

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
2 March 2006 (02.03.2006)

PCT

(10) International Publication Number
WO 2006/021746 A1

- (51) International Patent Classification⁷: **G01W 1/10**
- (21) International Application Number:
PCT/GB2005/003131
- (22) International Filing Date: 10 August 2005 (10.08.2005)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
0418989.0 26 August 2004 (26.08.2004) GB
- (71) Applicant (for all designated States except US): **ISIS INNOVATION LIMITED** [GB/GB]; Ewert House, Ewert Place, Summertown, OXFORD OX2 7SG (GB).
- (72) Inventors; and
- (75) Inventors/Applicants (for US only): **BORTHWICK, Alistair** [GB/GB]; Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ (GB). **TAYLOR, Paul** [GB/GB]; Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ (GB). **HUNT, Alison** [GB/GB]; Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ (GB).
- (74) Agent: **STRACHAN, Victoria, Jane**; Urquhart-Dykes & Lord LLP, Alexandra House, 1 Alexandra Road, Swansea SA1 5ED (GB).
- (81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.
- (84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).
- Published:**
— with international search report
- For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: PREDICTION OF EXTREME EVENTS AT BEACHES AND COASTAL STRUCTURES

(57) Abstract: A method and apparatus for predicting extreme, storm-driven events and their potential effect in respect of coastal structures and areas, using focussed wave groups. An appropriate focussed wave group is selected and transformed to simulate its run-up and/or breaking as it advances inshore and then the extent and/or probability of occurrence of the extreme event is predicted.

WO 2006/021746 A1

Prediction of Extreme Events at Beaches and Coastal Structures

This invention relates generally to the prediction of extreme, storm-driven events at beaches and coastal structures.

A remarkable quantity of scientific work has been performed over the years in respect of the analysis of statistical properties of stationary wind waves. The most significant distributions for coastal and offshore engineering, i.e. marginal distributions of both amplitudes and periods and joint amplitude-period distributions have been considered from many different perspectives.

Extreme wave events have been responsible for many marine accidents, some involving loss of life. They occur under storm conditions when the waves are already high. The very highest individual waves seem to appear with little warning and may be regarded as the statistical extremes in an already rough random sea, occurring sporadically in space and time. Although the occurrence of these events may be random, a significant amount of work has been done in determining whether in the vicinity of extreme wave crests, there is any predictable, expected configuration of the sea surface.

Furthermore, in the field of offshore engineering, knowledge of the statistical distribution of crest heights given the wave spectrum is central to the problem of setting deck heights for offshore platforms.

Major advances have been made in the past decade regarding the temporal and spatial profiles of the most extreme waves in unidirectional and spread deepwater seas.

The most extreme event in a random sea is atypical of the waves in that sea and waves change significantly as they propagate inshore. Thus, the modifications to a large but localised wave group as it advances inshore, particularly on the set-up and crest elevation, is more relevant for the prediction of sea defence overtopping and lee shore flooding than the behaviour of regular waves. It is likely that small changes to the

incident wave group affect the surface set-up and wave height and have a significant effect on coastal flooding.

Ad hoc empirical design rules for coastal engineering, and models based on regular wave and/or long duration random wave time histories have been proposed in the past. It is an object of the present invention to provide an improved method and apparatus for predicting extreme, storm-driven events at, for example, beaches and coastal structures.

In accordance with the present invention, there is provided a method of predicting an extreme event in relation to the effect of one or more waves from a body of water on a coastal structure or area, the method comprising selecting a focussed wave group likely to cause said extreme event in respect of said structure or area, said wave group emanating from a location in said body of water which is some distance from said coastal structure or area, transforming said wave type using a model to simulate the breaking and/or run-up of said focussed wave group as it advances inshore toward said coastal structure or area, predicting, using said model, the extent and/or probability of occurrence of said extreme event caused by said focussed wave group, and outputting data representative thereof.

The model is most preferably a phase resolving model.

Wave phase resolving formulae may be of two main types: Boussinesq-type models (see Madsen, P.A. & Schäffer, H.A. (1999) *A review of Boussinesq-type equations for surface gravity waves*. Advances in Coastal and Ocean Engineering (Ed.P.L – F Liu) Volume 5, Chapter 1, pp 1-94), and Reynolds-Averaged Navier-Stokes equations (see Ferziger, J.H. & Peric, M. (1999) *Computational Methods for Fluid Dynamics*, 2nd Edition, Springer-Verlag, Berlin Heidelberg).

Also in accordance with the present invention, there is provided apparatus for predicting an extreme event in relation to the effect of one or more waves from a body of water on a coastal structure or area, the apparatus being arranged and configured to select a focussed wave group likely to cause said extreme event in respect of said structure or area, said wave group emanating from a location in said body of water

which is some distance from said coastal structure or area, transform said wave type using a model to simulate the breaking and/or run-up of said focussed wave group as it advances inshore toward said coastal structure or area, predict, using said model, the extent and/or probability of occurrence of said extreme event caused by said focussed wave group, and output data representative thereof.

A focussed wave group is defined herein as a localised packet of waves carrying a significant concentration of energy. Wave run-up may be defined as height above still water level reached by the wave uprush on the surface of a beach or coastal structure.

