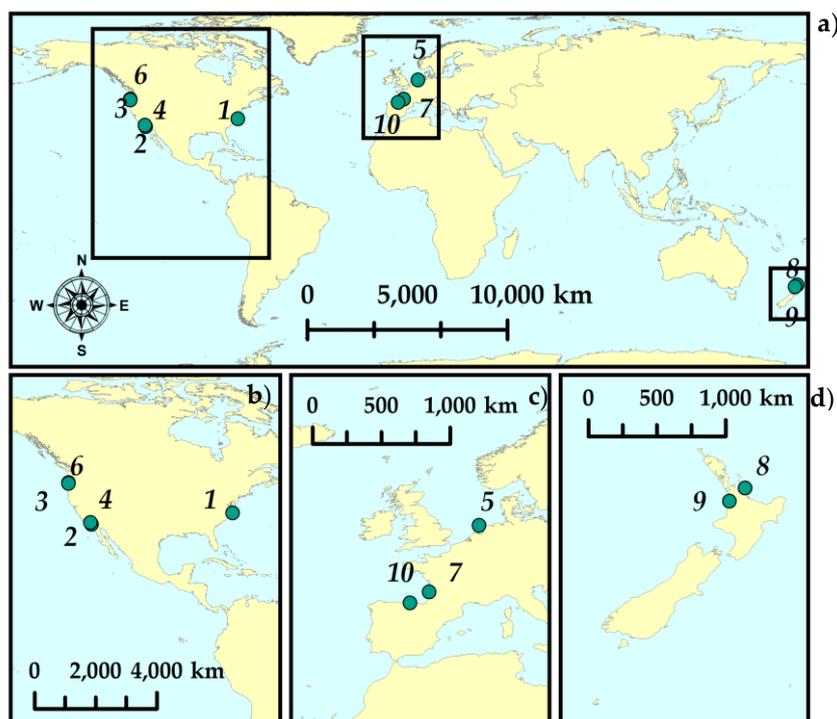
In particular, the importance of IG waves in runup (the maximum vertical extent of wave uprush on the beach) has been established on low sloping sandy beaches [9]. Defined as the elevation of the shoreline above still water level, runup comprises a mean (set-up) and oscillatory component (swash) [10]. The swash transfers energy from the waves to the shore, playing a key role

in sediment transport, and can drive significant erosion during storms [11]. Swash is often separated into infragravity and gravity ( $f = 0.05\text{--}1$  Hz) frequency bands and quantified as significant swash height,  $S$ , equal to  $4\sigma$ , where  $\sigma^2$  is vertical runup variance in each band. While infragravity swash has previously been studied on a range of sandy beaches, how its importance varies on different beach types, and with different mixes of swell and wind-waves, is currently unknown. Environmental conditions and significant infragravity swash height ( $S_{ig}$ ), observed during 13 prominent experiments which underpin much of the understanding of infragravity swash processes on sandy beaches, are presented in Table 1 and their locations and relative exposure in Figure 1. Mean values were obtained from [12] and ranges from [13]. Further information and reference to published works relating to the data in Table 1 can also be found in [10].

**Table 1.** Summary (range and mea of environmental parameters and significant infragravity swash height ( $S_{ig}$ ) sampled during previous research<sup>1</sup>. Subscript 0 indicates parameters calculated using deep water values, linearly deshoaled to 80 m water depth. N = number of observations.

Map No.	Site/Experiment	Date	$H_0$ (m)	$T_p$ (s)	$\tan \beta$	D50 (mm)	$\xi_0$	N	$S_{ig}$ (m)
1	Duck, NC (USA) Duck82	5–25 Oct 1982	0.7–4.1 1.71	6.3–16.5 11.9	0.09–0.16 0.12	0.75	0.68–2.38 1.44	36	0.4–2.4 1.2
2	Scripps, CA (USA)	26–29 Jun 1989	0.5–0.8 0.69	10–10 10	0.03–0.06 0.04	0.20	0.4–0.92 0.6	41	0.3–0.7 0.33
1	Duck, NC (USA) Duck90–Delilah	6–19 Oct 1990	0.5–2.5 1.40	4.7–14.8 9.3	0.03–0.14 0.09	0.36	0.44–1.70 0.90	138	0.4–1.7 0.91
4	San Onofre, CA (USA)	16–20 Oct 1993	0.5–1.1 0.8	13–17 14.9	0.07–0.13 0.1	-	1.6–2.62 2.2	59	0.5–1.8 0.96
3	Gleneden, OR (USA)	26–28 Feb 1994	1.8–2.2 2.1	10.5–16 12.4	0.03–0.11 0.08	-	0.26–1.2 0.9	42	0.9–1.9 1.4
5	Tershelung (Netherlands)	2–22 Apr 1994 1–21 Oct 1994	0.5–3.9 1.9	4.8–10.6 8.3	0.01–0.03 0.02	0.22	0.07–0.22 0.1	14	0.2–0.9 0.54
1	Duck, NC (USA) Duck94	3–21 Oct 1994	0.7–4.1 1.5	3.8–14.8 10.5	0.06–0.1 0.08	0.20–2.5	0.33–1.43 0.81	52	0.5–2.2 0.81
6	Agate, OR (USA)	11–17 Feb 1996	1.8–3.1 2.5	7.1–14.3 11.9	0.01–0.02 0.02	0.20	0.1–0.19 0.15	14	0.7–1.5 1.1
1	Duck, NC (USA) Duck97–SandyDuck	3–30 Oct 1997	0.4–3.6 1.3	3.7–15.4 9.5	0.05–0.14 0.09	0.90–1.66	0.34–3.22 1.1	95	0.3–1.8 0.88
7	Truc Vert (France)	3 Mar– 13 Apr 2008	1.1–6.4 2.4	11.2–16.4 13.7	0.05–0.08 0.06	0.35	0.49–0.9 0.68	88	0.63–2.37 1.3
8	Tairua (New Zealand)	15–17 Jul 2008	0.7–1.0 -	9.9–12.5 11.0	0.09–0.13 -	0.4	1.4–2.25 -	25	0.6–0.95 0.75
9	Ngarunui (New Zealand)	8–9 Nov 2010	0.6–1.3 -	8.1–12.4 9.0	0.01–0.03 -	0.29	0.13–0.42 -	32	0.24–0.90 0.60
10	Somo (Spain)	4 May 2016	0.3–0.7 0.31	11.0–13.0 12.0	0.04–0.1 0.06	0.28–0.35	0.9–2.5 1.5	12	0.28–0.90 0.57

<sup>1</sup>Further information and datasets are available for sites 1–6: <https://pubs.usgs.gov/ds/602/#intro>; site 7: [6]; site 8 [14]; site 9 [15] and site 10: <https://data.mendeley.com/datasets/6yh2b327gd/4>.



**Figure 1.** Location of sites previously studied, listed in Table 1, showing variation between ocean-facing and fetch-limited sites: (a): World map; (b): USA; (c): Western Europe; (d): New Zealand.

Table 1 and Figure 1 highlight the combined importance of incident wave height and period to infragravity response at the shoreline. The four experiments where mean values of  $S_{ig}$  exceeded 1 m were exposed, open ocean sites, where both wave height and period were large (Duck82, Glenderon, Agate (Figure 1b) and Truc Vert (Figure 1c)). In contrast, despite large wave heights ( $H_0$  up to 3.9 m), short wave periods (mean  $T_p$  8.3 s), typical of the fetch limited Tersheling (Figure 1c), resulted in a low mean  $S_{ig}$  of 0.54 m.

In an attempt to understand the conditions which result in infragravity frequencies becoming important in the swash, much of the sandy beach data presented in Table 1 has been used to try and establish empirical relationships between  $S_{ig}$ , wave statistics and beach gradient. One of the first attempts to parameterise  $S_{ig}$  in this way was that of [16] who demonstrated that monochromatic wave runup scaled well with the Iribarren number:

$$\xi = \tan \beta / (H_0 L_0)^{1/2} \tag{1}$$

where  $\tan \beta$  is the beach gradient, and  $H_0$  and  $L_0$  are the deep water (offshore) significant wave height and wavelength respectively. The Iribarren number represents a dynamic beach steepness comparing beach slope to wave steepness, with application of Equation (1) to natural data sets facilitating the examination of runup in a morphodynamic parameter space [17]. As such, the terms in Equation (1) form the basis of many runup (and more specifically) swash predictors.

The pioneering work of [18] demonstrated a contrasting relationship between  $H_0$  and horizontal swash in the gravity and infragravity band, whereby swash was seen to be saturated in the gravity band but increased linearly with  $H_0$  in the infragravity band. Other researchers have since reported a similar linear relationship between vertical significant infragravity swash height ( $S_{ig}$ ) and  $H_0$ , with a range of constants of proportionality [6,19,20].

Attempting to find a universal parametrisation of  $S_{ig}$ , applicable to a range of sandy beaches, [10] found that including a wavelength term,  $(H_0 L_0)^{1/2}$ , improved predictions of  $S_{ig}$ , a result corroborated under high energy conditions observed at a single site by [6]. While effective at parameterising infragravity energy in the swash, [8] found that, at an exposed sandy site, a stronger

correlation existed between infragravity wave height in the surf zone and  $H_0^2 T$ , citing its proportionality to deep water wave power as more physically correct than Stockdon's  $(H_0 L_0)^{1/2}$ .

