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COMBINING PHASE-RESOLVING WAVE MODELS WITH PHOTOGRAMMETRIC MEASUREMENT TECHNIQUES

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Abstract: A class of models, termed Boussinesq wave models, has been developed in the past to provide time dependent (phase-resolving) wave information for shallow and intermediate water depths. Recent extensions include wave breaking, runup and expansion into deeper water. There is a need for appropriate field data (spatial and time dependent) to control, calibrate and validate the models. Spatial quasi-continuous measurement techniques using high resolution digital cameras are applicable for this purpose. The research area is a groyne field on a North Sea island in Germany. First results are presented.

INTRODUCTION

Small-area high resolution numerical models, reproducing the kinematics of the sea surface in nearshore zones, are under development. Surfzone processes are in the focus of research interest with keywords like wave breaking, wave runup and wave overtopping. Among others, numerical Boussinesq wave models are increasingly used. Time-dependent field data with a sufficient spatial density, equivalent with the grid resolution of the models are often not available. Thus only a small number of locations of point measurements can be used for e.g. development, calibration of empirical strategies and verification. Generally speaking, point measurements are not really an adequate basis for spatial numerical modelling. The modelling techniques are constantly being advanced, but are lacking an appropriate combination with quasi-continuous field data in time and space. With a view to this fact the bilateral project WAVESCAN has been started at the University of Hannover. The Institute of Fluid Mechanics (ISEB) and the Institute of Photogrammetry and GeoInformation (IPI) are participating.

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PHASE-RESOLVING MODELLING OF THE SURFZONE

The wave field is calculated with the numerical model BOWAM2, developed at the ISEB that is based on an extended set of Boussinesq wave equations (Schröter et al. 1994). BOWAM2 was used with grid sizes up to 4 km². The model includes all significant processes of wave transformation due to wave-current-bathymetry interaction up to D/L = 1.5, such as diffraction, refraction, reflection, shoaling, wave breaking, wave runup and wave overtopping. For analyzing case studies in the transition zone and shallow water, Boussinesq models are efficient tools regarding computing time. The largest part of the German coastal waters can be regarded as transition zone and/or shallow water for the design case. It is possible to apply and validate successfully large area models with more than 500 000 grid points in the continuously flooded area except the surfzone. The description of the transformation in surfzones and at shorelines is decisive for the use of Boussinesq wave models in nearshore areas. At the beginning of wave breaking, the air in the "pipe" of the toppling wave crest leads to several free surfaces. At this moment, the hydrodynamic state can no longer be described by one solution. Even three-dimensional models are not necessarily in a position to describe this phenomenon. For the approximation empirical assumptions are indispensable. All Boussinesq-Models used in surfzones, such as BOWAM2 or Funwave have to include a number of empirical relations. BOWAM2 includes a more complex Extended-Eddy-Viscosity-Concept in order to determine with a higher accuracy the wave breaking point, the decreasing wave height and the wave asymmetry (see Fig. 1). The so-called Wet-Slope is a special strategy that allows to determine the wave runup and the water volume associated with wave overtopping (see Fig. 2) as an additional coastal engineering parameter of a Boussinesq wave model.