Preferably, selection of the focussed wave group is optimised such that the extreme event is maximised (so as to obtain the worst case scenario). This optimisation or maximisation is beneficially achieved by at least a) optimisation of focus position of the focussed wave group, b) optimisation of the wave group phase at focus, and c) optimisation of the group spectral content, all to be used as part of a numerical model to predict wave transformation in coastal waters, wave breaking, run-up and overtopping.

The data representative of the extreme event may be a numerical value. The extreme event may relate to inundation, and the data may be representative of an overtopping volume, whereby inundation can be defined as the horizontal distance that a wave penetrates inland. Beneficially, the output data is representative of a response of the coastal structure or area to the extreme event predicted as a result of a respective focussed wave group. In a preferred embodiment, the method includes assembling a long-term probability function of this response.

In a preferred embodiment, the method includes the determination by extrapolation from hindcast wave data produced from collected historic weather data of a focussed wave group most likely to cause said extreme event.

The model preferably includes energy dissipation when the focussed wave group breaks, and the model preferably tracks the turbulent bores of the focussed wave group as they are predicted to run up to the coastal area or structure and/or overtop the coastal structure or area. In a preferred embodiment, the model utilises a numerical

solver of wave-phase resolving equations for water motion (for example, the Boussinesq-type or the Reynolds-Averaged Navier-Stokes equations).

The method beneficially comprises employing feedback from the result of the above-mentioned transformation and/or prediction steps in order to optimise the selection of the focussed wave group likely to cause the extreme event. The method beneficially further comprises selecting one of a plurality of extreme events for evaluation.

The model is preferably based on hindcast data relating to collected historic weather data, and the data representative of the extreme event is preferably derived from the shape, duration and/or height of the energy of the focussed wave group following transformation thereof using the above-mentioned model.

These and other aspects of the present invention will be apparent from, and elucidated with reference to, the embodiment described herein.

An embodiment of the present invention will now be described by way of example only and with reference to the accompanying drawings, in which:

Figure 1 is a schematic flow diagram illustrating the principal steps of a method of coastal structural reliability assessment according to an exemplary embodiment of the present invention;

Figure 2 is a graphical illustration of a comparison between numerical predictions obtained by a method according to an exemplary embodiment of the present invention and Synolakis' (1987) experimental results on solitary wave run-up at a beach plane (See Synolakis (1987) *The runup of solitary waves*, Journal of Fluid Mechanics, 185: 523), wherein H_o is offshore wave height, h is mean water depth at the toe of the beach, and R is the vertical runup distance above still water level;

Figure 3 is a graphical illustration of a predicted and measured time series of free surface elevation for a unidirectional focussed wave at a 1 in 20 beach (solid line: experimental; broken line: numerical) a) at the toe of the beach, and b) 90% of the way up the beach; and

Figure 4 is a graphical illustration of a time series of a 1st order crest focussed wave group, based on a Pierson-Moskowitz frequency spectrum and a top-hat directional spectrum, propagating up a plane beach (solid line: experimental, broken line: numerical) (a) at the toe of the beach, and (b) 80% of the way up the beach.

As explained above, the present invention provides a new methodology for the prediction of extreme storm-driven wave events at beaches and coastal structures. The proposed methodology is intended to replace ad hoc empirical design rules and models based on regular wave and/or long duration random wave time histories, and a preferred exemplary embodiment can be summarised as follows: the use of a validated numerical model to simulate the transformation of a selected focussed wave group in shallow water and its interaction with the beach and/or coastal structure(s), the optimisation of the event to obtain the worst case scenario, and the overall prediction of the probability of occurrence of such an event.

It is well known in the field that a Swedish statistician named Lindgren was at least one of the first to consider the average shape of a large event in a linear random process. It was then shown that, for sufficiently large events, their average shape is simply the scaled auto-correlation function (see Lindgren, G. (1970) *Some properties of a normal process near a local maximum* Ann. Math. Statis. 41: 1870). More recent work by Bocotti (see Bocotti, P. (1983) *Some new results on statistical properties of wind waves* Applied Ocean Research, 5: 134) and, later, Phillips showed how these ideas could be used in oceanography as a model for water waves. This idea, which became known as NewWave, was then further developed by Tromans, Taylor and others in the late 1980's and early 1990's as a design wave for offshore engineering design and structural reliability assessment.

The present invention has arisen through development of the ideas originated by Lindgren and Bocotti and the application thereof in a new context, i.e. in coastal engineering, to the design and assessment of sea defences under wave attack, for example.

As explained above, a focussed wave group is a localised packet of waves carrying a significant concentration of energy and, the shape, duration and height of this energy packet can be related to the statistical properties of the underlying sea state through the Lindgren (NewWave) methodology. To create the focussed wave group, the free surface elevation of the input wave form to the flow solver may be expressed

$$\eta_{focus} = A \frac{\int S(k) \cos[k \cdot (x - x_f) - \omega t + \varphi] dk}{\int S(k) dk}$$

in which $S(k)$ is the power spectrum of the underlying sea state, ω is wave angular frequency, k is the associated wave number (related via the linear dispersion equation, $\omega^2 = gk \tanh(kh)$ where g is the acceleration due to gravity, k is the magnitude of the wave number, and h is the local water depth), x is horizontal distance, x_f is the position of the focus point, t is time, and φ is the relative phase of all the Fourier components. The most probable maximum of the focussed wave group is given by the Rayleigh distribution.

$$A = \sigma \sqrt{2 \ln N}$$

where σ is the standard deviation of the sea surface elevation and N is the total number of waves in the sea state.