While observations focusing specifically on infragravity swash are almost entirely limited to sandy environments, an example of similar research on gravel beaches is that of [17] who, without focusing specifically on infragravity frequencies, assessed runup elevation under extreme conditions, on a range of gravel beaches. They found that existing runup predictors developed on sandy beaches, including that of Stockdon, under-predicted runup elevation on gravel beaches, instead finding that  $(\tan \beta^{1/2} H_0 T_p)$  provided a more accurate estimate.

Observations of infragravity swash under storm wave conditions are limited to a small number of experiments carried out on sandy beaches, as discussed in Section 1.1 and presented in Table 1. Further, infragravity swash behaviour is yet to be compared on sand, gravel and mixed sediment beaches.

### 1.2. Scope of Research

The present research stands in contrast to previous contributions by observing infragravity waves in a wide range of high energy swell and wind-wave conditions across a range of beach morphologies and grain sizes not previously explored. Here, video observations of the shoreline under storm wave conditions ( $H_0$  up to 6.6 m and  $T_p$  up to 18.2 s) were collected at four contrasting beaches in the south of the UK. These were complimented by previously published data from one additional site, to produce a unique and novel dataset comprising observations of storm waves on one sandy beach, two gravel beaches and two compound/mixed sand and gravel beaches.

The present work aims to assess: *how the importance and dominance of infragravity waves varies at the shoreline?* by:

1. Compiling a dataset comprising observations in previously unrecorded combinations of wave and morphological conditions.
2. Assessing how swash height in the gravity ( $S_g$ ) and infragravity bands ( $S_{ig}$ ) relates to offshore wave height ( $H_0$ ).
3. Examining how accurately previous parameterisations of  $S_{ig}$ , developed over a limited range of wave and morphological conditions, can be used to predict  $S_{ig}$  across the range of morphologies in the new dataset and whether an improved parameter can be obtained.
4. Developing a conceptual model to illustrate the importance of infragravity swash at the shoreline on a wide variety of beach morphologies under a wide range of high energy swell and wind-wave combinations.

## 2. Materials and Methods

### 2.1. Description of Field Sites

Five beaches in the South of England, UK, were specifically selected as study sites owing to their contrasting wave climates, and morphology (Figure 2a–e). From west to east: One low-sloping sandy beach, Perranporth (PPT), two steep gravel beaches, Beesands (BEE) and Chesil (CSL) and two compound/mixed sand and gravel sites, Camber (CAM) and Minsmere (MMR). These two sites can be divided, according to the classification of [21], into a composite beach, (CAM) and a mixed sand and gravel beach (MMR).



**Figure 2.** Location (Top left corner), photographs (left) and representative profiles (right) of: (a): Perranporth (PPT); (b): Beesands (BEE); (c): Chesil (CSL); (d): Camber (CAM); (e): Minsmere (MMR). Dashed black lines on profiles represent mean high and low water spring tidal elevation. Chesil photograph (c) is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license (<https://creativecommons.org/licenses/by-sa/3.0/deed.en>).

Quality controlled, 30-min averages of significant wave height ( $H_s$ ) and wave period ( $T_p$ ) at each of the five sites collected at local ‘directional wave rider’ buoys were downloaded from [channelcoast.org](http://channelcoast.org). This time series of  $H_s$  and  $T_p$  was then linearly interpolated to obtain values every 20 min, consistent with the length of data runs measured at the shoreline (Section 2.2). Located within 5 km of the relevant beach, mean depths at the wave buoys ranged from 9.8 to 23 m. Consistent with the examples in Table 1, estimates of offshore significant wave height ( $H_0$ ) were obtained by linearly deshoaling  $H_s$  to a depth of 80 m. The range and mean  $H_0$  and  $T_p$  observed during data collection at each of the five sites are listed in Table 2. Maximum values are placed in bold to emphasise the unique experimental conditions.

In order to define wave conditions as ‘extreme’, 95% threshold values of offshore wave height ( $H_{0.95}$ ) and period ( $T_{p.95}$ ) were calculated, a statistic frequently used to define storm events [22]. The full data record at each local wave buoy, which in all cases was at least 6 years in length, was used to calculate  $H_{0.95}$  and  $T_{p.95}$  (Table 2). This statistic facilitates comparison of observed wave conditions between sites of contrasting exposure. Waves in excess of the 95th percentile  $H_0$  were observed at all 5 sites, with particularly extreme named storm events being observed at Beesands (*‘Emma’*), Camber (*‘Angus’*) and Chesil (*‘Petra’*), where mean  $H_0$  for the entirety of the experiment exceeded the 95th percentile (Table 2).  $T_{p.95}$  was exceeded at three of the five sites (Perranporth, Chesil and Beesands) which were susceptible to swell. Further, comparing Tables 1 and 2, it can be seen that the largest  $H_0$  (6.6 m at Chesil) and the largest  $T_p$  (18.2 s at Perranporth) in the new dataset exceeded the maximum values in Table 1 ( $H_0 = 6.4$  m Truc Vert) and ( $T_p = 16.5$  s Duck 82). This demonstrated that highly unusual wave heights and periods were observed during all five deployments, an innovative aspect of this work.

Typical ranges of  $\xi_0$ , calculated to indicate the prevailing wave breaking regime at each site using Equation (1) are presented in Table 2. Breaker types as defined by [23] were taken as surging ( $\xi_0 > 3.3$ ), plunging  $0.5 < \xi_0 < 3.3$  and spilling  $\xi_0 < 0.5$  respectively. It can be seen that Perranporth, the low sloping sandy beach is typically dominated by spilling breakers. At the mixed/compound sites breakers are typically spilling or plunging. On the steep gravel beaches, breakers range between plunging at Beesands to plunging and surging at Chesil.

**Table 2.** Site descriptors; storm name and return period in years; 95% exceedance threshold offshore wave height ( $H_{0.95}$ ) and period ( $T_{p.95}$ ); range of  $H_0$  and  $T_p$  over which measurements in the new dataset were collected with maximum values quoted in bold.

Site	Description	Storm Name	$H_{0.95}$ (m)	$H_0$ (m) Range	$T_{p.95}$ (s)	$T_p$ (s) Range	$\xi_0$ Typical Range *
		Date Return Period (Years)					
<b>Perranporth</b>	High energy, dissipative sandy beach, exposed to oceanic swell and locally generated wind waves	<i>Unnamed storm</i> 31st Jan–7th Feb 2017 1 in 1	3.1	1.6– <b>3.2</b>	15.4	11.1– <b>18.2</b>	0.14–0.33
<b>Chesil</b>	Medium energy, reflective gravel beach, partially exposed to oceanic swell and locally generated wind waves	<i>‘Petra’</i> 5–6th Feb 2014 1 in 10	2.6	1.6– <b>6.6</b>	15.3	10.3– <b>16.7</b>	1.1–5.5
<b>Beesands</b>	Low energy, reflective gravel beach, dominated by wind waves and occasional refracted oceanic swell	<i>‘Beast from the east/Emma’</i> 20–27th Feb 2018 1 in 60	1.9	0.4– <b>3.3</b>	14.3	5.1– <b>15.0</b>	0.5–2.4
<b>Camber</b>	Low energy, fetch limited, compound beach with steep gravel upper and low slope sandy terrace	<i>‘Angus’</i> 4–6th Nov 2016 1 in 10	2.0	0.9– <b>3.8</b>	11.1	5.5– <b>10.0</b>	0.06–1.5
<b>Minsmere</b>	Low energy, fetch limited, mixed sand and gravel beach. Steep upper shore face, low slope below low water. Submerged offshore bar	<i>Unnamed storm</i> 6–8th Jan 2018 1 in 5	1.9	0.52– <b>2.5</b>	8.3	3.3– <b>7.7</b>	0.14–1.5

\* Typical range of  $\xi_0$  taken as: The average value of  $\xi_0$ , calculated over the data record at each wave buoy,  $\pm 1$  standard deviation. Representative slope(s) ( $\tan \beta$ ) were selected per site as follows: PPT = 0.02; BEE = 0.1; CSL = 0.25; CAM = 0.02 (lower), 0.1 (upper); MMR = 0.03 (lower), 0.13 (upper). For the sites with 2 slopes, the lower value was used to calculate the lower end of the range, and the upper value to calculate the upper value  $\pm$ .