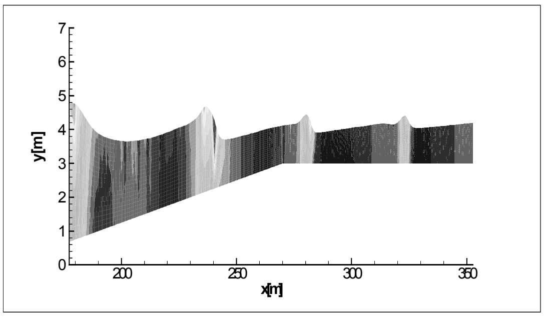

Fig. 1. Asymmetric wave evolution

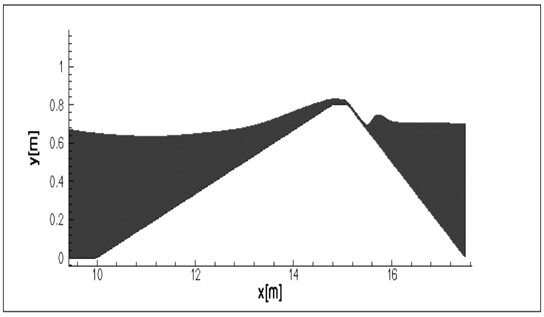

Fig. 2. Wave overtopping in BOWAM2

The periodically flooded area situated above the mean water level is modelled with a residuary water film (Strybny, Zielke 2000). The analysis of shape-describing parameters such as asymmetry and skewness is decisive for the calibration and verification. The number of available datasets with a sufficient spatial density of recorded points is somewhat limited. Only some typical laboratory-geometries are available. Figure 3 shows the propagation of spatial wave runup around a conical island calculated by BOWAM2. Due to a further development of numerical wave models for natural topographies, there is a need for a measurement technique with high resolution in time and space which is adequate to the phase-resolving numerical models.

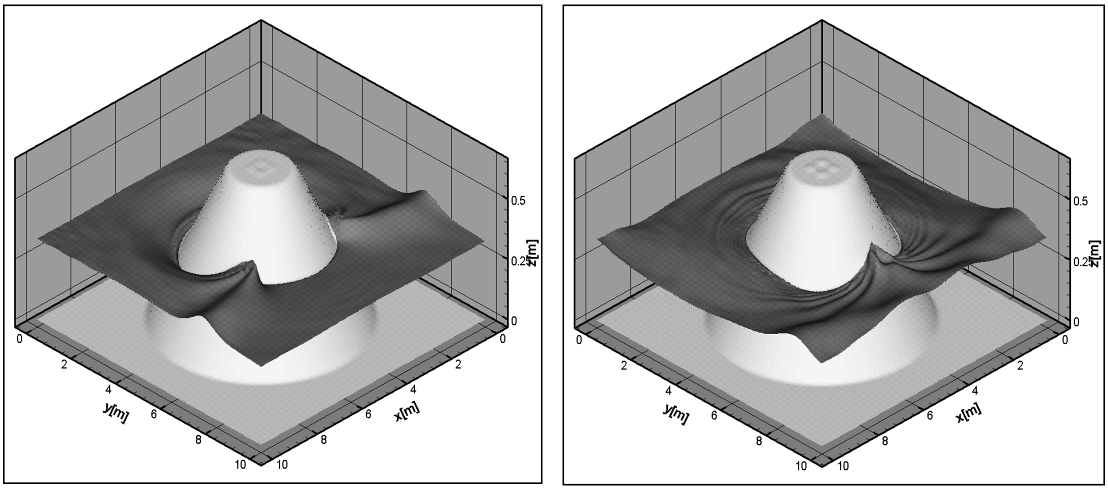

Fig. 3. Modelling of spatial wave runup with BOWAM2

MEASUREMENT TECHNIQUE REQUIREMENTS

The surface of a seastate area should be measured quasi-continuously and three dimensionally with an accuracy within centimeter range. The observed area should correspond to a typical nearshore situation, e.g. a groyne field, or the near-field of a jetty or breakwater. The technique, however, should be suitable for larger areas as well. In the project discussed in this paper the test area is a groyne field seawards Norderney Island (in the coastal waters of the German North Sea). The size is approximately 200 by 200 m^2. The situation is shown in Figure 4. The chosen groyne field is a classical research groyne field of the Coastal Research Station, equipped with a number of conventional instruments, such as current meters, gauges and wave rider buoys. For the purpose of comparison, single point measurements are being carried out. The resolution in space of the spatial measurement system has to correspond to the grid space of the phase-resolving numerical model, which depends on the wave length. Typical wave spectra in the vicinity of Norderney Island were published by Niemeyer and Kaiser (1997), and are shown in Figure 5.

