Institution: Imperial College London

Unit of Assessment: 14-Civil and Construction Engineering

Title of case study: 2: Modelling extreme waves and their loads on offshore structures

1. Summary of the impact

The impact arises from the study of extreme ocean waves and their interaction with marine structures. It is relevant to the offshore, shipping, coastal and marine renewables industries and has been both economic and regulatory, involving:

(a) The establishment of revised guidelines for the design of new structures / vessels.
(b) Enhancing best practice, both from an economic and a safety perspective.
(c) Reducing the uncertainty in critical design issues, thereby improving overall reliability.
(d) Enabling "end-of-life" extensions for existing structures.
(e) Facilitating the effective decommissioning of redundant structures.
(f) Contributing to the development of new industrial R&D equipment, thereby assisting specialist UK manufacturers to secure international orders.

2. Underpinning research

This has addressed theoretical, experimental and numerical studies of ocean waves, their statistical distributions in extreme seas, and their interaction with marine structures. The key achievements have been to provide an improved physical understanding of the evolution of the largest waves [1,2,3]; to incorporate the essential physics into improved numerical models [4]; to quantify the exceedence probabilities of the largest waves [5]; and to describe the nature of the wave-structure interactions, including the prediction of the applied fluid loads [6]. The work has been led by Professor Chris Swan and has involved close collaboration with leading industrial practitioners including major oil companies (BP, Conoco-Phillips, Maersk, Shell, Statoil, Talisman and Woodside), specialist consultancies (Arup, JP Kenny and WS Atkins) and international regulatory authorities (ABS, BV, DNV and UK HSE).

All sea states are characterised by their frequency and directional spectra. For design purposes, both are assumed constant over time-scales corresponding to hundreds of wave cycles. A key aspect of our research has been to establish that the underlying spectra may undergo rapid and highly localised change in the vicinity of a large wave event. In deep water this causes a broadening of the frequency spectrum, the potential for higher energy densities and hence larger crest elevations [1,2,3,5]. These effects are critically dependent upon both the steepness and directionality of the sea state and provide an explanation for the occurrence of "freak" or "rogue" waves [5]; the latter believed to be responsible for the damage/failure of fixed structures and numerous shipping losses.

In seeking to describe extreme waves, particularly the kinematics necessary for the calculation of fluid loads, our research has shown that it is essential that any model incorporates the underlying physics of the sea state; specifically its nonlinearity, unsteadiness and directionality. This had led to improved wave models based upon high-order spectral methods and new boundary element formulations [4]. By combining the respective advantages of experimental and numerical modelling, we have been able to describe and explain the increased crest heights arising at small exceedence probabilities, to provide fully nonlinear statistical distributions covering a broad range of sea states, to identify those sea states in which nonlinear effects are most likely to be significant, and to provide relatively simple (design-orientated) solutions appropriate to their quantification in both deep and shallow water [5].

Building upon the success of our wave models [4] three important aspects of wave loading have been addressed:

(a) The prediction of wave-in-deck loads. This has shown that the maximum fluid velocities high in the wave crest may be substantially (30%) larger than previously predicted. With impact loads dependent upon the square of the fluid velocity, the importance of accurate kinematic predictions is clear.
(b) The prediction of global sub-structure loads. With wave energy transferred to the higher frequencies, the spatial dimensions of the largest waves will differ from traditional solutions. As a result, the global loads acting on a space-frame structure with significant plan

dimensions will be critically dependent upon the applied wave model; the commonly applied solutions being excessively conservative.

(c) The interaction between waves and large volume structures. In such cases, unexpected loading components have been shown to relate to the scattering of high-frequency waves not predicted by existing diffraction solutions. These effects are closely related to the onset of transient structural deflections, the increased occurrence of wave slamming, and the loss of air-gap due to amplifications of the maximum crest elevation [6]

3. References to the research * References that best indicate quality of underpinning research

*[1] Johannessen, T.B. and Swan, C. (2003) ‘On the nonlinear dynamics of wave groups produced by the focusing of surface-water waves’. *Proc. Roy. Soc. A,* **459**, pp 1021-1052, doi: 10.1098/rspa.2002.1028

[2] Gibson, R.S. and Swan, C. (2007) ‘The evolution of large ocean waves: the role of local and rapid spectral changes’. *Proc. Roy. Soc. A,* **463**, pp 21-48, doi:10.1098/rspa.2006.1729

[3] Katsardi, V. and Swan, C. (2011) The evolution of large non-breaking waves in intermediate and shallow water. *Proc. Roy. Soc. A,* **467**, pp 778-805, doi:10.1098/rspa.2010.0280

*[4] Bateman, W.J.D., Katsardi, V. and Swan, C. (2012) ‘Extreme ocean waves. Part1: the practical application of fully nonlinear wave modelling’, *Applied Ocean Research*, **34,** 209-224. doi:10.1016/j.apor.2011.05.002

*[5] Latheef, M. and Swan, C. (2013). ‘A laboratory study of wave crest statistics and the role of directional spreading’. *Proc. Roy. Soc. A,* **469**, 20120696, doi:10.1098/rspa.2012.0696

