Use of video imagery to test model predictions of surf heights

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Abstract

This paper describes a new method of estimating breaking wave heights from video images of the surf zone, and uses the method to test real-time numerical model predictions based on global and regional winds. The test site is an exposed beach on the southwest coast of the United Kingdom (Perranporth, Cornwall). Breaking wave height estimates based on the video technique are found to be accurate to at least ±30%. The model predictions show a linear correlation with video-derived wave heights with a regression coefficient of 0.82 and slope of 0.93 However individual comparisons can differ by up to a factor of 2 for wave heights around 1m, reducing to around 1.5 for a wave height of 3m. The primary causes of error are likely to be inadequate bathymetry near the coast and wind speed errors offshore.
Keywords: breaking wave heights, coastal video imagery, wave modelling.

1 Introduction

Wave breaking at the shoreline creates one of the most energetic natural environments and is responsible for the generation of strong currents and for moulding the constantly changing morphology of the coastal environment. The processes of wave breaking and its consequences are however complex and still far from being fully understood.

Modelling and hindcasting breaking wave heights and associated currents and evolving nearshore morphologies over timescales of weeks and years appear to

www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/CP090041

be gaining some skill [1, 2], though parameter values can be physically unrealistic. In contrast, real time prediction of breaking wave heights has received relatively little attention, despite its obvious importance for the safe day-to-day management of shoreline and beach activities.

The UK Met Office has, since 2004, been providing real time forecasts of breaker heights at three locations around the UK for the Royal Navy in support of beach-based training activity. However to date there has been no independent, quantitative assessment of the accuracy of these breaker height predictions. The purpose of this paper is therefore to describe and assess a method of testing the predictions using video measurements of the surf zone at an exposed site on the southwest coast of the United Kingdom.

2 The Met Office breaking wave height model

The UK Met Office has for over 15 years provided forecasts of sea state on a global and regional scale using a suite wave models [3, 4]. The models are forced with hourly wind fields generated by Met Office Numerical Weather Prediction (NWP) models, which include observational data from ships and data buoys in their assimilation schemes. Wave energy (swell as well as wind-sea) is advected through the model domain at the group velocity, with bottom friction and refraction included for depths less than 200m. Output from the models is regularly updated and provides forecasts with lead times of up to 5 days.

This study used configurations based on the (then operational) Met Office second generation wave model. The Global Wave Model operates on a 5/9° latitude by 5/6° longitude grid (approximate 60 km square at UK latitude). This provides input to the boundaries of the UK Waters Wave Model, which uses a 1/9° latitude, 1/6° longitude grid (approximately 12 km square). This finer resolution model includes the effects of time-varying currents on the UK continental shelf, taking hourly currents from a 12km resolution Storm Surge Model.

In order to predict depth-limited breaker heights at the coast, the nearest grid point of the UK Waters Wave Model is used as input to an implementation of the SWAN model (Simulating WAves Nearshore [5, 6]). For the site to be discussed later, this grid point was 7.5 km from the shore in 30 m water depth. The SWAN model includes two shallow water effects not present in the offshore models; depth-limited wave breaking and triad (as opposed to quadruplet) wave-wave interactions. The Met Office SWAN configuration typically uses a grid size of 100-250 m, limited largely by the resolution of available local bathymetry and run time, and brings the waves to a minimum depth of 5m chart datum.

Two wave shoaling and breaking algorithms are then used to define the extent of the surf zone (assumed shoreward of the SWAN boundary point). The model of Goda [7, 8], uses empirical formulae for wave height transformation through shoaling and breaking based upon a large number of laboratory measurements and checked against a limited number of field measurements. The model divides the propagation of waves into a shoaling zone, a transition zone and a depth-limited breaking zone, with coefficients which depend upon the offshore wave steepness (ratio of wave height to wavelength) and the local beach slope. The Met Office prediction uses measured intertidal beach profiles with interpolation to offshore bathymetry, combined with modelled tide and surge levels, to provide the depth profile over which the waves propagate. The predicted quantity, the wave height at the outer edge of the surf zone, is taken as the height at the junction of the depth-limited and transition zones.