However, known NewWave techniques relate to open sea conditions, whereas for the direct evaluation of extreme statistics for wave run-up, overtopping volume, etc. in relation to coastal engineering requires the consideration of inshore conditions, including shallow water considerations and the topology of the inshore seabed, for example.

Thus, the present invention extends the principles pioneered in offshore engineering by Tromans et al to coastal engineering, using focussed wave groups as design events for the evaluation of extreme value statistics for wave run-up, overtopping volume, etc.

Accordingly, in the first instance, and referring to Figure 1 of the drawings, an accurate, robust numerical model for the numerical simulation of wave run-up and overtopping at coastal defences is necessary. In accordance with this exemplary

embodiment of the invention, such a model has been developed based on the Boussinesq and shallow water equations. The scheme uses Godunov-type finite volume techniques for shock-capturing and is computationally efficient. It uses the minimum of adjustable parameters: a bed friction coefficient and a wave breaking parameter. The numerical solver simulates the evolution of steep wave groups as they shoal in reducing water depth, the energy dissipation at wave breaking and then tracks the turbulent bores as, for example, they run up the beach or overtop a sea wall.

Boussinesq equations are essentially a shallow water approximation to the fully dispersive and non-linear water wave problem (see Madsen, P.A. & Sørensen, O.R. (1992), *A new form of the Boussinesq equations with improved linear dispersion characteristics*. Part 2: a slowly-varying bathymetry. *Coastal Engineering*, 18:183-204. For completeness, a brief explanation in respect of Boussinesq Equations will now be given.

In 1872, Boussinesq extended the shallow water equations to include low-order wave dispersion in water of constant depth. Peregrine (1967) (Peregrine, D.H. (1967) Long waves on a beach. *J. of Fluid Mechanics*, 27: 815-827) made a major contribution by deriving a more general variable-depth formulation using perturbation methods. Since then, a great many versions of the Boussinesq equations have been proposed, which have been categorised under the following headings by Chen *et al.* (1998) (Chen, Q., Madsen, P.A., Schäffer, H.A. & Basco, D.R. (1998) Wave-current interaction based on an enhanced Boussinesq approach. *Coastal Engrg*, 33: 11-39.):

(i) classical Boussinesq equations for wave motion; (ii) Boussinesq equations for modelling wave-current interaction; and (iii) Boussinesq-type equations with enhanced linear dispersion properties.

First, consider the Boussinesq equations with improved linear dispersion characteristics derived by Madsen & Sørensen (1992) in the reference given above. It is assumed that $O(\varepsilon_n) \approx O(\mu_d) \ll 1$ where the scaling parameters, $\varepsilon_n = a / h_s$, and $\mu_d = (h_s / \lambda)^2$ are measures of non-linearity and dispersion, respectively, and a is wave amplitude, λ is wavelength and h_s is the still water depth. After depth-

integration and rearrangement of the Reynolds-averaged mass and momentum equations, the dimensional form of Peregrine's (1967) Boussinesq equations is:-

$$\frac{\partial \eta}{\partial t} + \nabla_h \cdot \mathbf{q} = 0$$

$$\frac{\partial \mathbf{q}}{\partial t} + \nabla_h \cdot \frac{\mathbf{q}^2}{h} + gh \nabla_h \eta = \frac{\partial}{\partial t} \left[\frac{h_s^3}{6} \nabla_h \left(\nabla_h \cdot \frac{\mathbf{q}}{h} \right) + \frac{h_s^2}{2} \nabla_h (\nabla_h \cdot \mathbf{q}) \right]$$

where η is the free surface elevation, $\mathbf{q} = \mathbf{i}Uh + \mathbf{j}Vh$ is the velocity field, h is the total water depth, t is time, and (x, y) are horizontal co-ordinates, with U and V the corresponding representative horizontal velocity components, ∇_h is the horizontal gradient operator.

Expanding out the above equations, dropping higher order dispersive terms, we obtain

$$\frac{\partial \eta}{\partial t} + \frac{\partial(Uh)}{\partial x} + \frac{\partial(Vh)}{\partial y} = 0$$

$$\frac{\partial(Uh)}{\partial t} + \frac{\partial(U^2h)}{\partial x} + \frac{\partial(UVh)}{\partial y} + gh \frac{\partial \eta}{\partial x} = \psi_x$$

$$\frac{\partial(Vh)}{\partial t} + \frac{\partial(UVh)}{\partial x} + \frac{\partial(V^2h)}{\partial y} + gh \frac{\partial \eta}{\partial y} = \psi_y$$

in which the dispersive terms are

$$\psi_x = \frac{1}{6} h_s^3 \left(\frac{\partial^3 U}{\partial x^2 \partial t} + \frac{\partial^3 V}{\partial x \partial y \partial t} \right) + \frac{1}{2} h_s^2 \left(\frac{\partial^3 Uh}{\partial x^2 \partial t} + \frac{\partial^3 Vh}{\partial x \partial y \partial t} \right)$$

and

$$\psi_y = \frac{1}{6} h_s^3 \left(\frac{\partial^3 U}{\partial x \partial y \partial t} + \frac{\partial^3 V}{\partial y^2 \partial t} \right) + \frac{1}{2} h_s^2 \left(\frac{\partial^3 Uh}{\partial x \partial y \partial t} + \frac{\partial^3 Vh}{\partial y^2 \partial t} \right)$$