## 2.2. Field Data Collection and Video Data Processing

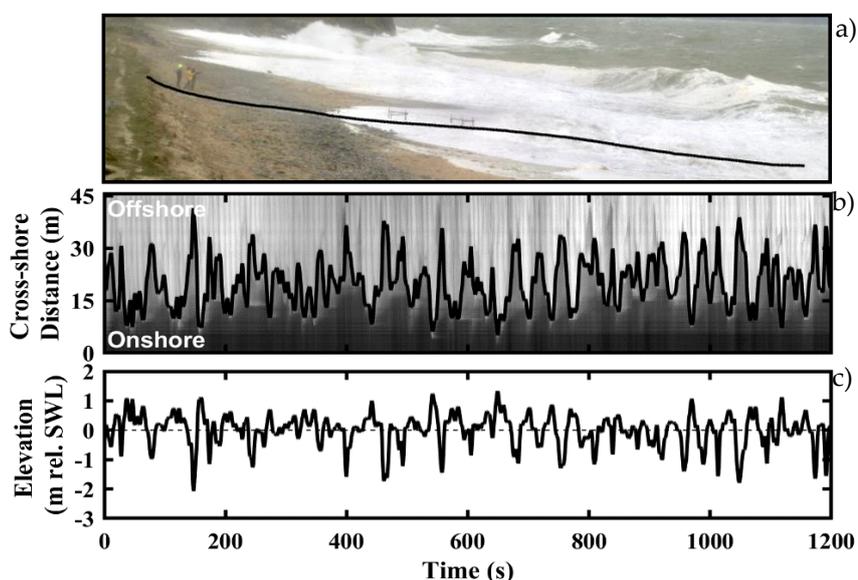
At each of the sites, data collection was targeted around storm events using Plymouth University’s Rapid Coastal Response Unit (RCRU). The RCRU is versatile and sheltered base, facilitating the collection of hydrodynamic and topographic data during extreme storms. Housing an array of in-situ and remote instrumentation, the unit is highly mobile and can be deployed with just hours notice, in order to capture the approach, peak and decay of a storm [24–26]. In the present example, a 10 m tower, equipped with high resolution video cameras fed data to a computer inside the RCRU, storing over 70 h of video images across the 5 deployments.

At all sites a representative cross-shore profile ('analysed profile' Figure 3a) was carefully selected to monitor runup, minimising the impact of longshore sediment transport, headlands or sea defenses on the beach profile. Daily monitoring of the profile was carried out using real time kinematic GPS, capturing changes every other low tide. A value of beach slope ( $\tan \beta$ ) was defined per 20-min data-run as, the average gradient between the 2% exceedance level of runup (R2%) and still water level (SWL), minus twice the offshore significant wave height ( $SWL-2H_0$ ), following [17].

In order to calculate swash statistics, images captured at a rate of 4 Hz by a Pointgrey Grasshopper camera fitted with a 25 mm lens were used to produce pixel stacks as follows. Ground control points, where both the real world and image positions were known, were used to generate a geometry solution, facilitating conversion of co-ordinates from a 2-D (U,V) image to a 3-D (X,Y,Z) real world system and vice versa. The method used here for obtaining photogrammetric relationships was developed by [27] and is widely used in comparable works [6,10,17]. The line of pixels corresponding to the 'analysed profile' (Figure 3a) were extracted from each image and stacked horizontally against time. The blue-red ratio and intensity of each pixel was evaluated and threshold values defined which corresponded to the discrete transition from dry beach to swash, after [10], yielding a digitized time series of swash. Finally, this was converted from UV to XY space to produce a time series of horizontal swash (Figure 3b) with the elevation (Z) associated with each cross shore position used to quantify vertical swash height (Figure 3c). 8-point unweighted sliding-average frequency smoothed spectral estimates were computed for each 20-min time series of vertical swash (Figure 4b,d,f,h,j), each with 16 degrees of freedom. The same frequency smoothing was applied to the offshore spectral estimates (Figure 4a,c,e,g,i). These were calculated using 20-min time series of raw surface elevation, collected at local wave buoys. Spectral variance was used to calculate total significant swash height (S) and separate incident ( $S_g$ ) ( $f = 0.05-0.3$  Hz) and infragravity ( $S_{ig}$ ) ( $f = 0.003-0.05$  Hz) band heights according to Equation (2):

$$S = 4\sqrt{\sum_{f1}^{f2} PSD(f)\Delta f} \tag{2}$$

where,  $f1$  and  $f2$  are the upper and lower frequency bounds of S,  $S_g$  or  $S_{ig}$  respectively,  $PSD$  is power spectral density,  $f$  is frequency and  $\Delta f$  is bandwidth in (Hz).



**Figure 3.** Video processing technique: Example from 26 February 2018 from 15:30–15:50 at Beesands: (a): Analysed profile to be extracted (black line); (b): Pixel stack with shoreline detected/ time series of horizontal swash (black line); (c): Vertical swash time series relative to still water level (SWL).

### 3. Results

#### 3.1. Environmental Conditions

Data collection was targeted around extreme storm wave events at each of the five sites, summarised in Table 3. At Chesil, both exceptionally long period waves (<16.7 s) in excess of the 95th percentile and shorter period swell waves (>10 s) yielded a mean period of 13.8 s. Perranporth was dominated by exceptionally long period swell waves with mean  $T_p$  (15.7 s) in excess of the 95th percentile threshold. At Beesands, two days of small swell waves extended the upper limit of observed  $T_p$  to 15 s. However, the comparatively low mean  $T_p$  (7.4 s) demonstrates that the deployment was dominated by locally generated wind waves. Deployments at Minsmere and Camber were characterised by large wind waves, as reflected in the mean period of 7.7 s and 6.4 s respectively.

Of the 5 sites the largest significant infragravity swash height ( $S_{ig}$ ) (11.4 m) and largest mean  $S_{ig}$  (5.1 m) was observed at Chesil. The extreme heights can be explained by the exceptionally high beach slope  $\tan \beta < 0.38$  and wave heights  $H_0 < 6.6$  m and are comparable to the exceptionally high runup values obtained by [17] during the same experiment (R2% up to 13 m). The second largest  $S_{ig}$  heights were observed at Perranporth, a site more typically associated with infragravity dominance. While the mean (2.2 m) and largest (3.6 m) observed  $S_{ig}$  were smaller than observed at Chesil, Perranporth was the only site where  $S_{ig}$  was always above 1 m. Significant levels of infragravity energy were also present in the swash at Beesands, where  $S_{ig}$  heights of up to 2.3 m and a mean height of 1.3 m were observed. The lowest  $S_{ig}$  heights were observed at the compound/mixed sand and gravel sites, Camber and Minsmere, where the maximum  $S_{ig}$  (0.81 and 0.68 m respectively) was lower than mean  $S_{ig}$  observed at any other site.

**Table 3.** Summary (range and mean) of environmental parameters sampled during the presented research. Subscript 0 indicates parameters calculated using deep water values linearly deshoaled to 80 m depth. N = number of 20 min data runs.

Site/Experiment	Date	$H_0$ (m)	$T_p$ (s)	$\tan \beta$	$D_{50}$ (mm)	$\xi_0$	N	$S_{ig}$ (m)
Beesands, U.K.	20–27 Feb 2018	0.4–3.3	5.1–15.0	0.09–0.11	-	0.53–2.84	75	0.20–2.3
		2.0	7.4	0.10	5	0.71		1.3
Perranporth, U.K.	31 Jan–07 Feb 2017	1.6–3.2	11.1–18.2	0.02–0.08	-	0.19–0.96	31	1.1–3.6
		2.4	15.7	0.034	0.25	0.44		2.2
Camber Sands, U.K.	5–6 Nov 2016	0.9–3.8	5.5–10.0	0.02–0.10 *	0.33–10 *	0.059–1.1	16	0.30–0.81
		2.2	7.7	-	-	1		0.53
Minsmere, U.K.	6–8 Jan 2018	0.52–2.5	3.3–7.7	0.03–0.13 **	0.33–20 **	0.1–0.97	43	0.01–0.68
		1.6	6.4	-	-	0.21		0.33
Chesil, U.K.	5–6 Feb 2014	1.6–6.6	10.3–16.7	0.24–0.38	65	2.21–3.84	40	0.65–11.4
		3.9	13.8	0.32	-	3.7		5.1

\* Camber is a compound beach with a steeper gravel upper and low slope sandy lower; \*\* Minsmere is a mixed sand and gravel site (as reflected in the wide ranging  $D_{50}$  with a steep gravel upper and lower sloped lower profile.

### 3.2. Comparison of Spectra at Wavebuoy and Shoreline

Offshore spectra calculated at local wave buoys (Figure 4a,c,e,g,i) were compared to those calculated at the shoreline from time series of vertical swash (Figure 4b,d,f,h,j). The examples presented in Figure 4 were specifically selected as most clearly representing extreme conditions at each site. Times where  $H_{0.95}$  being exceeded coincided with high water ( $\pm 1.5$  h) were targeted in order to minimise contamination of the spectra with tidal signal.

The buoy spectra can be divided into swell dominated (Perranporth and Chesil, Figure 4a,c respectively) and wind-wave dominated (Beesands, Camber and Minsmere, Figure 4e,g,i respectively).

At the shoreline, spectra can be divided into three groups: Infragravity dominated due to dissipation of gravity energy and growth of IG energy (Perranporth and Beesands, Figure 4b,f respectively); high energy gravity and infragravity due to minimal dissipation (Chesil, Figure 4d); low energy in both bands, due to maximum dissipation (Camber and Minsmere, Figure 4h,j respectively).

At Perranporth, a single, significant peak in the gravity band of the wave buoy spectrum (0.056 Hz, 17.9 s) (Figure 4a) was replaced by a single significant peak in the infragravity band in the shoreline spectrum (0.011 Hz, 90 s) (Figure 4b). As a result significant gravity swash height ( $S_g = 0.57$  m) remaining at the shoreline was less than 1/5 of the offshore wave height in the gravity band ( $H_{sg} = 3.1$  m) and infragravity swash ( $S_{ig} = 2.5$  m) was roughly 6 times larger than offshore infragravity height ( $H_{sig} = 0.42$  m).