The alternative model uses the method of Battjes and Janssen [9]. The maximum depth-limited wave height is defined by an equation after Battjes and Stive [10], resulting in a ratio of wave height to water depth which is a function of the offshore wave steepness and the local wavelength of the waves (itself a function of the wave period and local depth).

The output of these wave breaking prediction schemes consists of hourly predictions of significant breaking wave heights, maximum breaking wave heights (defined as the highest of a run of 250 waves) and the associated breaker depths, celerities and wavelengths.

3 The field site and video monitoring system

3.1 Field site

The site chosen for this hindcasting intercomparison was Perranporth, on the northern coast of Cornwall, UK (Figure 1). The beach at Perranporth is long and essentially straight, backed by a large dune system and facing Atlantic swell from the west. Typical offshore wave heights range between 1 and 3m, rising to more than 4m during major storm conditions. Perranporth is macrotidal, with a typical spring tide range of 7m and neap range of 3m. The beach slope is approximately 0.012 below the low water line but rises to approximately 0.04 at the spring high water line.

3.2 The Argus video system

Breaking wave heights were estimated using an Argus video camera system (Holman and Stanley [11] provide a recent review). Two video cameras were installed at a Youth Hostel on the crest of a headland to the south of the beach at Perranporth, at a height of 48m above the mean water line. Data from the cameras are controlled by a computer housed in the Hostel. The usual sampling regime involves capture every hour of images in the form of a snapshot, a 10-minute time exposure, a variance image (a measure of the variance of intensity at each image pixel over a 10 minute interval) and an image giving the brightest intensity measured at each pixel over a 10 minutes interval. These images are archived at the controlling computer and then downloaded to a server at the University of Plymouth each night when the video system is not operating. From Plymouth the data is placed on the Argus web site (http://cil-www.coas.oregonstate.edu:8080). This site has been in operation since August 1996 and has therefore to date built up over 13 years of almost continuous imagery of the beach at Perranporth.

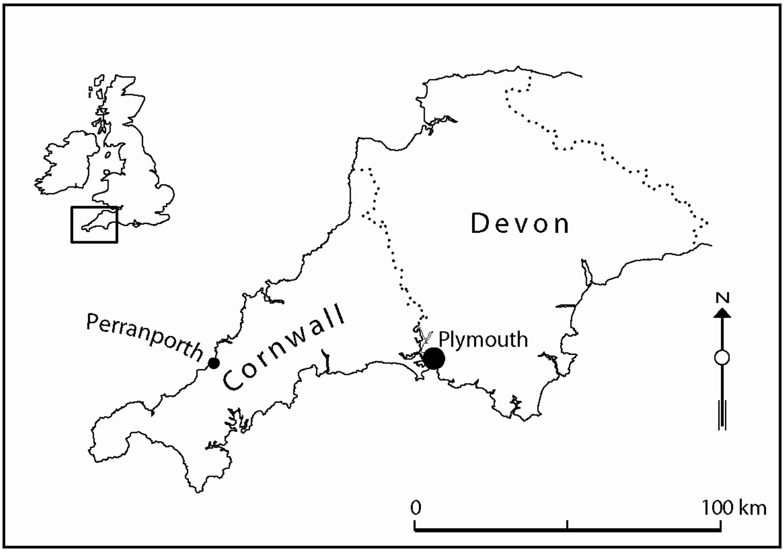

Figure 1: Location map.

Algorithms developed through the Argus program can be used to project the position of each image pixel onto the equivalent map location on either the UK national grid (OSGB36) or a local Argus grid chosen so that the x and y directions are cross-shore and alongshore respectively. These algorithms use GPS-surveyed ground control points in the field of view of the cameras and projects pixel locations onto the horizontal map plane at the known tide and surge water level. For the Perranporth data described in this paper, the pixel resolution is typically better than 5m in the cross-shore direction and 12m in the alongshore direction.