Using Padé approximants and making further mild slope assumptions, Madsen & Sørensen (1992) obtained the following improved dispersion terms

$$\psi_x = - \left(B + \frac{1}{3} \right) h_s^2 \left((Uh)_{xxt} + (Vh)_{xyt} \right) - Bgh_s^3 (\eta_{xxx} + \eta_{xyy})$$

$$- h_s \frac{\partial h_s}{\partial x} \left(\frac{1}{3} (Uh)_{xt} + \frac{1}{6} (Vh)_{yt} + 2Bgh_s \eta_{xx} + Bgh_s \eta_{yy} \right) - h_s \frac{\partial h_s}{\partial y} \left(\frac{1}{6} (Uh)_{xt} + Bgh_s \eta_{xy} \right)$$

and

$$\begin{aligned} \psi_y = & -\left(B + \frac{1}{3}\right)h_s^2((Uh)_{xyt} + (Vh)_{yyt}) - Bgh_s^3(\eta_{yyy} + \eta_{xyy}) \\ & - h_s \frac{\partial h_s}{\partial y} \left(\frac{1}{3}(Vh)_{yt} + \frac{1}{6}(Uh)_{xt} + 2Bgh_s\eta_{yy} + Bgh_s\eta_{xx} \right) - h_s \frac{\partial h_s}{\partial x} \left(\frac{1}{6}(Uh)_{yt} + Bgh_s\eta_{xy} \right) \end{aligned}$$

Madsen *et al.* (1991) showed that the exact linear dispersion equation for water waves over a flat bed may be represented by

$$\frac{c^2}{gh_s} = \frac{1 + B(kh_s)^2}{1 + \left(B + \frac{1}{3}\right)(kh_s)^2}$$

where c is the wave celerity and the coefficient B can take various values: $B = 0$ for best fit to depth-averaged velocity; $B = 1/6$ when fitted to the bed velocity; $B = -1/3$ for the mean sea level velocity; and $B = 1/15$ for optimum results for $kh < 5$ with improved frequency dispersion.

Figure 2 shows the excellent agreement achieved between the numerical model predictions and benchmark experimental measurements from Synolakis (1987), who conducted extensive tests on the run-up of solitary waves at a plane beach.

Comparison with the high quality laboratory-scale experiments undertaken in the U.K. Coastal Research Facility indicates that the scheme works for both long-crested and directionally spread waves and is able to incorporate significant seabed topography. Figures 3 and 4 show typical comparisons between the numerical predictions and experimental measurements of free surface time histories.

A complete reliability-based design procedure for coastal defences can then be defined. In order to evaluate the statistics of wave run-up and overtopping, there are three levels of optimisation required. With the spectral content of the wave group chosen and its focus point approaching the coast, the absolute phase of the oscillations within the group is varied to maximize run-up (but the relative phase between spectral components is assumed fixed). Here, spectral content is defined in terms of both the amplitude and the phase of each linear wave component defining the group. The focus position is defined as the point in both space and time where the wave group is

most compact. The second stage is the optimisation of this first procedure with respect to the position of the focus point of the wave group. Thirdly, the amplitudes of the spectral components within the wave group are optimised whilst remaining consistent with the statistics and underlying energy spectrum of the background sea-state (storm). In summary, the levels of optimisation are:

1st Level: Choose arbitrary focus point x_f , and then alter the relative phase φ over the complete range from 0 to 2π to give a first estimate of the maximised response.

2nd Level: Systematically alter x_f and φ to further maximise the response.

3rd Level: Alter the power spectrum of the focussed group consistent with the probabilistic structure of the underlying random sea state to find overall maximum response.

For a given storm, this three-stage procedure allows the probability of various levels of exceedance of run-up and/or overtopping to be estimated for that individual storm. This complete procedure identifies the combination of components arising by chance at the seaward boundary of the computational domain, which leads to the largest event on the coast – either run-up or overtopping. This optimisation is generally performed on the response parameter chosen by, for example, a coastal engineer. Thus, the wave is not necessarily the largest in the sea-state; it is, however, the wave producing the largest design response. This optimisation leads to a “design wave” – from a probabilistic viewpoint, the most likely time history for the wave system associated with a selected level of system response.

This analysis procedure yields robust estimates for the short-term variability in response arising within a sea-state. Existing (prior art) approaches to do this typically involve the synthesis of a random wave time history, representative of the assumed sea-state, and then modelling the interaction of this wave train with the coastal feature either computationally or by physical model test. Estimates of the statistics of run-up, overtopping, etc., are then drawn directly from this modelling. Unfortunately, the

existing approach is expensive and typically rather inaccurate, as the events of interest occur so infrequently within a specified period of perhaps a few hours at field scale. The new methodology of the present invention voids such problems of statistical variability within a short time series of a few hours by shifting the search for the rare but extreme events of interest into the probability domain and only running a modest number of numerical (or physical scale model) realisations of wave groups to drive the search for the extreme response.