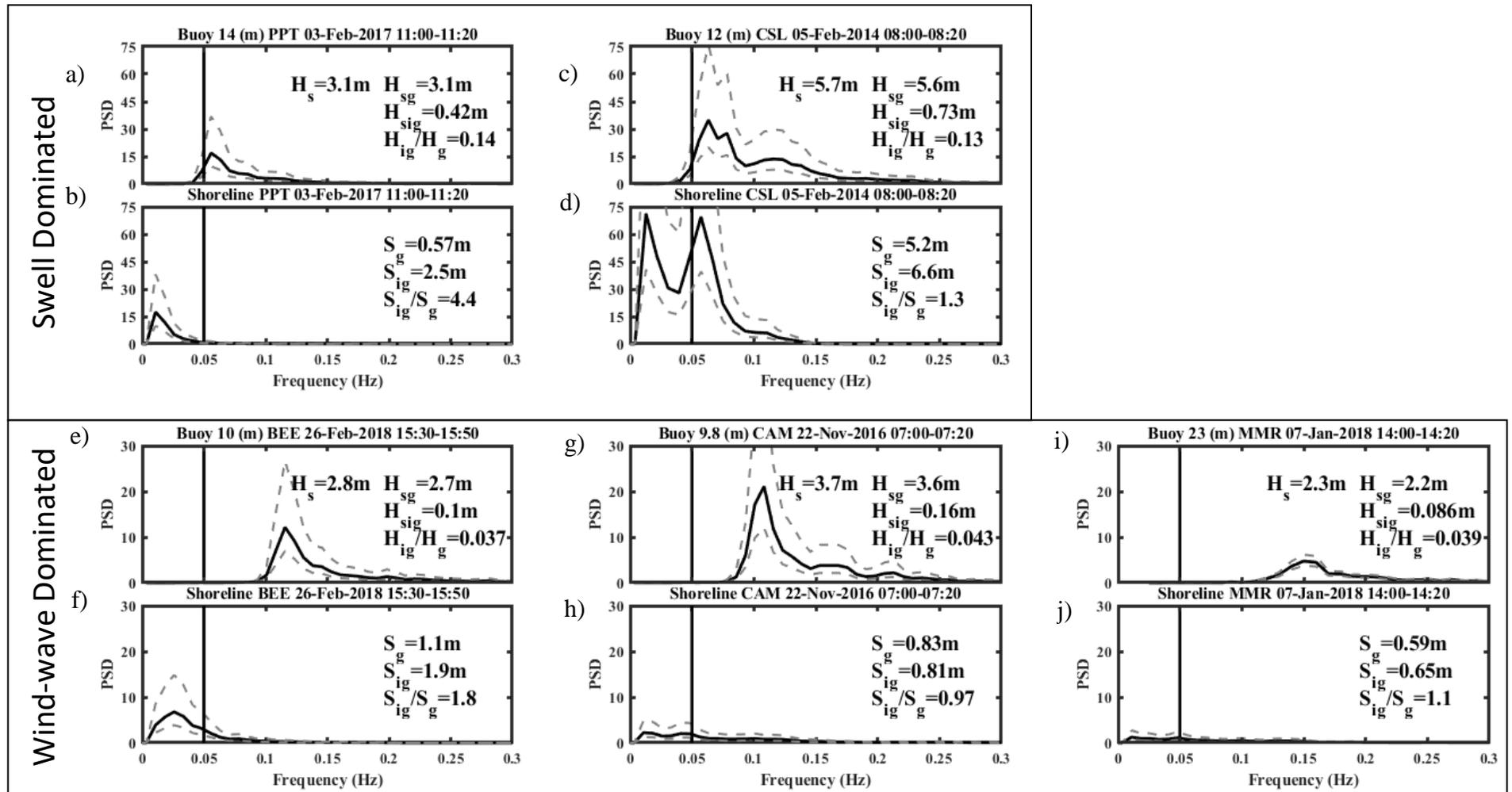
At Chesil, a single incoming peak (0.063 Hz, 15.8 s) in the gravity band of the wave buoy spectrum (Figure 4c) was maintained in the shoreline spectrum (Figure 4d). In addition, an IG peak at 0.013 Hz (77 s) was also present in the shoreline spectrum (Figure 4d). Significant wave and swash height were similar in the gravity band ( $H_{sg} = 5.6$  m,  $S_g = 5.2$  m) and increased by an order of magnitude between the buoy and the shoreline in the IG band ( $H_{sig} = 0.73$  m,  $S_{ig} = 5.2$  m).

The contrast in development of spectra between the buoy and the shoreline at Perranporth and Chesil resulted from differences in short wave breaking and dissipation. At Perranporth, incoming swell waves were efficiently dissipated across a wide surf zone as spilling breakers. At Chesil, dissipation of swell waves appeared to be minimal. The steep beach face and large, low-steepness incoming waves resulted in high energy surging and plunging breakers breaking directly on the beach face as a shore break, conserving the swell peak in the shoreline spectrum.

At the wind-wave dominated sites, a reduction in total energy from the buoy to the shoreline indicated energy dissipation, where steep storm waves produced spilling breakers on the shallow lower profile of the compound/mixed sites (Minsmere and Camber) and plunging breakers on the gravel site (Beesands).

At Beesands the shoreline spectrum (Figure 4f) shows energy at gravity band frequencies (incident wave peak, 0.12 Hz, 8.3 s) was dissipated with growth of a broad low frequency peak at 0.026 Hz (38 s). In the gravity band, swash height ( $S_g = 1.1$  m) reduced to around half that of  $H_{sg}$  (2.7 m) and in the infragravity band swash height ( $S_{ig} = 1.9$  m) was around 20 times larger than  $H_{ig}$  (0.10 m).

At Camber (Figure 4g) and Minsmere (Figure 4i) the majority of the incoming short wave energy (concentrated at wind-wave frequencies of around 0.11 Hz (9.1 s) and 0.15 Hz (6.0 s) respectively) was dissipated by the shoreline. This resulted in an absence of energy in the gravity band and a single low energy, low frequency peak in the shoreline spectra of both sites (Figure 4h,j).



**Figure 4.** Frequency smoothed wave spectra showing examples of simultaneous power spectral densities (PSD) offshore and at the shoreline. a,c,e,g and i: Waves measured at local wave buoys (solid black line). b,d,f,h and j: Vertical swash at the shoreline (solid black line). Both: 95% confidence interval (dashed grey line). Infragravity and gravity bands are separated by a vertical black line at 0.05 Hz. a + b = Perranporth (PPT), c + d = Chesil (CSL), e + f Beesands = (BEE), g + h = Camber (CAM), i + j = Minsmere (MMR).

### 3.2. Relationship between Swash and Offshore Wave Height ( $H_0$ )

Linear regression was used to assess the relationship between swash and offshore wave height, where a significant relationship at the 99.5% confidence limit was given by ( $p < 0.005$ ). Goodness of fit was summarised by correlation squared ( $R^2$ ) and root mean square error (RMSE) and the relationship quantified by regression slope ( $m$ ) and y-axis intercept ( $c$ ). Partitioning vertical significant swash height into the gravity ( $S_g$ ) and infragravity ( $S_{ig}$ ) bands highlighted their contrasting relationship with increasing offshore significant wave height ( $H_0$ ) (Figure 4, left and right respectively). Regression statistics for the relationship between  $S_{ig}$  and  $H_0$  at each of the sites individually and all sites combined are summarised in Table 4.

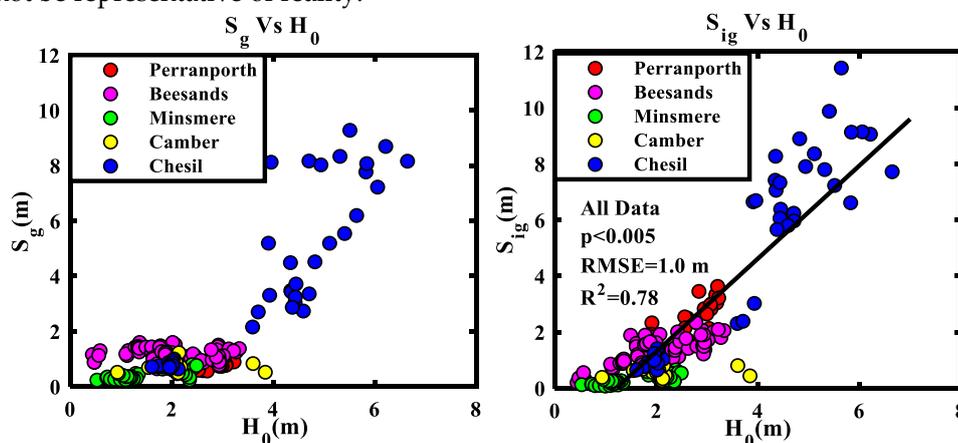
Significant swash height in the *gravity band* ( $S_g$ ) showed no significant increase with  $H_0$  ( $p > 0.005$ ) at all sites (except Chesil) implying saturation in the gravity band. As such, no line of best fit is shown in Figure 5 (left). At Chesil the increase of  $S_g$  with  $H_0$  shows that the gravity band was not saturated, resulting in large amounts of energy in the gravity band reaching the shoreline during large offshore wave conditions.