Fig. 4. Groyne field at Norderney Island

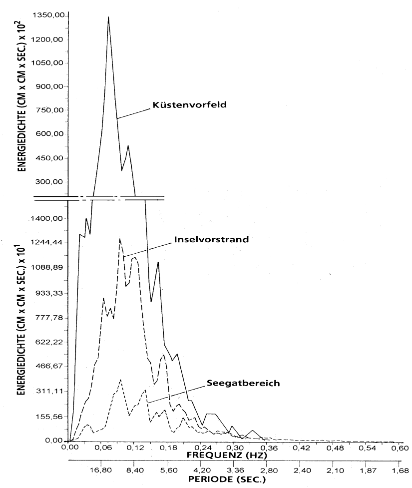

Fig. 5. Spectra near Norderney (Niemeyer & Kaiser, 1997)

The period of the shortest considered wave is between 3 and 2 s with a shallow water wave length between 10 and 5 m. These waves should be resolved with a minimum of 10 nodes per wave length. The result is a grid space between 1.0 and 0.5 m. The requirements on the duration and resolution in time vary strongly, depending on the investigated problem. In this project we have to distinguish between the comparison to phase-resolving numerical results and the comparison to statistical analysis of conventional buoy data. The minimum period for collecting data is the time needed by the incident wave to cross the surfzone from the seaward boundary to the line of highest wave runup. A duration of about one minute is required for this process. A high resolution in time must be chosen in order to be able to describe the kinematics of the seasurface induced by seastate. The time step of the numerical model is given by the Courant criterium and lies between 10 and 20 Hz. The measurements have to be done over a period, which is long enough to allow a short time statistic analysis at every grid point. The mean wave period in a groyne field near Norderney is approximately 6 s. To get an acceptable standard deviation of the wave parameters, some 200 waves have to be analyzed. Consequently, the chosen measurement system must be able to sample data over a period up to approximately 20 minutes. The sampling-frequency of wave rider buoys is only 1.5 Hz, and therefore no limiting condition for the new measurement system. The main reason for the shape-transformation of the waves in the surfzone lies in the interaction between wavefield and underwater topography. For analyzing the waves it is essential to measure nearly simultaneously the seastate as well as the topography. The new system is intended to combine the measurement of different media, in this case water and sand. Algorithms should also have the potential to analyze further image attributes concerning wave runup and turbulence in breaking waves. Another research goal is to arrive at a fully automatic analyzing system. It should work without any contact to the aggressive media water and sand and from a distance of some hundred meters.

AVAILABLE 2D AND 3D MEASUREMENT SYSTEMS

Table 1 shows a comparison of some spatial measurement systems. The bolded symbols in the table are referenced in the text. The photo- or videobased documentation of areas under observation in laboratory or nature is a long-established technique. It is possible to obtain two-dimensional measurements from single images or image sequences and to locate, for example, the wave runup line. But with one camera it is impossible to measure a spatial object in three dimensions. It was found that when using radar systems in navigation it is possible to measure the seastate. One of the most widely spread systems is the WAMOS-II-System developed by the German GKSS research center (Reichert et al. 1999) and certified by the German Lloyd and the Norske Veritas. The statistical seastate parameters are recalculated as secondary information by analyzing the running times of the reflected radar signal. The advantage lies in the wide range and complete independence of weather. The collected data are two-dimensional. A centimeter-resolution in space and a high-frequent time resolution are, however, not feasible. Taking (radar) images from aircraft or satellite is a further method. It allows the recording of 3D objects by sampling data of the same object from a lot of different locations, e.g. aerial images were taken with two cameras with synchronized shutters in separate airplanes (Yamazaki et al. 1998). By observing static objects on the earth surface it is possible to get three-dimensional measurements within a large area (some 100 km^2) and higher resolution, but only in space (meter range), not in time. This technique does not meet the requirements with regard to small-area high resolution modelling.

