Wave grouping and harbour design

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We wish to compliment the Author on a well-written Paper on a topic which has troubled many experimentalists in coastal engineering for some time. The Author develops the theory on wave generation and the long wave phenomenon in a clear and concise way. The following discussion is intended to elucidate those aspects which we believe to be misunderstandings contained in, or shortcomings of the method proposed by the Author.

53. We must point out that the Author's reference to the original Danish Hydraulic Institute (DHI) method of reproduction of natural wave trains, or the reference to the National Research Council of Canada (NRC, Canada) method described by Funke and Mansard¹¹ is not directly relevant to the long wave suppression method used by these two laboratories. The DHI method of irregular wave generation, by means of the reproduction of natural wave trains, dates back to 1972.¹² This period is the dawn of random wave generation testing in a laboratory. The DHI method proved useful in many applied research projects, but was abandoned some time ago in favour of other more up-to-date techniques. It is, therefore, misleading to imply that the two methods referred to above are the only wave generation techniques employed by the two respective laboratories. For a review of wave synthesis methods we refer the reader to Funke and Mansard¹³ and Miles and Funke.¹⁴

54. With regard to our methodology for spurious long wave suppression, we wish the Author had referred to the paper by Barthel *et al.*¹⁵ which followed the early work by Ottesen-Hansen.¹⁶ This paper resulted from a combined effort by three laboratories in solving the long wave suppression problem. Perhaps the confusion on the part of Bowers in suggesting that the method described in Funke and Mansard¹¹ relates to spurious long wave suppression, stems from the fact that Barthel *et al.*¹⁵ used an irregular demonstration wave, synthesized by the SIWEH method (Funke and Mansard¹¹) to prove the proper functioning of the suppression technique. However, the method by Barthel *et al.* is applicable to any synthesized or naturally recorded wave train for the suppression of spurious long wave components for physical wave generation.

55. The interested reader will notice that there are many similarities in the mathematical formulation and the general description of the problem between the publication by Bowers and the paper by Barthel *et al.*¹⁵ However, there are also many differences.

56. The method by Barthel *et al.*¹⁵ performs its calculation off line as part of the wave synthesis process, using the Fourier transform, whereas the method by

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Bowers performs its calculation by approximate integration in the time domain. Although there are subtle differences between time domain and frequency domain calculations, these can, in theory, be made equivalent. From this point of view, it is not appropriate to consider the method by Bowers to be either different from or superior to the method which has been practised for the last five years by the DHI, the NRC, Canada, and the Delft Hydraulics Laboratory.

57. Since the publication of Barthel *et al.*,¹⁵ additional research work has been carried out. The theory for the suppression of spurious long waves has been extended to the general case, including wave board motions from the piston to the flapper mode of operation (see Sand and Donslund¹⁷ and Barthel and Mansard¹⁸). Investigations into the importance of the spurious long wave suppression technique to physical model studies have been reported in Mansard and Pratte,¹⁹ Barthel *et al.*²⁰ and Pedersen *et al.*²¹ A further important development incorporates the suppression of spurious higher harmonic waves.²² As Bowers points out, the water surface elevation may be considered, by a first approximation, as the superposition of (independent) frequency components, each satisfying the dispersion equation for surface waves. However, since the problem of spurious long wave activity is dominant in shallow water and is of particular interest in the study of nearshore problems, it is not sufficient to consider only the spurious long wave activity. The superharmonic wave components, which are not statistically independent, need to be considered as well. Analysis of this problem indicates that its mathematical description is very similar to the subharmonic or long wave problem.¹³ The main difference is that, instead of the frequency difference terms involving frequencies ($f_{n+m} - f_n$), as required for long wave suppression calculations, frequency summation terms involving frequencies ($f_{n+m} + f_n$), $2f_{n+m}$ and $2f_n$ will now be involved. When solving these equations by the Fourier transform, the same program can be used to accommodate the sub- as well as the superharmonic spurious wave suppression. This is one distinct advantage of the method described by Barthel *et al.*¹⁵

58. There are other arguments which lead us to prefer the Fourier method. The most common method used by us for the synthesis of irregular waves is based on the inverse Fourier transform. A recent publication by Miles and Funke¹⁴ compares this method to most of the other known wave synthesis methods, including that of the Hydraulics Research (HRS) Wallingford synthesizer. The most important conclusion to come out of this study by numerical simulation was the apparent fact that the Fourier transform model for wave synthesis is superior to most other synthesis models. Therefore, if one undertakes the primary process of synthesis in the frequency domain, it makes practical sense to perform the secondary process of spurious long and short wave suppression in the frequency domain as well.