In contrast, significant swash height in the *infragravity band* ( $S_{ig}$ ) showed significant ( $p < 0.005$ ) and well correlated relationships ( $R^2 = 0.65\text{--}0.86$ ) with  $H_0$  at all sites (except Camber where  $p = 0.51$ ), showing that  $S_{ig}$  at the shoreline continued to increase with increasing  $H_0$ . The diversification in behaviour of swash in the gravity and infragravity band at all sites except Chesil shows that an increase in offshore wave height ( $H_0$ ) has no influence on gravity band swash heights, but leads to a linear increase of infragravity band swash heights. This implies that swash heights in the gravity band are saturated as a result of shortwave dissipation.

Both the largest offshore wave ( $H_0 < 6.7$  m) and shoreline infragravity swash heights ( $S_{ig} < 11.4$  m) were observed at Chesil, resulting in the steepest regression slope ( $m = 2.0$ ). The next largest  $S_{ig}$  heights were observed at Perranporth where  $S_{ig}$  ranged between 2.5–3.2 m for  $H_0 = 2.5\text{--}3.6$  m, over twice the  $S_{ig}$  heights (1.4–2.6 m) observed over the same range of  $H_0$  at Beesands. Despite their contrasting regression slopes, Chesil ( $m = 2.02$ ), Beesands ( $m = 0.51$ ) and Perranporth ( $m = 1.1$ ), showed comparable  $S_{ig}$  heights (0.75–2 m) when  $H_0$  ranged between 1.5–2.5 m.

The dataset as a whole showed a strong and significant linear correlation between  $S_{ig}$  and  $H_0$ , ( $p < 0.005$ ,  $R^2 = 0.78$ ) with a regression slope ( $m$ ) of 1.7 and an intercept ( $c$ ) of  $-2.0$ . The negative value of  $c$  caused the line of best fit to intercept the x-axis, facilitating the tentative definition of a threshold of  $H_0$  of around 1.3 m, above which infragravity energy becomes apparent in the swash.

The spread of values of  $S_{ig}$  for a given value of  $H_0$  at Chesil may be attributed to variability in the incoming wave conditions and/or the profile and beach slope over which waves were breaking and running up. It is feasible that values of  $H_0$  varied within a given 20-min run, resulting in variability in  $S_{ig}$ , owing to the linear relationship described in Figure 5. Further, gravel morphology is known to respond rapidly to wave forcing [28] and so the assumption of a constant slope throughout a tidal cycle may not be representative of reality.



**Figure 5.** Significant swash height against offshore significant wave height ( $H_0$ ). Left: Incident gravity band ( $S_g$ ). Right: infragravity band ( $S_{ig}$ ), where black line represent linear best fit for all sites.

**Table 4.** Relationship between significant swash in the infragravity band ( $S_{ig}$ ) and offshore wave height ( $H_0$ ).

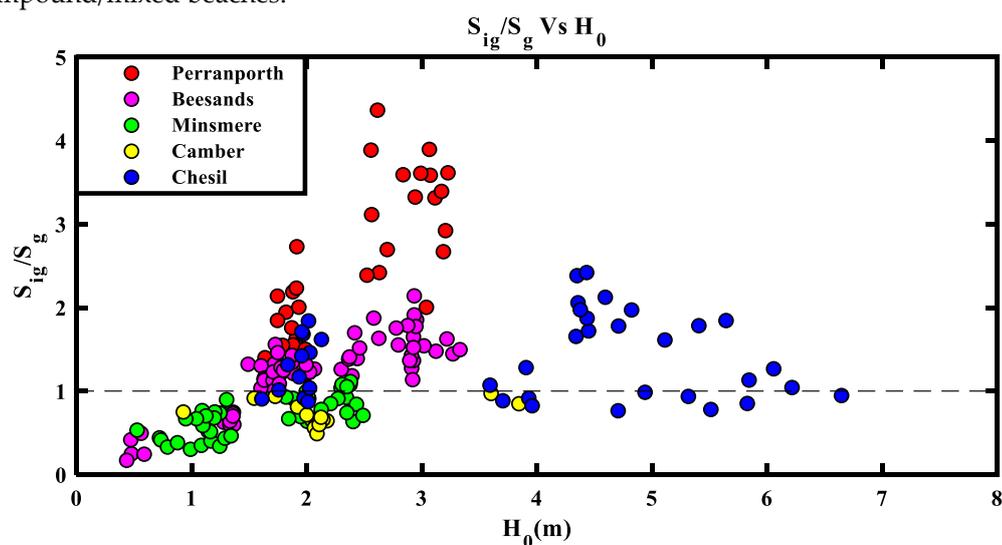
Site	Regression Slope ( $m$ )	Intercept ( $c$ )	$R^2$	$p$	RMSE (m)
CSL	2.02	-2.82	0.86	<0.005	1.29
PPT	1.06	-0.40	0.67	<0.005	0.44
BEE	0.51	0.30	0.65	<0.005	0.28
MMR	0.25	-0.06	0.67	<0.005	0.11
CAM	0.04	0.44	0.03	0.51	0.16
<b>Combined</b>	<b>1.66</b>	<b>-2.01</b>	<b>0.78</b>	<b>&lt;0.005</b>	<b>1.00</b>

The relative contributions of infragravity and gravity energy to the swash were assessed using the ratio  $S_{ig}/S_g$ , where values greater than (less than) one imply infragravity (gravity) dominance. Figure 5 shows the ratio  $S_{ig}/S_g$  plotted against  $H_0$ .

Perranporth was most dominated by infragravity swash, with an  $S_{ig}/S_g$  ratio of up to 4.4 for the largest incident wave conditions,  $H_0 = 3.2$  m (Figure 5). At Chesil, despite the absolute magnitude of  $S_{ig}$  being largest at this site (Figure 4, right), values of  $S_{ig}/S_g$  were smaller and varied between 0.7 and 2.5 across the entire observed range of wave heights ( $H_0 = 1.6$ – $6.8$  m). The difference in infragravity dominance at the two sites can in part be explained by the contrasting short wave dissipation pattern shown in Figure 4 (left). Spilling breakers dissipated much of their energy across the wide surf zone resulting in saturated values of  $S_g$  at Perranporth. In contrast, high energy plunging and surging breakers produced a shorebreak on the steep beach face at Chesil, resulting in a lack of dissipation and  $S_g$  increasing linearly with  $H_0$ .

Infragravity dominance increased with offshore wave height ( $H_0$ ) at Beesands. However, it can be seen from Figure 6 that  $S_{ig}/S_g$  at Beesands increased at a lower rate than Perranporth, implying that, for a given wave height, infragravity frequencies were less dominant. Unlike at Perranporth, short wave dominance ( $S_{ig}/S_g < 1$ ) was observed at Beesands. At this site specifically, a transition from gravity dominated to infragravity dominated swash occurred at a threshold of  $H_0 1.5$  m.

At Minsmere, the ratio of  $S_{ig}/S_g$  increased with low values  $H_0 (<1.3$  m) but crucially, barely exceeded 1, signifying gravity dominance. At Camber, no relationship with  $H_0$  was apparent, with the maximum observed ratio of  $S_{ig}/S_g = 0.9$ . This clearly demonstrated that, even during large waves ( $H_0 > 1.3$  m), infragravity frequencies rarely became dominant over gravity frequencies in the swash on the compound/mixed beaches.



**Figure 6.**  $S_{ig}/S_g$  against  $H_0$ . Transition from  $S_g$  (below) to  $S_{ig}$  dominated (above) (horizontal dashed line).

### 3.3. The Role of Wave Height, Period and Beach Slope

In addition to wave height, previous research has highlighted the potential importance of wave period and beach slope in the prediction of significant infragravity swash height ( $S_{ig}$ ). As such, in the Sections 3.3.1–3.3.3, three predictors of  $S_{ig}$  are applied to the presented new dataset and the strength of relationship assessed using linear regression and bias as:

$$\text{Bias} = \sum(X_{\text{predicted}} - X_{\text{observed}}) / n \tag{3}$$

where  $n$  represents the number of observations in both  $X_{\text{predicted}}$  and  $X_{\text{observed}}$ .

In addition to the combinations of wave and beaches statistics presented in Sections 3.3.1–3.3.3 ( $(H_0L_0)^{0.5}$ ,  $(\tan \beta)^{0.5} H_0 T_p$ ,  $(H_0^2 T)$ ), the following parameters were tested and found to show weak or no significant relationship with  $S_{ig}$ :  $\tan \beta (H_0 L_0)^{0.5}$ ,  $(\tan \beta H_0 L_0)^{0.5}$ ,  $(\tan \beta)^{0.5} (\tan \beta)^{0.5} H^2 T$ , and as such are not presented.

#### 3.3.1. Stockdon (S2006)–Sandy Beaches

Equation (4), [10](S2006) was developed empirically using a range of data from 10 sandy beaches:

$$S_{ig} = 0.06(H_0L_0)^{0.5} \tag{4}$$

where  $H_0$  is deep water wave height and  $L_0$  deep water wave length. Note that Stockdon forced the intercept ( $c$ ) through the origin.