4 Estimation of breaker height using video images

4.1 Imaging breaking waves

Breaking waves create a clear signature in video images due to the high reflection from aerated water at the wave crest. The seaward edge of the surf zone in principle shows the location of the highest breaking waves and therefore can be used to estimate breaker heights. The 'brightest' images, showing the highest intensities over a 10 minute interval, provide particularly clear images of the outer edge of the surf zone. Figure 2 is an example from Perranporth which shows how clearly the surf zone is revealed. The 'brightest' images have not to date been used for breaker height estimation but they have a number of advantages over alternative methods. In particular they give a sharp and unambiguous outer edge (Figure 3 shows an example), in contrast to other images where the intensity profile often approximates a Gaussian shape. They thus provide a direct video-based measure of the location where the largest wave

Figure 2: A 'brightest' image from camera 1 (landward-facing), showing the brightest intensity for each pixel over a 10 minute interval. The dark line shows the transect line used in this study.

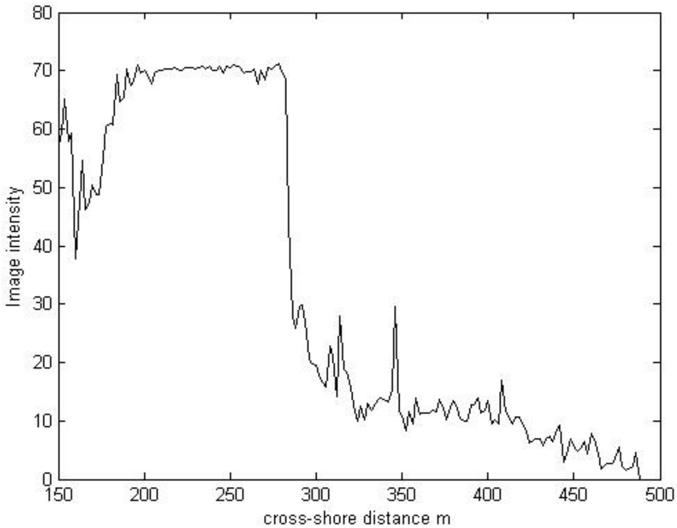

Figure 3: An intensity profile along the line shown in Figure 2 from a 'brightest' image from camera 1. The surf zone is characterised by a high and almost constant intensity, with sharp cut-offs, particularly at the seaward edge at approximately 280m offshore.

over the 10 minute interval started to break. One potential disadvantage, of course, is the statistical uncertainty in the height of the largest wave over a 10 minute period; in contrast to other images the brightest images do not involve averaging over many waves. We shall see later however that this uncertainty is limited and does not overwhelm the advantages. We have therefore chosen to use brightest images for this study.

4.2 Use of brightest images to estimate breaker height

The process of estimating breaker heights at Perranporth involved a number of steps.

1. Intensity profiles along a cross-shore line were extracted from the images by rectifying each image based on the mean water level at the time the image was captured. For this purpose tide level was determined by interpolation of coastal tide gauge records in the region using a 2DH numerical model (K. George, University of Plymouth – personal communication), and surge levels were taken from a Proudman Oceanographic Laboratory Storm Surge model run operationally at the Met Office. Figure 3 is an example profile from camera 1.

2. The seaward-facing camera, camera 2, was found generally to have a lower intensity than camera 1 and a systematic variation of intensity across the field of view, with the highest intensity in the centre of the image. In order to merge images from the two cameras, these effects in camera 2 were removed by fitting a simple parabolic curve, as a function of offshore distance, to the intensity profiles and by matching the intensities at the junction with the field of view of camera 1. This simple process removed spurious sharp edges at the boundary of the two cameras and was found to work well in most cases.

3. Single sharp intensity peaks due to offshore white-capping were reduced in height by applying a two-point low pass filter to the intensity profiles.

4. An intensity threshold was chosen as a fraction of the peak intensity. Values of 0.7 or 0.5 were used but the results were, as expected, found to be relatively insensitive to the actual value.

5. The edge of the surf zone was then determined as the point of first intersection of the intensity profile with the threshold value, moving from offshore.