[6] Sheikh, R. & Swan, C. (2005). ‘The interaction between steep waves and a vertical, surface-piercing column’ *J. Offshore Mech. and Arct Eng.*, *ASME*, **127**(1), pp 31-38, doi:10.1115/1.1854701

4. Details of the impact

The impact of the work arises at a number of different levels. In several instances evidence is provided that research results, proposed methodologies or developed models have been incorporated into best practice for the design of new, and the re-assessment of existing, offshore structures. This is often achieved by the inclusion of the work within the recommendations arising from Joint Industry Projects (JIP’s); the latter representing a co-ordinated study addressing a specific problem area that has been highlighted by industry as being of practical concern, both from an operational and/or a safety perspective. In other instances, research results have been used to solve particular design problems. During the period covered, Swan has been involved in six JIP’s, each producing its own design guidelines. Most importantly, he has played a major role in setting the scope for two of the largest JIP’s ever undertaken in ocean modelling; the *CREST* and *SHORTCREST* JIP’s. In considering this work it is essential to recognise that, following the loss of the Piper Alpha structure in the North Sea, offshore regulation is much less prescriptive, requiring safety cases to be prepared and justified by owners/operators. Where research results have been successfully employed in such cases, a material or practical impact has been achieved in the sense that the required reliability (hence safety) has been achieved or the design uncertainty reduced.

During 2006-2008 Noble Denton, a leading UK certification agency, undertook a JIP to re-appraise the loading methodology appropriate to Jack-up structures; the purpose of this work being to expand their safe working range [A]. An essential element of this revised methodology was an empirically corrected wave kinematics model; the empirical coefficients being calibrated using the fully nonlinear wave model proposed by Swan [5]. Without the fully nonlinear model, the revised methodology could not have been achieved.

The *CREST* JIP was undertaken from 2007-2010. The technical work was conducted by internationally leading experts and supported by 24 industrial sponsors; the latter including all the major oil companies and numerous regulatory authorities. The only university involved in this work was Imperial College; Swan leading WP2 on nonlinear wave modelling and contributing significantly to WP4 on fluid loading. A key output from this study was the recommendation that the existing crest-height distributions are non-conservative in the most severe sea states; the recommendation being that an additional 5-8% is added to account for the full nonlinearity. This was entirely based upon the work outlined in [5] An additional 1-2 metres of crest elevation has major implications for both the cost / design of new structures and the re-appraisal of existing structures. Evidence of the importance of this work being provided by the studies undertaken in respect of the North Rankin A platform (Australia) [C,D], the Arbroath platform (UK - North Sea) [C] and the Tyra field (Denmark – North Sea) [D].

The *CresT* JIP also considered the prediction of the wave-induced velocities; the commonly applied design solutions being bench-marked by comparison to the models outlined in [4]. Recommendations were made concerning the need to incorporate the essential physics and, in the case of the most extreme waves, to include the full nonlinearity [B]. Building on this work, the latest revision of the International Standards Organisation (ISO) design guidance note for offshore structures (Part 1: Metocean design and operating considerations; ISO 119901-1. [E]) notes that commonly applied design wave solutions may be "*non-conservative*" and that nonlinear wave models are "*recommended*". Indeed, a new section on nonlinear wave modelling has been introduced. This emphasises the physical properties of real sea states noting that *"for many purposes, a more accurate nonlinear wave model may be helpful or essential".* Indeed, the standard goes further noting that for the calculation of wave-in-deck loads and the wave forces on a fixed structure in steep waves, *"a fully-nonlinear wave model is required"*. To date, the only fully nonlinear wave models applied in practical offshore engineering design are based upon those developed by Swan at Imperial College [4].

Project specific examples of the impact arising from these wave models are provided as follows. In 2008, kinematics calculations undertaken for Conoco Phillips were incorporated into a DNV (one of the largest certification agencies worldwide) technical note concerning the re-appraisal of an existing North Sea structure [F]. They concluded that accurate fully-nonlinear velocities may differ from typical design calculations by as much as 25%; whilst the total sub-structure loads could be reduced by 15%. More recently (2008-2010), calculations undertaken for Woodside Energy Ltd. [C] showed that under tropical cyclone conditions the total sub-structure loads would be reduced by more than 18%. In this case the certification authority (Lloyds Registry) questioned the significant departures from the American Petroleum Institute (API) guidelines. In addressing this point it was shown [C] that the results were not inconsistent, but that accurate kinematics predictions allowed the API guidelines to be extended to the most severe sea states. In both cases the reduction in the applied substructure loads was key to achieving the required reliability and hence the desired life extension.