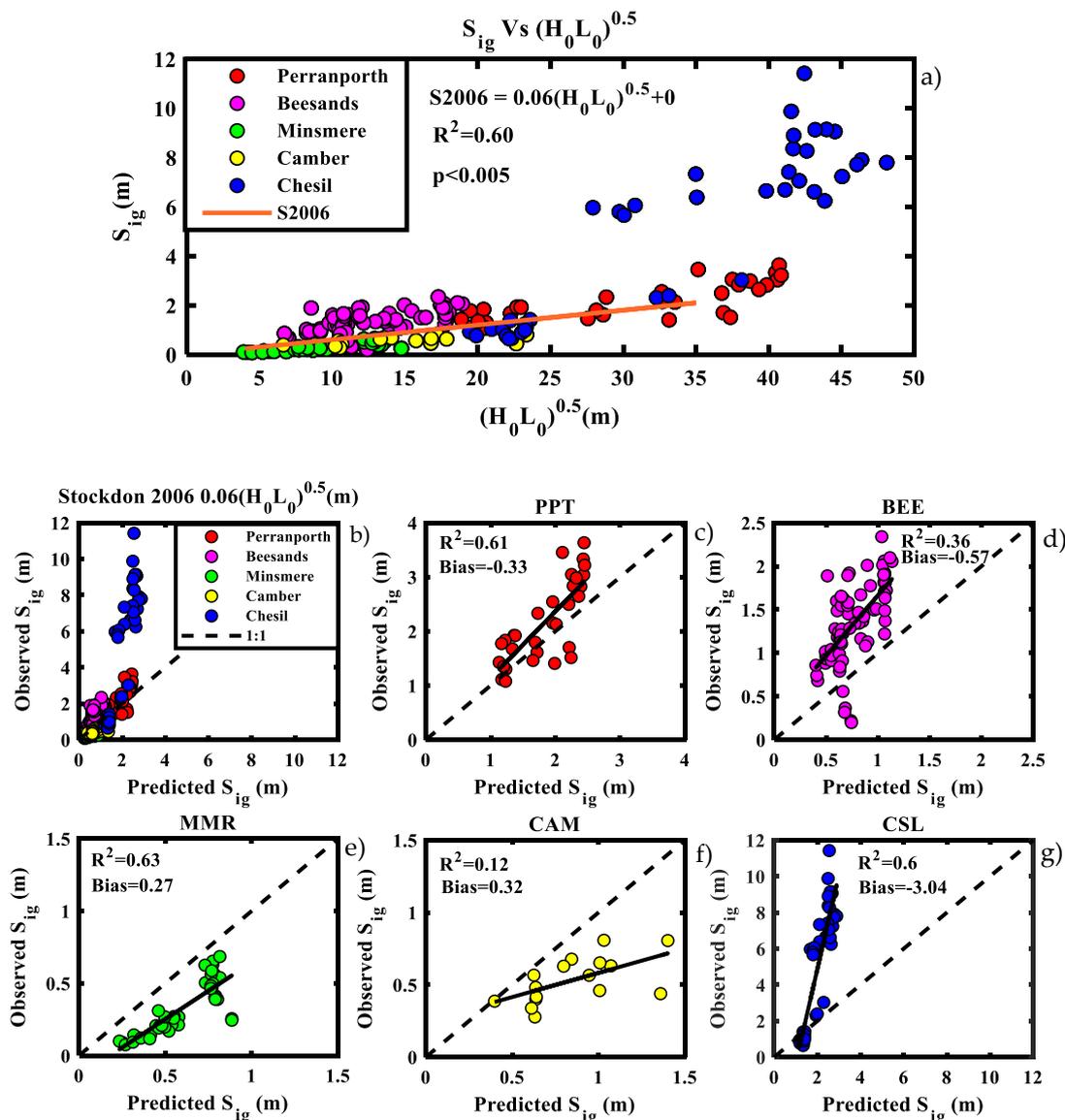
$S_{ig}$  observed at our five sites was plotted against  $(H_0L_0)^{0.5}$  to assess how the relationship compared with Stockdon’s observations (Figure 7a), yielding a significant correlation ( $p < 0.005$ ) at all sites except Camber, with a variety of regression slopes.

$S_{ig}$  at Perranporth (red points) plotted well with the S2006 equation (orange line) over a comparable range of  $(H_0L_0)^{0.5}$  (20–35 m), an unsurprising result, given the similarity of Perranporth to the beaches in Stockdon’s dataset. The majority of the Beesands data plotted above the S2006 line (Stockdon under-predicting), while the compound/mixed sites fell on or narrowly below it (Stockdon over-predicting). At Chesil, moderate values of  $(H_0L_0)^{0.5}$  (19–24 m) matched closely the S2006 line, while large values were severely under-predicted, implying that infragravity frequencies in the swash were enhanced under high energy conditions at this site.

The largest  $S_{ig}$  values observed at Perranporth ( $> 2.5$  m) were slightly under-predicted by S2006, resulting in a negative bias of  $-0.33$  m (Figure 7c). Of the significantly correlated sites, the largest biases and lowest correlations were observed at the gravel sites (Beesands and Chesil) where S2006 under-estimated  $S_{ig}$  heights by 0.57 m and 3 m respectively (Figure 7d,g respectively).

Overall,  $S_{ig}$  was well-predicted by S2006 at Perranporth and Minsmere, under-predicted at the gravel sites (Beesands and Chesil) and showed no significant relationship at Camber (Figure 7f). This shows that S2006 can be applied over a similar range of conditions to that which it was developed, but cannot be extended to use on gravel beaches or beyond the range of conditions in the original dataset.

Poate et al. (2016) showed an underestimation of runup on gravel beaches, under high energy conditions when employing a runup predictor containing S2006. The findings here suggest that this is due to an underestimation of the IG component of swash.



**Figure 7.** (a) Significant infragravity swash height  $S_{ig}$  against  $(H_0L_0)^{0.5}$  after Stockdon et al. (2006). Linear best fit for Stockdon 2006 data (solid orange line), limited to the original range of  $(H_0L_0)^{0.5}$ . (b): Comparison of  $S_{ig}$  heights observed and those predicted by S2006 at all sites. (c–g): as above but for individual sites.

### 3.3.2 Poate–Gravel beaches

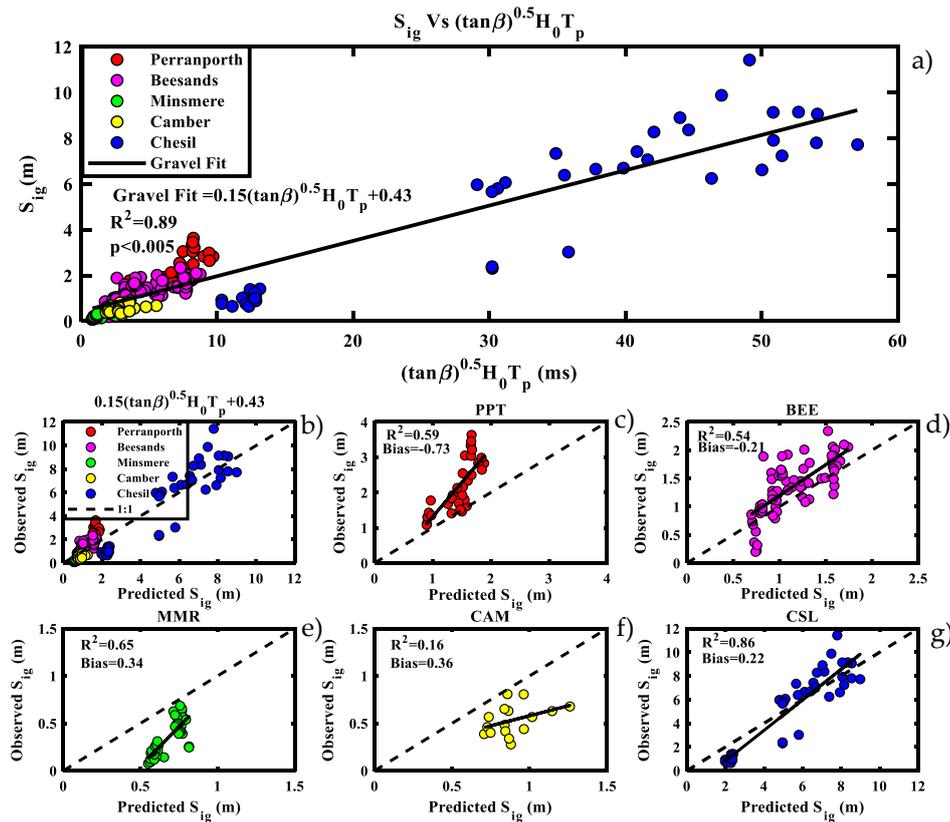
While no gravel specific predictors of  $S_{ig}$  exist, [17] (P2016) developed a predictor of runup elevation using a range of data from four gravel beaches and synthetic data from the gravel specific numerical model, X-beach-G, finding that inclusion of a beach slope term yielded the most accurate predictor:  $R2\% = C (\tan \beta)^{0.5} H_0 T_p$  where  $C$  is a constant. Given that P2016 was designed to predict runup, as opposed to  $S_{ig}$ , the constant suggested by [17] ( $C = 0.33$ ) is not applicable to the prediction of  $S_{ig}$ . Instead, using the terms in P2016, a value of  $C$  was derived here by applying a linear best fit to the combined set of data from the gravel sites (Beesands and Chesil) (Figure 8a), yielding a gravel specific predictor of  $S_{ig}$ , Equation (5).

$$S_{ig} = 0.15(\tan \beta)^{0.5} H_0 T_p + 0.43 \tag{5}$$

Given that in S2006 wave height is square rooted, a greater emphasis is placed on  $H_0$  in Equation (5). This increased emphasis on  $H_0$ , combined with the introduction of a  $\tan \beta$ , imply that

wave height and beach slope play a more critical role in the control of  $S_{ig}$  on gravel beaches than sandy ones.