Once a method for the accurate derivation of extreme value behaviour within a given sea-state is available, the issue of long-term statistics of extreme response can be convoluted into the probability analysis. A typical meteorological/oceanographic database, available to coastal engineering consultants, contains estimated significant wave heights, zero-crossing periods and associated energy spectra on a 3-hourly basis for several consecutive decades. This can be regarded as providing the source of waves at the seaward boundary of the computational domain over the long term. For each storm (or 3 hour interval), the procedure described above can be re-run using waves input at the seaward boundary. For each storm, probabilities of occurrence of various levels of run-up and/or overtopping can be produced. Then, by pooling the results for all the individual storms a global set of risk levels for specified levels of system response can be determined. Given these risk estimates, standard statistical extrapolation techniques can be used to estimate the probability of occurrence of events more severe but of lower probability than those contained within the original database. Extreme events with return periods of the order of 1 in 10, 100, 1000, 10000 years are of concern in coastal engineering. The typical met-ocean databases cover a period of the order of a few decades, so accurate extrapolation is crucial. The extrapolation of the design parameter relevant to an individual particular structure or coastal feature is a key feature of the method of this exemplary embodiment of the invention. Previous implementations of this type of approach in offshore rather than coastal engineering are given by Tromans and Vanderschuren (1995) *Response based design conditions in the North Sea*, Offshore Technology Conference Paper 7683, Houston, and Vanderschuren, Tromans and Bloemasma (1998) *Strongly directional currents in the calculation of structural reliability and response-based design conditions*, Reliability Engineering and System Safety, 61:151-158.

It will be appreciated that the approach afforded by the method and apparatus of the present invention replaces the current ad hoc empirical rules and will be of significant value to the coastal engineering community as a new approach to design and structural re-assessment. As well as major implications for Codes of Practice, the proposed approach has ramifications for both numerical computations and physical experiments at laboratory scale.

It should be noted that the above-mentioned embodiment illustrates rather than limits the invention, and that those skilled in the art will be capable of designing many alternative embodiments without departing from the scope of the invention as defined by the appended claims. In the claims, any reference signs placed in parentheses shall not be construed as limiting the claims. The word "comprising" and "comprises", and the like, does not exclude the presence of elements or steps other than those listed in any claim or the specification as a whole. The singular reference of an element does not exclude the plural reference of such elements and vice-versa. The invention may be implemented by means of hardware comprising several distinct elements, and by means of a suitably programmed computer. In a device claim enumerating several means, several of these means may be embodied by one and the same item of hardware. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

CLAIMS:

1. A method of predicting an extreme event in relation to the effect of one or more waves from a body of water on a coastal structure or area, the method comprising selecting a focussed wave group likely to cause said extreme event in respect of said structure or area, said wave group emanating from a location in said body of water which is some distance from said coastal structure or area, transforming said wave type using a model to simulate the breaking and/or run-up of said focussed wave group as it advances inshore toward said coastal structure or area, predicting, using said model, the extent and/or probability of occurrence of said extreme event caused by said focussed wave group, and outputting data representative thereof.
2. A method according to claim 1, wherein said model is a phase resolving model.
3. A method according to claim 1 or claim 2, wherein said selection of the focussed wave group is optimised or the extreme event is maximised (so as to obtain the worst case scenario).
4. A method according to claim 3, wherein said optimisation or maximisation is achieved by at least (a) optimisation of focus position of the focussed wave group (b) optimisation of the wave group phase at focus, and (c) optimisation of the group spectral content numerical model to predict wave transformation in coastal waters, wave breaking, run-up and overtopping.
5. A method according to any one of claims 1 to 4, wherein the data representative of said extreme event is a numerical value.
6. A method according to any one of claims 1 to 5, wherein the extreme event relates to inundation, and said data is representative of an overtopping volume.

7. A method according to any one of claims 1 to 6, wherein said output data is representative of a response of said coastal structure or area to the extreme event predicted as a result of a respective focussed wave group.
8. A method according to claim 7, further including assembling a long-term probability function of said response of said coastal structure or area.
9. A method according to any one of claims 1 to 8, further including determining, by extrapolation from hindcast data relating to collected historic weather data, a focussed wave group most likely to cause said extreme event.
10. A method according to any one of claims 1 to 9, wherein the model includes energy dissipation when the focussed wave group breaks.
11. A method according to any one of claims 1 to 10, wherein the model tracks the turbulent bores of the focussed wave group as they are predicted to run up the coastal area or structure and/or overtop the coastal structure or area.
12. A method according to any one of claims 1 to 11, wherein the model comprises a wave phase resolving model, such as one based on a Boussinesq equation set.
13. A method according to any one of claims 1 to 12, further comprising employing feedback from the result of the transformation and/or prediction steps in order to optimise the selection of the focussed wave group likely to cause the extreme event.
14. A method according to any one of claims 1 to 13, further comprising selecting one of a plurality of extreme events for evaluation.
15. A method according to any one of claims 1 to 14, wherein said model is based on hindcast data relating to collected historic weather data, and the data representative of the extreme event is preferably derived from the shape,