6. Three 'quality control' measures were used to omit values which were deemed to be suspect:

   a) Omit profiles where the intensity contrast across the profile falls below a threshold value. This process removes profiles from poor images caused primarily by poor visibility or very low light levels.

   b) Omit profiles where the tide level is below mean water level. This ensures that most edges are within or close to the surveyed beach profile line and thus minimises the influence of seaward extrapolation of the profile.

   c) Remove estimated breaker locations which are near the seaward boundary of the profile. This also removes points well seaward of the measured beach profile line as well as points where the camera distortion is largest.

7. Finally a visual check was made on outliers. In fact very few points were found to be in error in this process, though correction was made for one point where the surf zone edge coincided with the junction between the two cameras.

The resulting values for the location of the edge of the surf zone were then converted to local breaker depths using a measured beach profile and known mean water level, as shown schematically in Figure 4. As for the image rectification, the water level for each image time was determined from the interpolated coastal tides and the surge level from the Storm Surge model. Pixel resolution, described in section 3.2, has a negligible effect on the accuracy of these height estimates, giving an uncertainty of only around 0.05m in the worst case scenario of waves over the steepest part of the beach profile.

In principle the video system itself can provide regular beach profiles by imaging the shoreline at different tide and surge water levels [12], but for this study we used data from a single total station (Electronic Distance Meter, EDM) survey carried out on 4th July 2000. Some error is introduced by assuming that this survey profile remains appropriate for the periods used in this study, but there is evidence that for this wide macrotidal beach the error is likely to be small. The maximum difference in beach elevations along the profile line for surveys on 7 May 1997 and on 4 July 2000 was found to be 0.4m, with a standard deviation value of 0.2m, for offshore distances between 80 and 550m, and these changes are equivalent to maximum and standard deviations of breaker height of only 0.12m and 0.06m respectively.

The final step is to convert the resulting breaker depths to an equivalent significant breaker height. There are various ways in which this can be done, including the use of a simple constant breaker index. However a more satisfactory method is to convert the depth into the height of the highest breaking wave, H_{max}, and then relate that height to the equivalent significant wave height, H_s. Of the available equations relating individual maximum wave heights and water depths, we have used the equations of either Goda ([7, 8]):

$$H_{max} = A\, L_0\, [\, 1 - \exp\, (\, - 1.5\, \pi\, (h_b / L_0)\, (1 + 15 \tan^{4/3} \theta))] \tag{1}$$

or Battjes and Janssen [9] and Battjes and Stive [10]:

$$H_{max} = (0.88 / k\,)\, \tanh\, (\gamma\, k\, h_b\, /\, 0.88) \tag{2}$$

$$\gamma = 0.5 + 0.4 \tanh\, (33\, H_0 / L_0\,) \tag{3}$$

where A is a constant, taken to be 0.17, L_0 is the deep water wavelength, h_b is the depth of breaking, θ is the angle of beach slope, k is the local wavenumber (2π/wavelength) and H_0 is the deep water wave height.

Calculation of L_o in equations 1 and 3, and k in equation 2 requires input of the incident wave period. In principle wave period can be measured by the video technique using ‘timestacks’, time series of images with a sampling interval much shorter than the wave period. Unfortunately however no ‘time stacks’ were available for the data sets considered in this study. We have therefore used the wave periods predicted by the SWAN model.