On the compound/mixed sites,  $S_{ig}$  was reasonably well-predicted at Minsmere, although Figure 8e reveals a small but systematic over-prediction of  $S_{ig}$ , yielding a bias of 0.34 m while Camber showed no significant relationship between  $S_{ig}$  and Equation (5). Of the significantly related sites (all except Camber)  $S_{ig}$  was least well-predicted by Equation (5) at Perranporth (Figure 8a–c), with a large negative bias (−0.73) representing an under prediction of  $S_{ig}$ . The enhanced infragravity levels at Perranporth may result from the efficient transfer of energy to lower frequencies across the wide, dissipative surf zone.



**Figure 8.** (a): Significant infragravity wash height  $S_{ig}$  against  $(\tan \beta)^{0.5} H_0 T_p$ . Linear best fit for Beesands and Chesil (Equation (5)), black line. (b): Comparison of  $S_{ig}$  heights observed and those predicted by Equation (5) at all sites. (c–g): As above but for individual sites. Equation (5) has a y-axis intercept (c) of 0.43 resulting from the linear fit being extended beyond the lowest observed values of  $0.15(\tan \beta)^{0.5} H_0 T_p$ . Given the positive intercept, Equation (5) should not be extended beyond the range of observed values of  $(\tan \beta)^{0.5} H_0 T_p$  and is therefore only applicable for values above 0.8 ms.

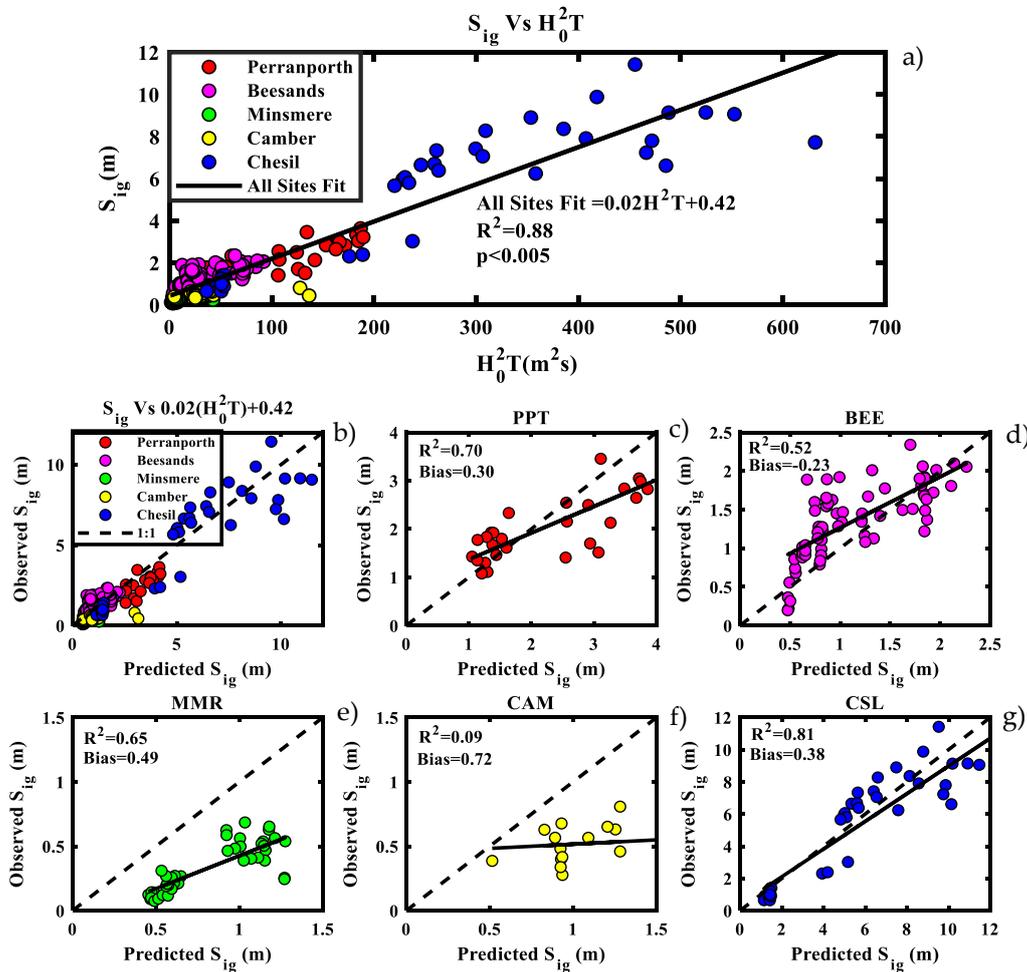
### 3.3.3. Deepwater Wave Power

S2006 and Equation (5) have been shown to skillfully predict  $S_{ig}$  at a specific type of beach over specific range of conditions. In order to examine whether  $S_{ig}$  could be predicted with any skill during the extreme waves at contrasting sites, the relationship with deep water wave power was tested. Wave power has frequently been used in the parameterisation of storm hydrodynamics [29–31]. Removing the constants from the deep water waver power equation yields  $P \propto H_0^2 T$ , a useful parameterisation previously applied to infragravity waves on a dissipative sandy beach by Inch et al. (2017).  $S_{ig}$  was regressed against  $H_0^2 T$  for the combined data set of all five sites (Figure 9a), deriving a linear equation for predicting  $S_{ig}$ :

$$S_{ig} = 0.02(H_0^2 T) + 0.42 \tag{6}$$

Equation (6) skillfully predicted  $S_{ig}$  at Beesands, Perranporth and Chesil with small biases of −0.23, 0.30 and 0.38 m respectively (Figure 9d,c,g respectively), suggesting that infragravity wash

height is proportional to deep water wave power in extreme wave conditions at these three contrasting sites, all of which are susceptible to infragravity dominance at the shoreline (Figure 6). Equation 6 was a less suitable predictor of  $S_{ig}$  at the mixed sand and gravel sites, yielding larger biases at Minsmere (0.49 m) (Figure 9e) and showing no significant relationship with  $S_{ig}$  at Camber ( $p = 0.248$ ) (Figure 9f).



**Figure 9:** (a): Significant infragravity swash height  $S_{ig}$  against  $(H_0^2 T)$ . Linear best fit for all sites (Equation (6)), black line. (b): Comparison of  $S_{ig}$  heights observed and those predicted by Equation (6) at all sites. (c–g): As above but for individual sites. Equation 6 only valid for high energy conditions.

### 3.3.4. Comparison of Parameterisations

Section 3.3 thus far has demonstrated that the relationship between wave and beach statistics and  $S_{ig}$  varies between sites. The predictive skill of S2006, Equations (5) and (6) at the five contrasting sites is compared in Table 5.

$S_{ig}$  at Perranporth was accurately predicted by both S2006 and Equation (6), with marginally higher  $R^2$  for the later. At Beesands both Equations (5) and (6) were strong predictors of  $S_{ig}$ . The low levels of  $S_{ig}$  observed at Minsmere were well predicted by all three equations, with S2006 yielding the lowest biases.  $S_{ig}$  at Camber was generally low and showed no relationship with any of the 3 equations. At Chesil,  $S_{ig}$  was well predicted by Equations (5) and (6).

Given that Equation (5) was derived from data collected at Beesands and Chesil, a more skillful predictor is Equation (6). Of the sites susceptible to IG dominance (Perranporth, Beesands and Chesil),  $S_{ig}$  can be accurately predicted by Equation (6), under high energy conditions, demonstrating that large offshore wave powers associated with big swell waves are the main driver of large infragravity energy in the swash across these widely varying beach types.

**Table 5.** Comparison of relationships between observed  $S_{ig}$  and  $S_{ig}$  predicted by S2006, Equations (5) and (6).