59. Last, but not least, there is a consideration which deserves mention. As Bowers points out, because of the characteristics of available wave generating machines, the maximum permissible stroke of wave boards limits the frequencies over which successful spurious long wave suppression may be realized. This is a consequence of the fact that the lowest frequencies require the longest wave board stroke, which is much in excess of any practical wave generator design. For this reason, it is necessary to cut off spurious long wave compensation at a frequency compatible with the sea state conditions and the available wave machine. If the compensation calculations are carried out off line (that is, not in real time), then one may do two things: firstly, the cut-off frequency can be adjusted until the

wave board excursions are within acceptable limits; secondly, the wave machine command signal can be biased in a positive or negative sense, so that the board excursions are the same in the forward as in the backward direction. This makes better use of the available mechanical stroke of the wave board. Evidently, these operations are simply done beforehand but are impossible to execute in real time.

60. In this connection, we also wish to explain how and why the wave synthesis method described by Funke and Mansard¹³ is being used for wave generation. This method is capable of synthesizing a pseudo-random wave train which matches, at the same time, both a specified variance spectral density and a specified wave energy envelope. This envelope can also itself be synthesized from either a groupiness spectrum, such as a band limited Pinkster²⁴ groupiness spectrum, or a wave set-down spectrum. Because of the stroke limitations for spurious long wave compensation, it is desirable to limit wave grouping to those frequencies for which effective compensation may be carried out. This is possible by the SIWEH method described by Funke and Mansard.¹¹ Apparently, there is no other method available for this purpose. It is not known, at this time, whether it is worse not to compensate for parasitic waves which exceed the wave board stroke, or to distort the groupiness spectrum by a low frequency cut-off, and thereby avoid the generation of these parasitic waves. Needless to say, this method is also a powerful research tool to establish the sensitivity of a structure to specified wave grouping.

61. The HRS Wallingford method of wave synthesis by means of a binary pseudo-random noise source, which was used by Bowers, is generally favoured by researchers who wish to produce extremely long recycling periods for their wave generation process. However, with the availability of modern low cost computers and practically unlimited memory storage, the production of long wave records by Fourier methods is now practical and efficient. There is also no difficulty in matching the expected groupiness spectrum as defined by Pinkster.²⁴ Therefore, it seems reasonable to take advantage of the convenience and power of the Fourier transform method for the predetermination of spurious wave compensation.

62. In § 32, Bowers states that: 'amplitudes of wave grouping disturbances, such as free long waves and set-down itself, can be defined in terms of the wave spectrum without having to retain information about phasing of components in the spectrum'. We believe that Bowers is referring here to the expected groupiness spectrum, which is uniquely defined by the expected variance spectral density of the process and is therefore independent of phases. We concur with this statement. However, it might be misleading to those who do not recognize that the set-down wave propagates bound to a wave group and, therefore, has a unique phase relationship with constituent frequency components of the wave record. In order to simulate the correct structural response, it is usually very important to maintain this phase relationship correctly. This can be verified by comparing the theoretical and the measured set-down in the time domain at several locations in the test flume (cf. Figure 19 in Barthel *et al.*¹⁵). The 'long period spectra' by themselves are not sufficient evidence that satisfactory suppression has been accomplished. It would have been helpful to see such a time domain comparison for the experimental work by Bowers.

63. Anyone who is accustomed to the trials and tribulations of physical model studies knows that, in spite of all the progress which has been made in wave generation technology, there are still many unsolved problems. One of the more important ones deals with the general physics of surf beats and the control of partial long wave reflections from a beach in a wave flume or a wave basin. As

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Bowers points out, such reflections, which are not known beforehand, are re-reflected from the wave board and then form a standing wave pattern in the tank. Hence, these cannot be included in the suppression calculations and, therefore, they pose a difficulty. At the present time, this problem is minimized by enhancing the absorption characteristics of the beach. Evidently, there is a need to develop an understanding of the surf beat phenomenon, and, in this context, to develop a method for the active absorption of such surf beat reflection in the laboratory. This is a task which should be well within the scope of present day wave generation technology.

Dr Bowers

Before replying to specific points raised in the discussion, I think it is worth saying that I now feel I am 'preaching to the converted'. One of the main purposes of my Paper was to show, through both theory and experiment, that the random phase assumption in wave modelling provides a sound statistical framework for the description of wave grouping responses of harbours and moored ships, and leads, in particular, to a well-defined return period for those responses. In making this point, some limitations of the methods of wave generation that avoid the use of random phases were mentioned (§ 7); one of these methods was pioneered at the Danish Hydraulic Institute (DHI) and another was developed at the Hydraulics Laboratory of the National Research Council of Canada (NRC, Canada). However, it is now clear from the discussion that the DHI have abandoned their natural wave train method (§ 53) and, recently, the NRC, Canada, have been experimenting with techniques that employ the random phase assumption.¹⁴

65. The synthesizer, developed at Hydraulics Research (HR) in the early 1970s, was used for the experimental work described in my Paper, but it is just one of a number of possible methods of generating truly random waves when the device is set to produce long, non-repeating, wave cycles. Therefore, the benefits of using random phases are not restricted to the synthesizer. However, we at HR do feel that the synthesizer, which is as accurate as other random phase techniques, does have an advantage because it works in 'real time' instead of calculating the entire time series before wave generation.