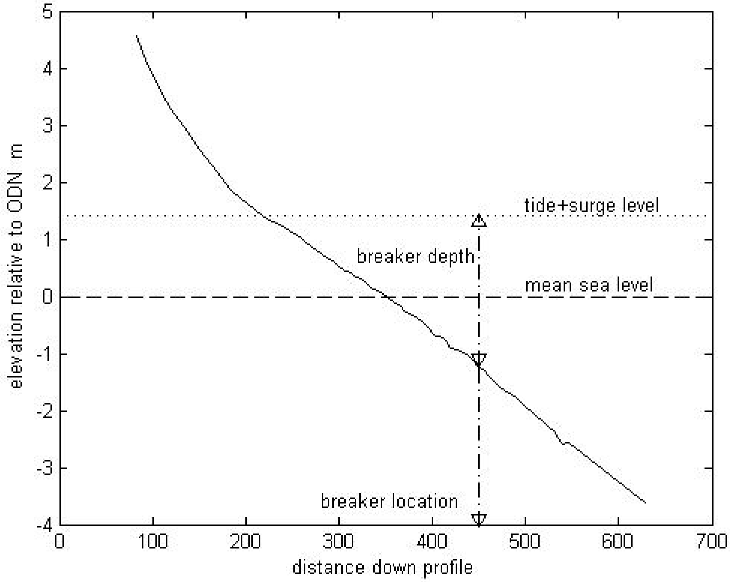

Figure 4: A schematic of the method used to determine breaker depth from the measured cross-shore position of the outer edge of the surf zone. The solid line is the depth profile. The breaker depth for an offshore distance of 450m is shown as the profile depth below mean sea level plus the tide and surge water level.

The maximum wave heights were then converted to equivalent significant wave heights, H_s, by assuming a Rayleigh distribution of wave heights [13, 14] using an equation derived by Longuet-Higgins [15]:

$$H_{max} = [\sqrt{\ln N} + 0.2886 / (\sqrt{\ln N}) - 0.247 / (\sqrt{\ln N})^{3/2}]\, H_s / 1.416 \qquad (4)$$

where N is the number of waves over the 10 minute interval, given by 600/T where T is the wave period in seconds.

It is important to note that the definition of significant breaker height, H_s, computed in this way is based on the location where the highest wave over a 10-minute period begins to break, whereas the Met Office model predictions are based on the location where depth-limited breaking causes the significant wave height to begin to decrease towards the shore. In comparing the predicted and video-derived breaker heights we are therefore assuming that these two definitions are equivalent. The validity of this assumption will be discussed in Section 6.

5 Results

Two months have been selected to test the Met Office predictions. August 2005 is characterised by bright images and relatively low wave conditions. It was chosen for initial analysis since the edge of the surf zone was generally within the field of view of camera 1 alone (for tide height above the mean water level). January 2001 provided a greater test of the methods, generally with less illumination, larger waves and inclusion of camera 2.

Figure 5 shows the result of comparing predicted and Argus-observed breaking wave heights for both months. In this case the Goda equation, equation 1, was used to obtain the observed breaker height. The overall agreement is good, with a best-fit slope of 0.93 and a regression coefficient of 0.82. The slope shows that overall the predictions underestimate the observed heights by 7%, and the 95% bounds on the slope (0.92 to 0.98) suggest that this underestimation is marginally statistically significant. Separate regressions of the August and January data (see Table 1) give very similar slopes but lower regression coefficients, as might be expected for the more limited wave height ranges. Table 1 also shows that observed wave heights computed using the alternative equations 2 and 3 give very similar results. Use of a constant breaker index, on the other hand, results in significantly lower regression coefficients. Table 1 also shows that marginal improvement in the overall fit is obtained by averaging measured breaker heights from three profiles separated alongshore by 30m and by comparing daily-averaged rather than hourly wave heights. However the improvement is generally small.

Despite the overall good agreement, there is considerable scatter in the individual points. Proportionately the scatter is larger at lower wave heights, amounting to approximately a factor of 2 for heights less than 1m, but reduces slightly with increasing wave height, to a factor of around 1.5 for heights above 2m. Overall the rms scatter about the best fit line is approximately 0.28m. In the