Equation	Site	R <sup>2</sup>	Bias	p-Value
S2006				
$S_{ig} = 0.06 (H_0 L_0)^{0.5}$				
	Perranporth	0.61	-0.33	<0.005
	Beesands	0.36	-0.57	<0.005
	Minsmere	0.63	0.27	<0.005
	Camber	0.12	0.32	0.014
	Chesil	0.60	-3.0	<0.005
Equation (5)				
$S_{ig} = 0.15(\tan \beta)^{1/2} H_0 T_p + 0.43$				
	Perranporth	0.59	-0.73	<0.005
	Beesands	0.54	-0.21	<0.005
	Minsmere	0.65	0.34	<0.005
	Camber	0.16	0.36	0.123
	Chesil	0.86	0.22	<0.005
Equation (6)				
$S_{ig} = 0.02 H_0^2 T + 0.42$				
	Perranporth	0.70	0.3	<0.005
	Beesands	0.52	-0.23	<0.005
	Minsmere	0.65	0.49	<0.005
	Camber	0.09	0.72	0.248
	Chesil	0.81	0.38	<0.005

#### 4. Discussion

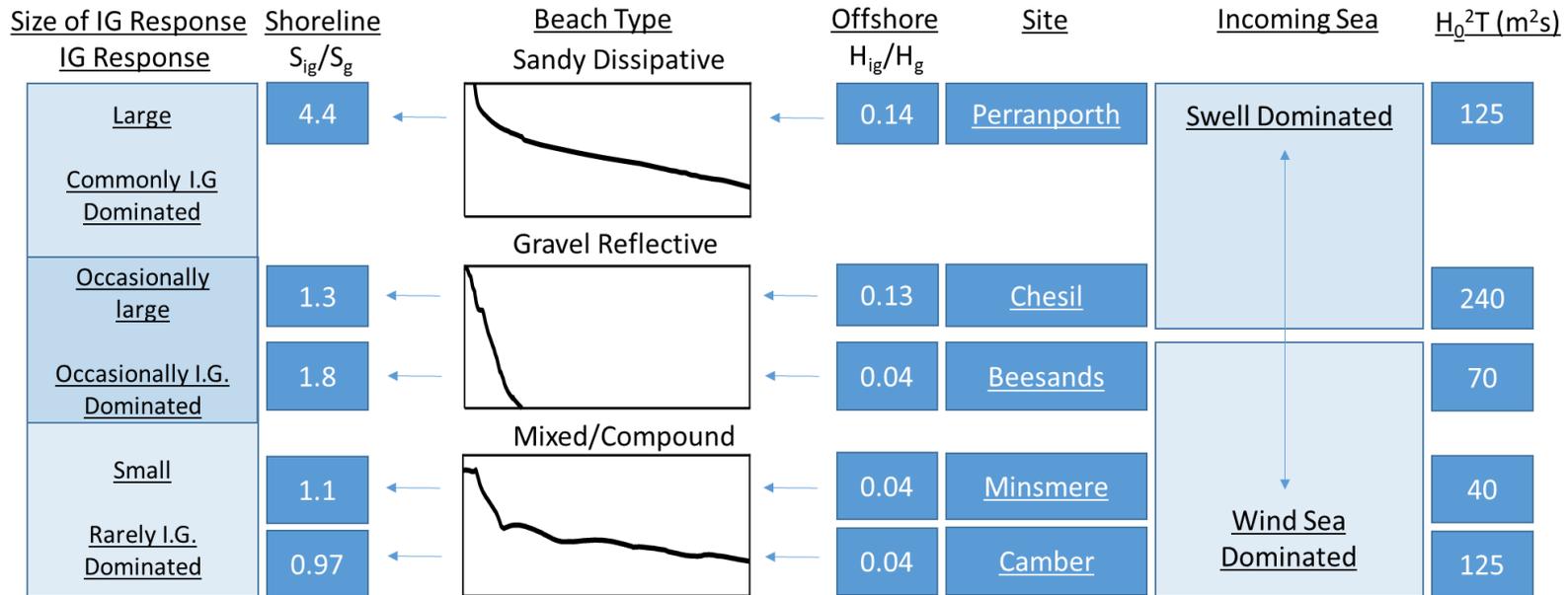
##### *Conceptual Diagram—When and Where Are Infragravity Waves Important at the Shoreline?*

Table 6 and Figure 10 summarise the contrasting behaviour of energy in the gravity and infragravity band from offshore to the shoreline, under extreme conditions, on three distinct morphologies; sand, gravel and compound/mixed. Taking the data runs presented in Figure 4 as examples of high energy/ extreme conditions, from right to left the diagram displays the following for each of the five study sites: Incoming wave power and sea state; ratio of infragravity to gravity offshore; representative profile; resultant infragravity to gravity ratio at the shoreline and a relative size and dominance attributed to each of the three distinct morphologies.

Despite contrasting values of incoming wave power, the ratio  $H_{ig}/H_g$  was the same (0.12) at both the swell dominated sites (Perranporth and Chesil). This value of  $H_{ig}/H_g$  was the largest observed across all sites.

Despite a larger increase in infragravity height between the offshore ( $H_{ig}$ ) and the shoreline ( $S_{ig}$ ) on gravel beaches than sand (Table 6), the ratio of  $S_{ig}/S_g$  was largest on the sandy site (Perranporth) (4.4), over 3 times as large as Chesil and twice as large as Beesands. This demonstrated that a lack of short wave dissipation on steep gravel morphology, compared to the sandy one limited infragravity dominance at the shoreline. Of the two gravel sites the relatively steeper waves and lower beach slope at Beesands compared to Chesil resulted in more efficient short wave dissipation and an increased ratio of  $S_{ig}/S_g$  observed in Table 6 and Figure 10.

Despite the range in values of  $H^2T$ , the ratio  $H_{ig}/H_g$  was comparable at Beesands, Minsmere and Camber (~0.04). These are all fetch-limited sites, dominated by local wind-waves. This along with the lower values of  $H_{ig}$  at Beesands, Camber and Minsmere compared to Perranporth and Chesil, demonstrated a clear separation between swell and wind-wave dominated sites (Figure 10).



**Figure 10.** Conceptual diagram summarising the contrasting development of infragravity energy at the shoreline on 3 distinct morphologies: Sand, gravel and mixed/compound. The numerical values used in the diagram are taken from Figure 4 and are representative of high energy conditions at each site.

Of the wind wave dominated sites, contrasting response in both the ratio and IG height between offshore and the shoreline was observed between the gravel and mixed/ compound morphology. The gravel profile was susceptible to IG dominance with a ratio of up to 1.8. The compound sites were either never or rarely IG dominated.

**Table 6.** Representative infragravity heights and dominance, at the shoreline and offshore during the times of high incident wave energy presented in Figure 4.

Site	Shoreline:		Offshore:	
	S <sub>ig</sub> (m)	S <sub>ig</sub> /S <sub>g</sub>	Hs <sub>ig</sub> (m)	H <sub>ig</sub> /H <sub>g</sub>
PPT	2.5	4.4	0.42	0.14
CSL	6.4	1.3	0.73	0.13
BEE	1.9	1.8	0.10	0.04
MMR	0.7	1.1	0.09	0.04
CAM	0.8	0.97	0.16	0.04

### 5. Summary and Conclusions

Significant swash height in the gravity (S<sub>g</sub>) and infragravity band (S<sub>ig</sub>) was obtained from video runup data, under an unprecedented range of wave and beach conditions. Observations included extreme waves, in excess of the 95<sup>th</sup> percentile at five contrasting sites ranging from both wind-wave and swell-dominated gravel beaches, through fetch-limited mixed sand and gravel, to a swell-dominated, low-sloping sandy beach.

- Infragravity waves were observed in the swash at all sites, becoming important when H<sub>o</sub> exceeded approximately 1.3 m. For a given wave height infragravity waves in the swash were enhanced on gravel and sandy beaches but suppressed on mixed/compound beaches.
- Infragravity waves were observed to become most dominant in the swash on the low sloping sandy beach, where S<sub>ig</sub>/S<sub>g</sub> exceeded 4. They occasionally dominated the gravel beaches but to a lesser extent (<1.8) and rarely or never dominated the mixed/compound sites (<1.1). This was attributed to differences in short wave dissipation patterns resulting from contrasting morphology and wave steepness.
- A previously published empirical relationship [10] S<sub>ig</sub> = 0.06 (H<sub>o</sub>L<sub>o</sub>)<sup>0.5</sup>, developed on sandy beaches, predicted S<sub>ig</sub> well on the sandy beach and the mixed sand and gravel beach, over a comparable range of conditions over which it was developed. Stockdon was shown to under-predict S<sub>ig</sub> for higher energy conditions and for data collected on gravel beaches, suggesting S<sub>ig</sub> was enhanced under these conditions.
- A new gravel specific predictor of S<sub>ig</sub> was proposed, by linearly fitting observations of S<sub>ig</sub> from two separate field deployments to terms from Poate’s gravel runup equation, (tan β)<sup>1/2</sup> H<sub>o</sub>T<sub>p</sub>. This was seen to underestimate values of S<sub>ig</sub> on the sandy beach.
- H<sub>o</sub><sup>2</sup>T, proportional to offshore wave power, was a good predictor of S<sub>ig</sub> at the sites where IG could become dominant, yielding the equation: S<sub>ig</sub> = 0.02(H<sub>o</sub><sup>2</sup>T) + 0.42, valid for high energy conditions.
- The relationship between S<sub>ig</sub> and H<sub>o</sub><sup>2</sup>T, across a diverse range of sites implied that under extreme wave conditions, wave height and period became more important than local morphology as a control on infragravity in the swash. Conversely, at sites where IG rarely dominated, infragravity swash height remained small at the shoreline regardless of offshore conditions. This highlights the importance of collecting data over the unique range of heights and periods present here.

A conceptual model was presented summarising the contrasting development of infragravity energy at the shoreline on three distinct morphologies: Sand, gravel and compound/mixed. This showed that increases in IG height between offshore and the shoreline were greatest on gravel beaches, moderate on sandy beaches and smallest on compound/mixed beaches. Infragravity became more dominant in the swash on sand rather than gravel sites. This resulted in the swash

being commonly IG dominated on low sloping sandy beaches, occasionally IG dominated on gravel beaches and rarely IG dominated on compound/mixed beaches.

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