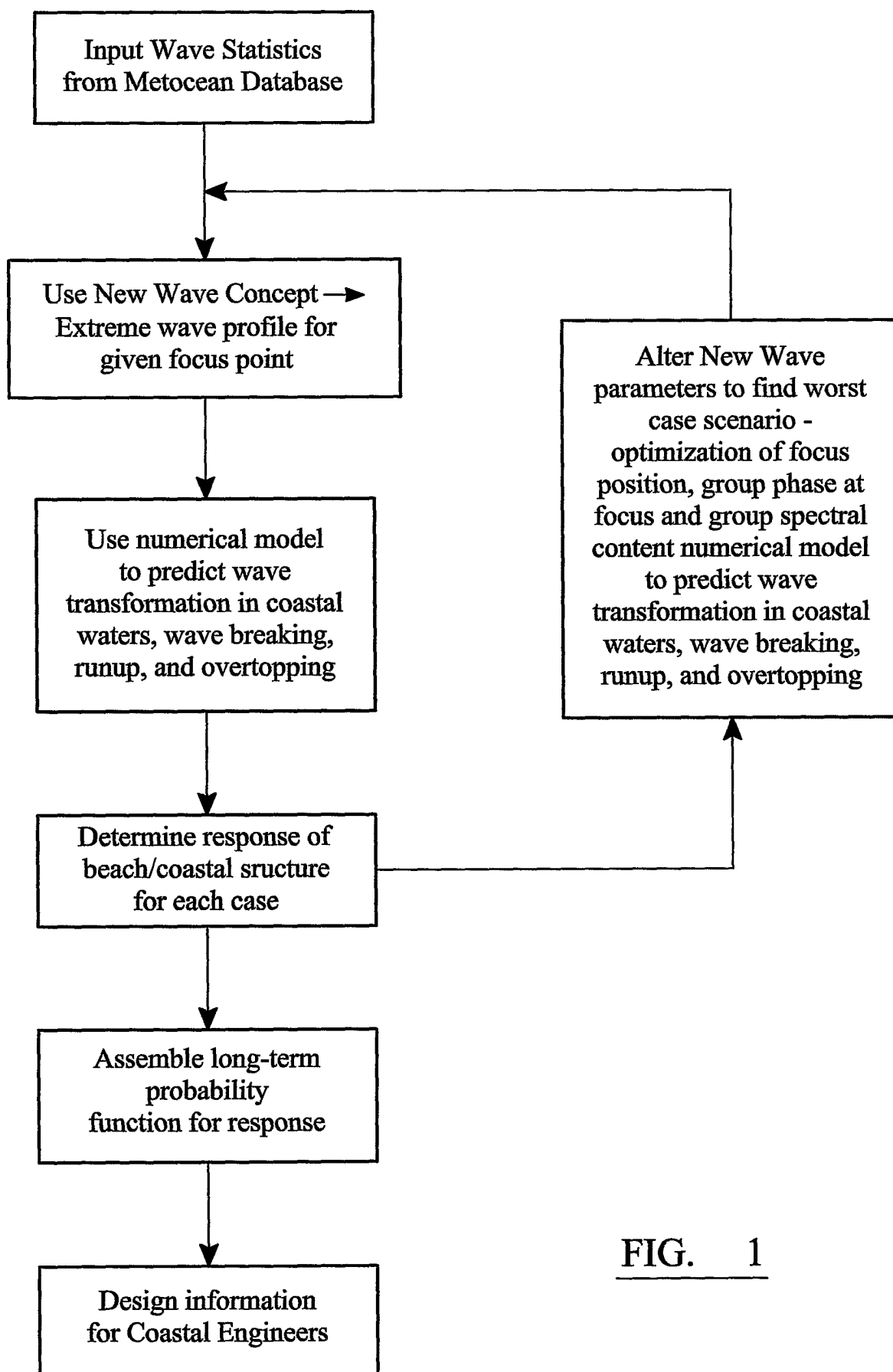
duration and/or height of the energy of the focussed wave group following transformation thereof using said model.

16. A method of predicting an extreme event in relation to the effect of one or more waves from a body of water on a coastal structure or area, the method being substantially as herein described with reference to the accompanying drawings.
17. Apparatus for predicting an extreme event in relation to the effect of one or more waves from a body of water on a coastal structure or area, the apparatus being arranged and configured to select a focussed wave group likely to cause said extreme event in respect of said structure or area, said wave group emanating from a location in said body of water which is some distance from said coastal structure or area, transform said wave type using a model to simulate the breaking and/or run-up of said focussed wave group as it advances inshore toward said coastal structure or area, predict, using said model, the extent and/or probability of occurrence of said extreme event caused by said focussed wave group, and output data representative thereof.
18. Apparatus according to claim 17, further arranged and configured such that selection of the focussed wave group is optimised or the extreme event is maximised (so as to obtain the worst case scenario).
19. Apparatus according to claim 18, wherein said optimisation or maximisation is achieved by at least (a) optimisation of focus position of the focussed wave group, (b) optimisation of the wave group phase at focus, and (c) optimisation of the group spectral content numerical model to predict wave transformation in coastal waters, wave breaking, run-up and overtopping.
20. Apparatus according to any one of claims 17 to 19, wherein the data representative of the extreme event is a numerical value.
21. Apparatus according to any one of claims 17 to 20, further arranged and configured to determine, by extrapolation from hindcast data relating to