Table 1. Comparison of available 2D and 3D measurement systems

<table>
<tr><td colspan="2" rowspan="3"></td><td colspan="4">System</td></tr>
<tr><td rowspan="2">photo or video documents</td><td rowspan="2">nautical radar system</td><td colspan="2">photogrammetry</td></tr>
<tr><td>aircraft</td><td>terrestrial</td></tr>
<tr><td colspan="2">observation area</td><td>lab. + nature</td><td>nature</td><td>nature</td><td>lab. + nature</td></tr>
<tr><td colspan="2">dimension</td><td>2D</td><td>2D</td><td>3D</td><td>3D</td></tr>
<tr><td colspan="2">range</td><td>-</td><td>+ +</td><td>+ +</td><td>-</td></tr>
<tr><td colspan="2">independ. of weather</td><td>-</td><td>+ +</td><td>- -</td><td>-</td></tr>
<tr><td rowspan="2">resolution</td><td>space</td><td>+ +</td><td>-</td><td>+</td><td>+ +</td></tr>
<tr><td>time</td><td>+ +</td><td>- -</td><td>- -</td><td>+ +</td></tr>
<tr><td colspan="2" rowspan="2">results</td><td rowspan="2">easy determ. of parameters like wave-runup-line</td><td rowspan="2">H_s, T_m, θ</td><td>$z = f(x,y)$
$\eta = f(x,y)$</td><td>$z = f(x,y,t)$
$\eta = f(x,y,t) \rightarrow$
$w(t)$, $\theta(t)$</td></tr>
<tr><td colspan="2">further parameters</td></tr>
<tr><td colspan="2">modelling-measurement relation</td><td></td><td colspan="2">phase-averaged</td><td>phase-resolving</td></tr>
</table>

A solution for our problem is the terrestrial photogrammetry. This technique simulates the natural spatial vision. A given area is recorded by two or more cameras which synchronously take images from different locations. In the overlapping area, one can determine the kinematics of the wave field in 3D with high resolution. For almost 100 years photogrammetry has been used for the recording of wave surfaces. Measurement campaigns were published resulting in single wave stereo photos. Wave analysis from image sequences however is very complex, and therefore expensive. A further restriction for the length of sequences was given by the use of analogous films. With the availability of high resolution digital cameras and sufficient image-sequencing these problems have been overcome. Present developments and research with regard to automated matching procedures and interpretation of digital images are important for wave analysis, considering the fact that photogrammetry is the only highly accurate method with a continuous spatial and temporal data acquisition. Finally it has to be pointed out that there are relations between measurement and numerical modelling systems. Radar results (WAMOS-II) and aircraft based large scale images could be used rather for control and comparison to phase-averaged models (e.g. SWAN). The multi-image photogrammetry is the counterpart of phase-resolving models (e.g. BOWAM2).

IMAGING SYSTEM AND DATA AQUISITION

The measurements at Norderney Island are carried out over distances of some 100 meters from the top of high buildings. The camera positions are marked in Figure 6 with white points. For the photogrammetric survey of the test area four digital video-cameras with a 2/3 inch interline progressive scan CCD are used. The system prototype can handle four cameras and can thus in principle be extended to record an area of arbitrary size by adding additional cameras. The CCD-sensor has a radiometric resolution of 10 bit greyscale (monochrome) and a geometric resolution of 6.7 x 6.7 µm² per pixel. The frame sensor size is 1300 x 1030 pixel, the maximal frame sequence is 12 frames per second.

Fig. 6. Camera locations at the beach

The system allows a max. observation period of approximately 20 minutes due to the current disk space. The exposure time can be controlled by an external trigger signal. Therefore, an external synchronization is possible. In this context, IPI developed a wireless system to transmit an external trigger signal from a master station to all slave stations (three in our case) approximately every 1.5 ms.