66. Working in real time, and this is in answer to points raised in § 61 of the discussion, is particularly useful in representing wave grouping effects where, as shown in my Paper, there is a clear need to generate relatively long cycles of random waves. For example, some tests need to be about an hour long in the model to achieve a good statistical representation of the low frequency response. Such a wave sequence would require 2^{15} data values for a single run and hence the fast Fourier transform (FFT) of 2^{13} complex Fourier components when using the 'off line' technique mentioned in §§ 56 and 61 of the discussion. The set-down compensation then requires the appropriate sums from 2^{26} complex products of component pairs before applying the FFT to obtain the time series, and this is a large amount of calculation even for modern computers. (The alternative is to patch together a number of shorter runs but, while this can be justified for the linear signal, it is not clear that the second order signal obtained in this way will be correct.) Calculations of this magnitude are avoided with real time set-down compensation where there is no limit on the length of test that can be carried out. However, it is emphasized that we do not claim (see § 56 of the discussion) that the HR synthesizer with real time set-down compensation is more accurate than other

methods of wave generation employing the random phase assumption. The differences here simply relate to convenience in use.

67. Paragraphs 53–55 of the discussion appear to be prompted by a fear that readers of the Paper will not understand that, in § 7, I am discussing the limitations of some of the techniques of primary wave generation, and will, instead, think that I am questioning the accuracy of the method of set-down compensation, or spurious long wave suppression, developed at the DHI^{6, 7} and subsequently extended jointly by the NRC, Canada, the DHI and Delft.¹⁵ As already mentioned, this compensation method employs Fourier analysis to calculate an appropriate wave generator signal for suppression of spurious long waves before model tests are carried out, and there is no reason to suppose that the method is inaccurate for a given technique of primary wave generation. I believe this method of set-down compensation, correct in itself, grew out of the reproduction of natural wave trains: the technique of primary wave generation pioneered at the DHI. The link here with set-down compensation is that both amplitudes and phases of spectral components are needed for reproduction of measured wave trains. Given all these Fourier components for the primary wave motion, it is natural to use them to calculate the extra wave-maker signal needed for set-down compensation, and I had this historical link in mind when referring to the earlier DHI work^{6, 7} on set-down compensation in § 7 of my Paper.

68. In § 57 of the discussion, suppression of spurious waves at harmonics of the primary wave is considered. These harmonics become more pronounced in coastal waters where they cause wave crests to become sharper and troughs shallower: characteristics of shallow water waves. At HR we have not seen a need to compensate at the wave-maker for these harmonic wave components for two reasons. Firstly, it is usual to represent the appropriate seabed contouring in front of a structure under test, which means the harmonics have time to develop naturally in the model before waves reach the structure. In travelling into shallower water these harmonics should grow dramatically and become much larger than spurious harmonic waves from the wave-maker. Secondly, harbours and moored ships are not sensitive to harmonics of the ordinary waves, because the wave lengths involved are so short and resonant response periods are so long compared with harmonic periods. This contrasts with set-down where compensation at the wave-maker is needed because the wave lengths involved are so long and resonant responses can occur at wave group periods.

69. Some recent work at the NRC, Canada, is discussed in § 58. Here, reference is made to a paper¹⁴ yet to be published in the *Proceedings of the 21st Coastal Engineering Conference* held in June 1988. As I have not seen the paper, I can base my comments only on the abstract which has been published. Details of the comparison between various methods of random, or irregular, wave generation do not appear in the abstract; however, § 58 gives the most important conclusion as: ‘the apparent fact that the Fourier transform model for wave synthesis is superior to most other synthesis models’. I find this surprising as, provided that the Fourier transform uses random values for both components, it is, as implied in § 56 of the discussion, completely equivalent to a white noise filter in the time domain. In fact, the HR synthesizer uses a binary random input, and its ability to reproduce Gaussian statistics in primary wave generation was checked at the time of its development in the early 1970s. Also, the following point can be made. In carrying out the experimental work described in my Paper, the HR synthesizer was used, with real time set-down compensation, to show that with a long enough

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model test the measured set-down spectrum tended to the expected set-down spectrum (Figs 5 and 6 of the Paper): a spectrum that remains the same for any method of generation of truly random waves. This proves the ability of the HR synthesizer to produce the required wave grouping effects in random or irregular waves.