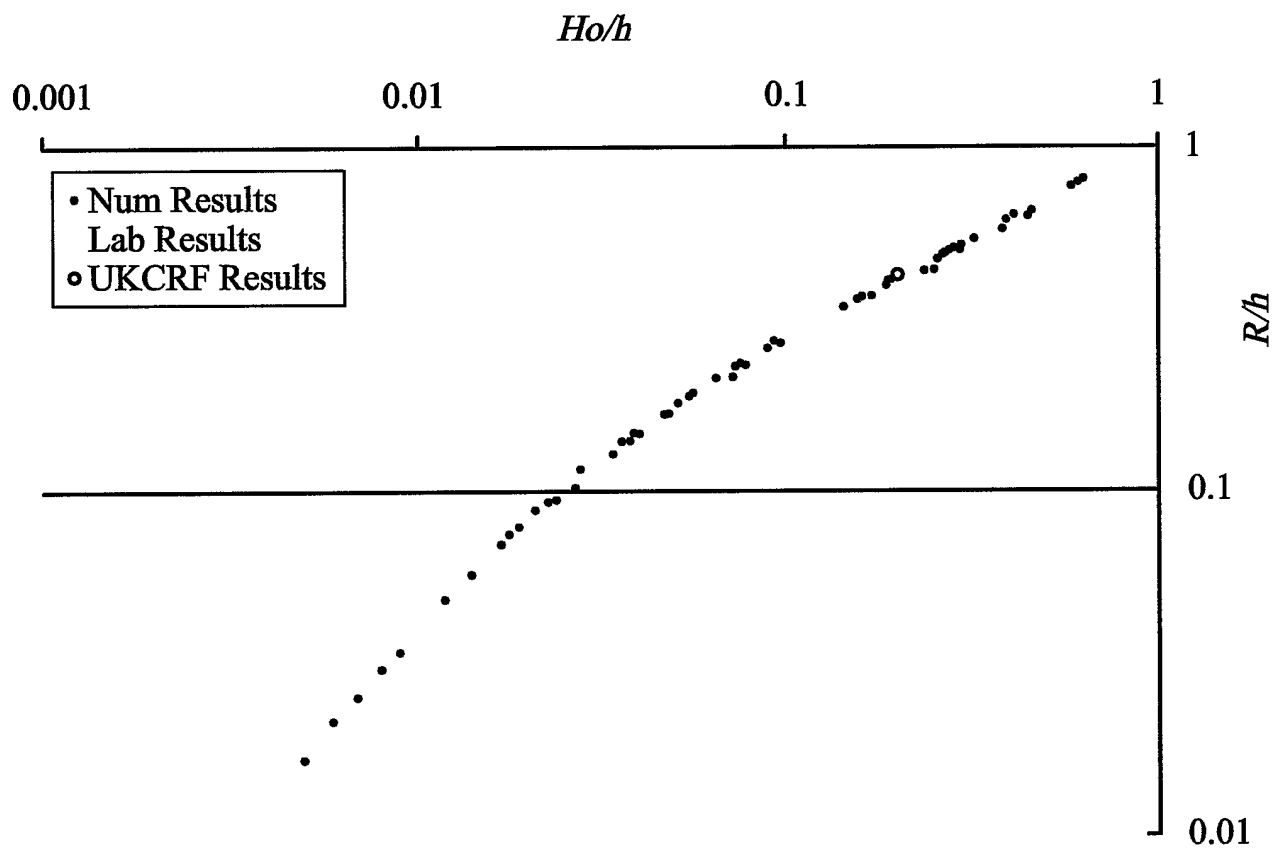
collected historic weather data, a focussed wave group most likely to cause said extreme event.

22. Apparatus according to any one of claims 17 to 21, further arranged and configured to employ feedback from the result of said transformation and/or prediction in order to optimise the selection of the focussed wave group likely to cause the extreme event.
23. Apparatus according to any one of claims 17 to 22, further comprising selection means for selecting one of a plurality of extreme events for evaluation.