CAMERA ORIENTATION

For the reconstruction of the 3D position and the shape of objects from images the relation between image and object coordinates must be known. The mathematical model uses the collinearity equations (see Eq. 1). The transformation requires the knowledge of the so-called exterior and interior orientation of the images.

$$
\begin{aligned}
X &= X_O + (Z - Z_O)\frac{r_{11}(x'-x_O') + r_{12}(y'-y_O') - r_{13}c}{r_{31}(x'-x_O') + r_{32}(y'-y_O') - r_{33}c} \\
Y &= Y_O + (Z - Z_O)\frac{r_{21}(x'-x_O') + r_{22}(y'-yo') - r_{23}c}{r_{31}(x'-x_O') + r_{32}(y'-y_O') - r_{33}c}
\end{aligned}
\qquad (1)
$$

The image coordinates of the principal point x_o', y_o' and the focal length c (the distance between the principal point and the projection centre) are the elements of the interior orientation. In this manner the position of the projection centre relative to the image plane is defined. The parameters of the exterior orientation are the object coordinates of the projection centre X_o, Y_o and Z_o and the three rotation angles (r_{ij} are the elements of the space rotation matrix). By means of these six elements the position and attitude of the camera in the object coordinate system is defined. The accuracy (standard deviation) of the X-, Y- and Z-coordinates is directly proportional to the image scale. The image scale is the ratio between the focal length and the distance between camera position and object (e.g. wave).

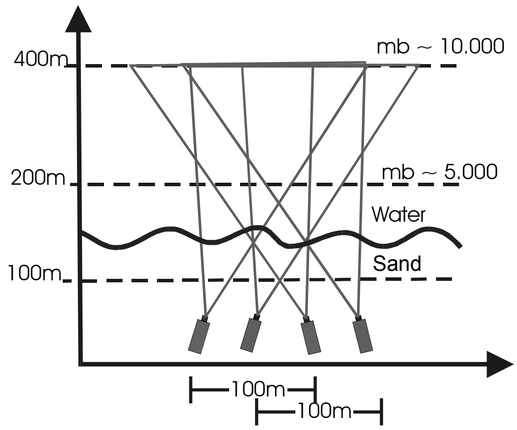

Fig. 7. Camera constellation

The achievable accuracy is influenced by the object size, the number of available cameras and the camera locations. An area of 200 by 200 m^2 can be recorded with an accuracy < 4 cm in X- and Z-direction and < 8 cm in Y-direction at the seaward boundary. In the discussed case an image scale of 1 : 10 000 and an accuracy of the image coordinate measurements of 3.5 µm, corresponding to 0.5 pixel was assumed.

MATCHING METHODS

The 3D recording of the wave surface from images requires (in addition to the information of the interior and exterior orientation) corresponding points in two or more images, also called conjugate points. For the reconstitution of a wave the manual determination of conjugate points is very time consuming and expensive. For an observation period of approximately 10 minutes with a frequency of 12 Hz, for example, 7200 images are generated. Since a number of years automatic matching methods have been investigated as a major issue in the digital photogrammetry. The automatic methods for image matching can be divided into three classes, the area-based, the feature-based and the symbolic or relational matching (Schenk 1999). The area-based matching is associated with matching grey levels, e.g. the grey values of the wave foam in the images. The matching entities are the grey levels of small areas of two images and the similarity is measured by correlation or the highly accurate least squares technique. On the other hand these methods require very good initial positions. The feature-based matching determines the correspondence between edges (e.g. the wave runup line) or other features derived from the original images to determine conjugate features. The similarity (e.g. the shape, sign and strength of the runup line) is detected by a cost-function. The initial values for the feature-based matching can be less accurate as needed for the least squares matching. But some a priori information like the approximate orientation parameters etc. are still necessary. The symbolic matching method refers to methods which compare symbolic descriptions of images, for example the breaking waves, and measures the similarity also by a cost function. In contrast to the other methods, the symbolic description may be related to grey levels or to derived features. These matching methods exist and work very well for many photogrammetric applications. At the moment no software is available which is optimized for the matching of wave surfaces. An important task in the project WAVESCAN is to optimize the reconstruction of wave surfaces in terms of level of automation, accuracy and speed using digital image matching. First tests were carried out with the software DPCOR based on least squares matching. This software has been used in a large number of photogrammetric projects before (e.g. Heipke et al. 1994, 1996, Rieke-Zapp et al. 2001). Results with images from a campaign on Norderney Island (in August 2001) are shown in Figure 8. The results show the high potential of the automatic measurement method.