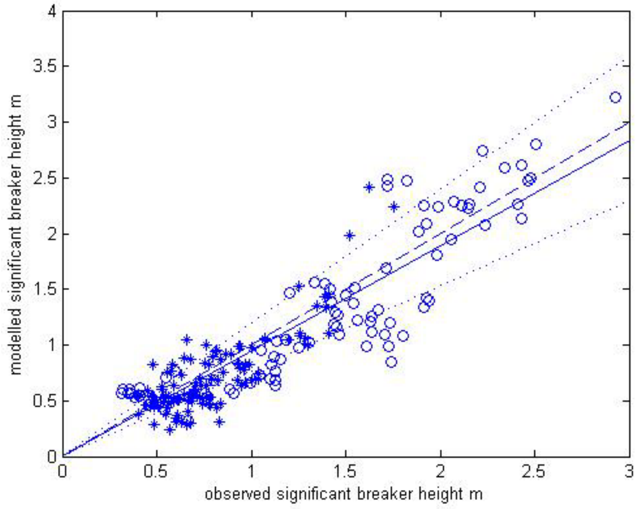

Figure 5: Plot of modelled vs. observed significant breaker heights. The asterisks are for August 2005 and the open circles for January 2001. The solid line is the regression fit through the origin and the dashed line the 1:1 line. The dotted lines show 95% confidence bounds.

Table 1: Linear regression fits between observed and predicted breaker heights.

Conditions	Equation	Regression Coeff R^2	Slope
All data	1	0.82	0.93
August	1	0.67	0.92
January	1	0.79	0.93
All data	2 & 3		
August	2 & 3	0.67	0.94
January	2 & 3	0.77	0.99
August	Constant γ=0.29	0.56	1.2
January	Constant γ=0.29	0.55	1.3
Alongshore averages All data	1	0.83	0.96
August	1	0.59	0.87
January	1	0.79	0.98
Daily averages All data	1	0.82	0.96
August	1	0.74	1.00
January	1	0.81	0.95

following section we investigate possible reasons for this scatter, leading to some suggestions for further work.

6 Discussion

We have investigated several potential causes of the scatter seen in figure 5. Perhaps the most obvious is the statistical uncertainty in the highest wave in a ten minute interval. However, based on an equation given by Goda [8] the 95% confidence bounds are only approximately 0.8 and 1.27 of the mean value so are too small to account for the scatter between observed and predicted wave heights and furthermore are unable to explain the wider scatter associated with smaller wave heights.

A second potential cause of scatter is the difference in the definition of the break point for the measured and predicted breaker heights. We have investigated the impact of this using a variety of available models for wave breaking, including Battjes and Janssen [9], Thornton and Guza [13], Baldock et al. [14] and Lippmann et al. [16]. These models produce very different relationships between the fraction of breaking waves and the mean surf zone wave heights but we find that, for the range of conditions studied, the resulting differences in measured wave height are less than 30% and in most cases considerably smaller, again too small to account for the observed scatter.

Other possible causes include errors in tide and surge levels, errors in the cross-shore beach profile and uncertainty about the appropriate breaker index. However each of these factors is found to have only a minor influence. We conclude therefore that the primary cause of the scatter is error in the predictions rather than the measurements.

This conclusion appears to be generally consistent with previous assessments of the accuracy of the Met Office offshore wave predictions involving comparison between buoy observations and predictions at neighbouring model grid points, and suggests that the nearshore modelling system does not significantly add to the errors inherent in the offshore modelling system. Bidlot and Holt [4] use data from 28 buoys located around the globe but mainly on continental shelves and find good overall agreement but, as with Figure 5, considerable scatter in individual values. Interestingly the slope of their least squares fit is 0.90, again suggesting a small overall underestimation of wave heights; they also find that wave heights above 4-5 m metres tend to be overestimated, a trend also consistent with our data. Wind speed error is suggested as the primary source of the model errors. Bradbury et al. [17] report similar intercomparisons for buoys in much shallow water depths (2.5m to 12.7m) along the southern coast of England.

In conclusion, the new video technique is found to measure breaker heights to an accuracy of at least 30% and this might be considerably improved by appropriate temporal and/or spatial smoothing. This level of uncertainty is likely to be acceptable for most practical applications. Further improvement awaits the development of more accurate representations of the link between breaker height and the fraction of breaking waves, either by refined models or direct observations. The Met Office predictions are good on average but underestimate breaker heights by around 7%, in approximate agreement with comparisons offshore. However individual predictions can be in error by up to a factor of 2 for wave heights around 1m, falling to a factor of around 1.5 at 3m.

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