-1/3-

FIG. 1

-2/3-

FIG. 2

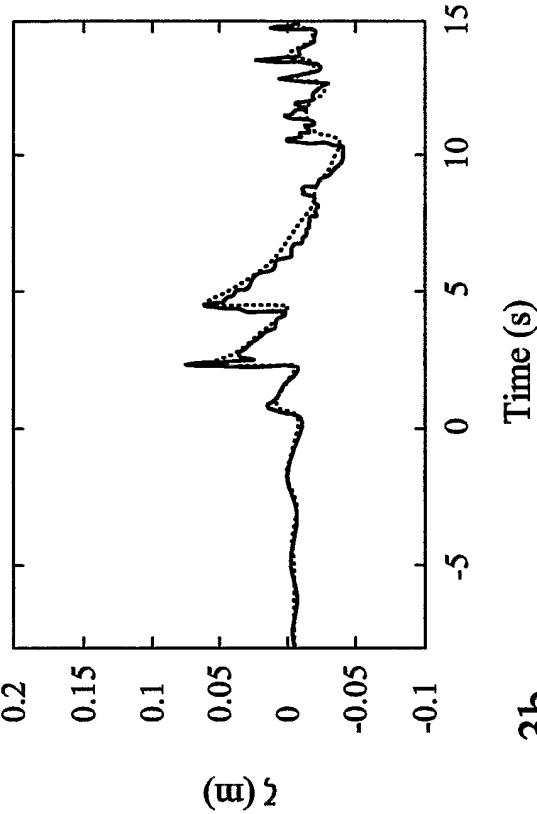


FIG. 3b

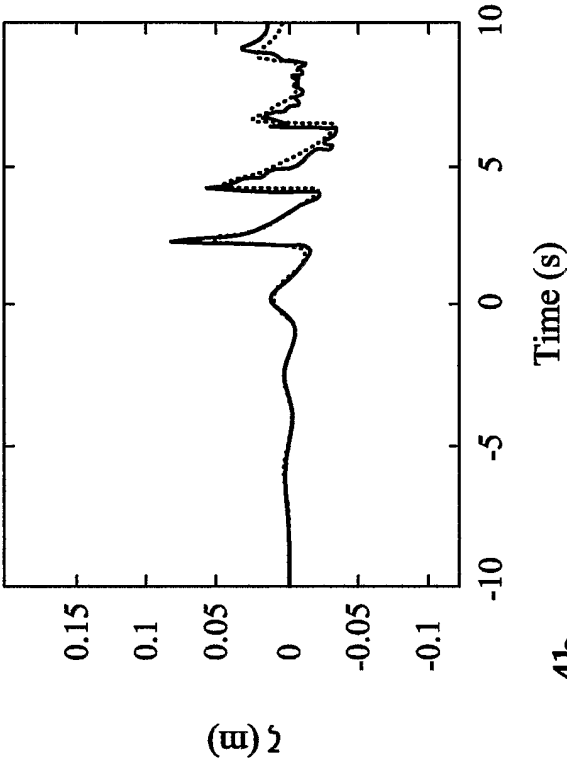


FIG. 4b

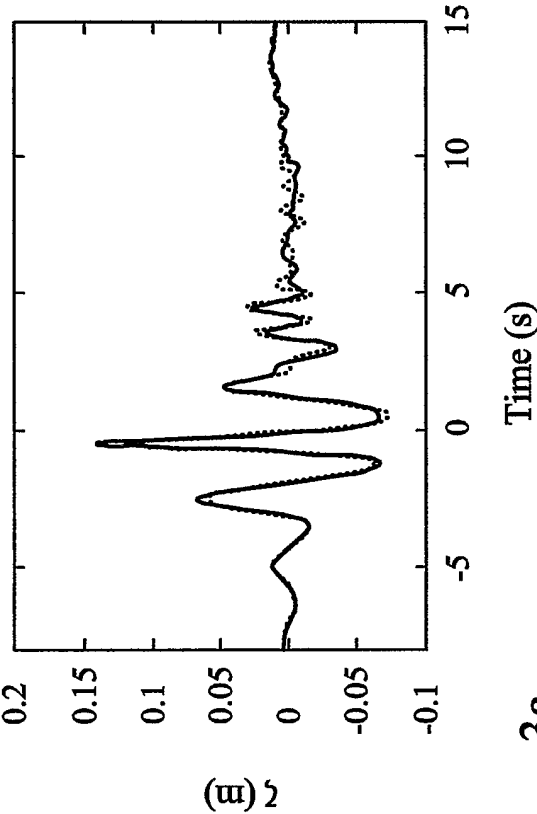


FIG. 3b

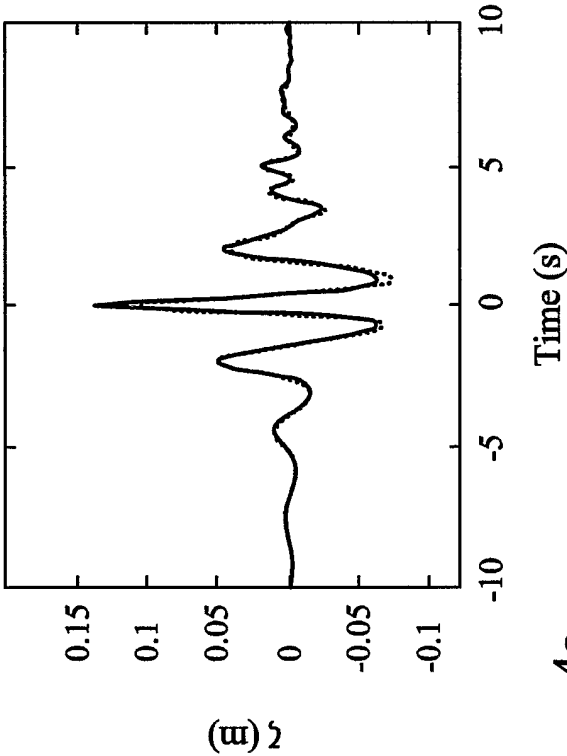


FIG. 4b

INTERNATIONAL SEARCH REPORT

Application No

PCT/GB2005/003131

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01W1/10

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G01W

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	S.F. SMITH, C. SWAM: "Extreme two-dimensional water waves: an assessment of potential design solutions" OCEAN ENGINEERING, vol. 29, April 2002 (2002-04), pages 387-416, XP002347329 the whole document	1-23
X	KENNEDY ANDREW B ET AL: "An unsteady wave driver for narrowbanded waves: Modeling nearshore circulation driven by wave groups" COAST. ENG.; COASTAL ENGINEERING JULY 2003, vol. 48, no. 4, July 2003 (2003-07), pages 257-275, XP002347330 the whole document	1-23



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

° Special categories of cited documents:

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

T later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

Y document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

* & * document member of the same patent family

Date of the actual completion of the international search

30 September 2005

Date of mailing of the international search report

10/10/2005

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer

Arca, G

INTERNATIONAL SEARCH REPORT

Application No
PCT/GB2005/003131

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	C.J.F. ANDREW: "Bibliographic Review of Neashore Wave Models" DSTO AERONAUTICAL AND MARITIME RESEARCH LABORATORY, 'Online! XP002347331 Melbourne, Australia Retrieved from the Internet: URL: http://www.dsto.defence.gov.au/publications/2144/> the whole document -----	1-23