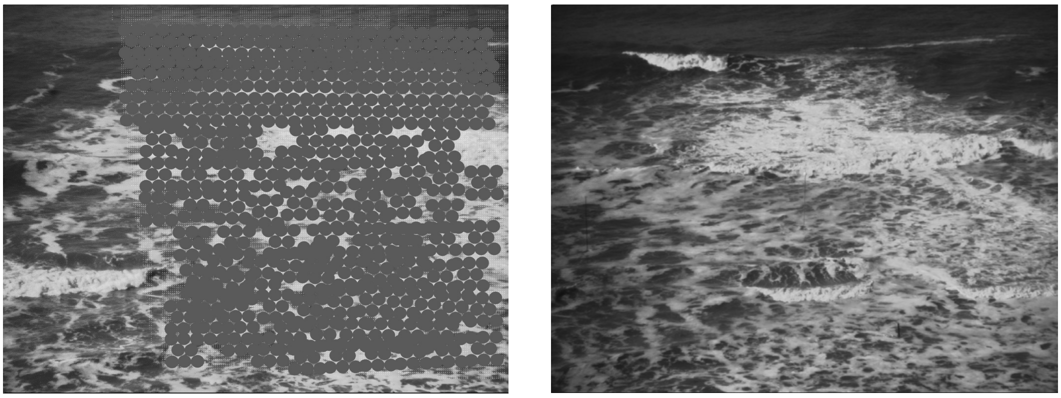

Fig. 8. Matching of conjugated points

Figure 8 represents two photographs from an image sequence and approximately 36 000 automatically determined conjugate points superimposed to the left image in dark grey. The visible small gaps are areas in which the matching software was unable to find identical points, probably due to a low local contrast. Figure 9 shows a photogrammetrically measured surfzone in 3D. At each time step the X-, Y- and Z-coordinates of the wave surface are quasi-continuously known. Because of the matching quality of the current used algorithm some further problems occur. This is reflected in the somewhat noisy appearance of the 3D model.

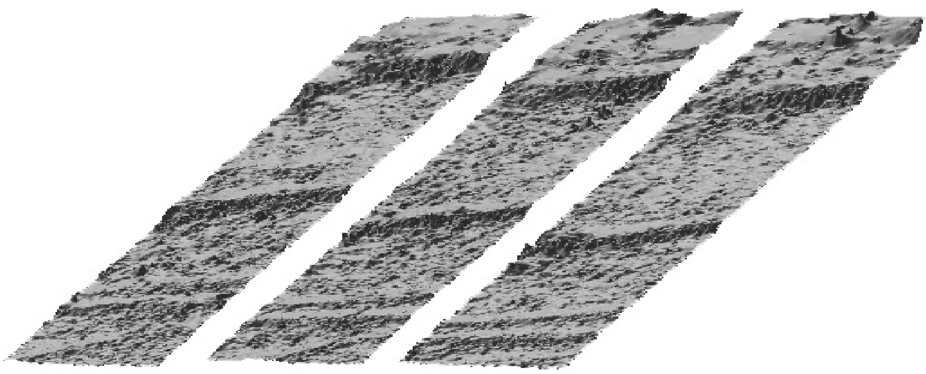

Fig. 9. Sequence of 3D photogrammetrically measured wave surfaces ($\Delta t = 1.7$ s)

COMBINING PHASE-RESOLVING MODELS WITH PHOTOGRAMMETRY

Figure 10 shows the combination of a phase-resolving model with photogrammetric results. The finite difference grid of the numerical model is designed in such way that it describes a rectangular segment of the trapezoidal photogrammetrically derived surface. It is possible to record the topography by the same photogrammetric camera system used for the surveying of the waves. The seawards side below low water level is completed by using a ship-based echosound-scanner. The initial condition of the surface is detected by photogrammetry.