Swan's work concerning the nonlinear wave interactions with large volume concrete structures [6] has also produced important impacts. In the first instance the work was applied to explain the occurrence of wave impacts on the Brent Bravo gravity based structure (GBS) in the North Sea. Having established that the integrity of the structure was not threatened, but that the size and layout of the legs were such that significant wave impacts could arise, the areas of greatest susceptibility were identified together with the magnitude of the maximum loads and the areas over which they act. This was important for the continued operation of the structure. Following this work, the UK HSE funded a JIP on nonlinear inertial loading; the resulting guidance note listed under [G]. This work was subsequently incorporated into the ISO technical note on the design of offshore concrete structures [H]. This specifically comments on the unexpected occurrence of wave impacts and the need for detailed model testing. Based on this approach we have: (a) Examined the optimal column size and layout from the perspective of wave loading and wave impacts on a new-build GBS. (b) Addressed difficulties arising at the Sleipner A GBS in the North Sea; a structure that is integral to the UK gas supply from Norwegian fields and which has suffered unexpected shut downs due to the occurrence of wave impacts. This work has considered the wave impact loads arising on the column face, the underside of the deck structure, on essential safety equipment (including free-fall life boats) and, most recently, the loads on newly installed processing equipment [I]. (c) Assessed the implication of the wave-structure interaction for the decommissioning of the Brent Delta GBS. This structure is the first of its kind/size to be decommissioned. Work undertaken by Swan has quantified the kinematic enhancement factors, allowing the fluid loads on subsea infrastructure, essential to the initial stages of the decommissioning, to be calculated [C]. This information was vital to ensure the proposed decommissioning can be undertaken with the appropriate environmental safeguards.

Our work on shallow water wave modelling [3] has also produced a number of key impacts. This work led to our participation in the *LOWISH* JIP. This project was managed by Shell International and supported by 5 major oil companies. A key output from this study was a new laboratory data base generated by Swan at Imperial College. The immediate impacts arising from this work were (a) design guidance on shallow water wave statistics, (b) updated breaking criteria for waves on mild bed slopes and (c) guidance on kinematics predictions [D]. More recently, others have applied this data base producing the following impacts: (a) Improved calibration of the breaking module within the *SWAN* shallow water wave model [D]. This model originates from TUDelft and is extensively applied in design applications world-wide. This work was supported by the US National Oceanographic Partnership Programme (*NOPP*) and funded by the US Office of Naval Research. (b) The formulation and validation of a new empirical wave height distribution model developed in-house by Shell [D]. (c) The overall recommendations of the *LOWISH* JIP, to which the laboratory data generated by Swan contributed greatly, have been incorporated within a leading hindcast model; the latter work undertaken by Ocean Weather Inc. as part of the Southern North Sea Extension Hindcast (*SNEXT*) JIP [D]. (e) It has also provided new design wave kinematics for the *PLUTO* pipeline, a large infrastructure project extending across the continental shelf of north-west Australia [J].

Finally, our expertise in nonlinear wave modelling and laboratory wave generation led to the development of a theoretical transfer function, optimising the performance of force controlled wave machines. This has facilitated further industrial impact in terms of assisting specialist UK manufacturers to secure international orders. Edinburgh Designs Ltd., implemented this work as an integral part of their software control, regarding it as a key component in successful bids to supply wave makers for two very large model testing facilities [K]. The first of these was at MARIN (the Maritime Research Institute, Netherlands), and the second the Naval Surface Warfare Centre at Carderock, USA. The costs of these facilities were €17M and $25M respectively.

5. Sources to corroborate the impact

[A] Smith S.F, *et al*. (2006). 3D nonlinear wave spreading on jackup loading and response and its impact on current assessment practice. OTC paper: 18622. DOI:10.4043/18266-MS

[B] CresT JIP summary report (2010). Summary and recommendations on crest distributions. Edited by Buchner, B. Available on request.

[C] Director, Atkins Energy to confirm the impacts arising from the application of fully nonlinear wave modelling

[D] Principal Met-Ocean Engineer, Shell Malaysia to confirm the impacts arising from the application specifically the North Rankin A platform and the Tyra-East and West developments

[E] ISO (2013). Petroleum & natural gas industries: Specific requirements for offshore structures - Part 1: Metocean design and operating considerations. ISO (draft) report: 119901-1. Available at http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=34586 or on request

[F] DNV (2008). Technical Report: Greater Ekofisk Area. Jacket load comparison, Stokes 5th-order regular wave and fully nonlinear random wave kinematics. Report No:2008-1264. Available on request

[G] Tromans, P.S., Swan, C. & Masterton, S.R. (2005). Technical report: Nonlinear potential flow forcing: the ringing of concrete gravity based structures. UK HSE Report No: RR468 Available at http://www.hse.gov.uk/research/rrhtm/rr468.htm. Also available here

[H] ISO (2006). Standards for the Petroleum and natural gas industries – Fixed concrete offshore structures. Report number ISO 19903:2006. Available at http://www.iso.org/iso/catalogue_detail.htm?csnumber=22994 or on request

[I] Swan, C., Katsardi, V. (20012). Wave-structure interaction at the Sleipner A gravity based structure. The third in a series of reports prepared for Statoil ASA, Norway. Available on request.

[J] Swan, C. and Katsardi, V. (2008). Wave-induced loads on sea bed pipelines. A report prepared for Woodside Energy Ltd., Australia. Available on request.

[K] Director, Edinburgh Designs Ltd. to confirm the modelling was an integral part of their control software and a key ingredient in securing two very large international orders(MARIN and the Naval Surface Warfare Centre at Carderrock, USA; the latter being the largest research facility of its type world-wide