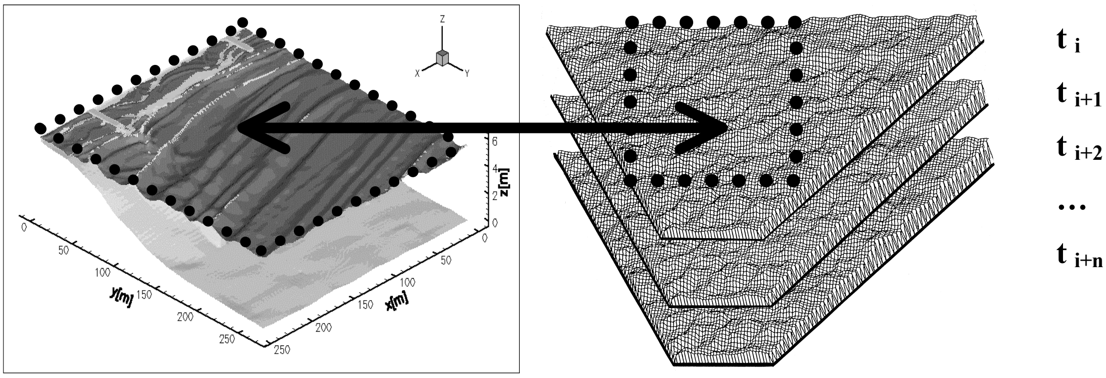

Fig. 10. Combining a phase-resolving model with sequences of photogrammetry

In future, the generating of open boundary conditions will also be done in the classical way by using a system of nested models with larger scales finally controlled by atmospheric parameters. For the purpose of development and calibration, the model BOWAM2 offers interfaces to include photogrammetrically measured boundary conditions at the open boundary. Because the numerical model is similar, but not identical with the natural situation, the boundary condition at the open boundary must have one degree of freedom. In this way, any reflected wave can always leave the numerical calculation grid when arriving at the open boundary. This boundary condition is implemented in BOWAM2 in a way that allows the use of surface elevation $\eta(t)$ and a local wave direction $\theta(t)$ as input data. $\eta(t)$ is directly supplied by photogrammetry, $\theta(t)$ can be recalculated from the photogrammetric data. The phase-resolving model calculates the state variables $\eta(t)$, $u(t)$, $\mathrm{v}(t)$ within the inner area and the results can be verified by comparison to the measured results at every grid point. For the development, calibration and verification of surfzone strategies included in numerical models, shape-describing wave parameters such as asymmetry and skewness can be derived from and compared with the photogrammetric data quasi-continuously. The possibility of an automated analysis of further image attributes regarding additional hydrographic information is another focal point of both participating institutes. Additional hydrographic information indicates parameters such as location and intensity of breaking waves, or particle velocities.

CONCLUSIONS

The paper emphasizes the need for the calibration and verification of Boussinesq wave models in surfzones. A limiting factor is the lack of appropriate field data. The requirements from a numerical wave modelling point of view regarding a future-oriented measurement technique are discussed. The advantages and disadvantages of different 2D and 3D measurement systems are compared. Digital photogrammetry is the only accurate measurement system with a continuous spatial and temporal data acquisition. It seems to be possible to use this method for the recording of wave kinematics in surfzones. Due to accuracy, the area under observation, duration and resolution in space and time the results are adequate to the results of phase-resolving numerical wave models. Results of a first measurement campaign at Norderney Island are published. One groyne field is quasi-continuously measured and numerically modelled. The employed photogrammetric matching methods will be adapted to the special characteristics of natural water surfaces. In a next step, shape-describing parameters such as asymmetry and skewness can be calculated quasi-continuously from the photogrammetric data. They will be the input for the optimization of surfzone strategies. A further subject of research is the separation of sand and the automatic determination of breaking waves. This paper gaves an overview on an ongoing research project. Updated information will be available on www.wavescan.de.

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