70. The need to limit wave paddle strokes is discussed in § 59, where it is stated that this is possible off line but impossible in real time. This again contradicts the point already made in discussion in § 56, where it is pointed out, quite correctly, that equivalent operations off line and in real time can be devised. This is indeed the case and the experimental results reported in my Paper, using real time generation, could have been achieved only by filtering out the very long period components in set-down compensation to avoid running out of paddle stroke. The synthesizer itself is also a real time filter that enables the required wave spectrum to be represented. It is equally possible to provide an appropriate steady offset of the mid-position of the wave board in a real time generation method, if it were needed. In practice, we have found an asymmetry between the speed of travel of the wave board forward and backwards: an effect that would be expected on account of the nature of set-down. In relatively long model tests there does not, however, appear to be any great asymmetry between the maximum amplitudes of forward and backward movements about the equilibrium position, making an offset unnecessary.

71. The points made in § 60 of the discussion relate to reproduction of the expected wave grouping spectrum for just those periods for which set-down compensation is possible. It is claimed that this can be achieved with a special pseudo-random time series generated by the SIWEH method.^{8, 11} The difficulty here is still one of realism if relatively short wave sequences are used. Firstly, difficulty will be experienced in producing the expected grouping spectrum at all positions in a wave basin or flume; this is because waves of different period travel with different phase velocities, making the wave grouping pattern vary with position. Therefore, producing an expected grouping spectrum at one position will not guarantee its presence at other positions: a problem that is overcome with long enough sequences of random waves because, although the grouping pattern will alter from place to place, there are enough wave group components still to produce the expected spectrum at all positions. This corresponds with the situation with primary waves in that a long enough random wave sequence (and this will be much shorter than the sequence needed for wave groups)—e.g. one with about 60 waves—will contain enough wave components to produce, within acceptable limits, the same average wave height at all positions, even though individual wave heights vary from place to place. The second problem with relatively short sequences is that long period resonant responses of harbours and moored ships are among the quantities of ultimate interest. Given that these responses are usually non-linear—e.g. subharmonic sway of a moored vessel against stiff fenders²⁵—the only safe way of representing them adequately in a model is to carry out a sufficiently long test. This point is discussed in § 43 of my Paper. Therefore, sufficiently long tests with random waves serve two purposes: one is to achieve the expected set-down spectrum; the other is to ensure that the long period responses of harbours and moored ships are well represented. The second point made in § 60 concerns limitations imposed on set-down compensation by the maximum allowable wave paddle stroke. Here, of course, it is important to ensure that set-down compensation takes place over a wide enough range of wave

group periods to cover the resonances of interest in harbour and moored ship studies.

72. Some clarification is needed of the discussion given in § 62. As explained in § 70, the set-down spectrum will tend to the expected spectrum at all positions in a wave basin or flume when a long enough sequence of random waves is generated; this will happen even without set-down compensation at the wave-maker because set-down is generated by non-linearities in the wave motion itself and not by the wave-maker. This leads to its unique correlation with wave groups in both the real sea (Fig. 2 of the Paper) and in model waves. However, spurious long waves will also develop in the model in the absence of set-down compensation, and these waves will cause the combined set-down and spurious long wave spectrum to differ from the expected set-down spectrum. In this situation, it is sufficient to show that the combined spectrum tends to the expected set-down spectrum—i.e. the spurious long wave energy is absent—in order to prove that set-down compensation is working. This point is demonstrated in Figs 5 and 6 of the Paper.

73. A second indirect proof that the real time method of set-down compensation is working comes from the application described in my Paper (see Table 1). It is found that wave group responses decrease with compensation which is consistent with the idea of removing spurious long wave energy. If the phasing of the compensation signal relative to wave groups at the wave-maker were not correct, this would not happen. The confusion that arises in discussion in § 62 may again be due to using short sequences of waves where, as explained in § 70, the set-down spectrum itself can vary from place to place, making it difficult to prove an absence of spurious long wave energy by spectral measurements alone.

74. The arguments given so far are true for purely progressive waves, but in both nature and model, set-down reflects from the coastline (and model boundaries—even beaches) to produce surf beat: another source of long wave energy (see also § 12 of my Paper). While the effects of surf beat on the total long wave spectrum can be minimized in flume tests, using the measurement technique described in the Paper, its presence in the total long wave time history cannot be ignored. This throws some doubt on the sort of time domain comparisons described in § 62 of the discussion, as the surf beats will alter the clear 'depression beneath wave groups' that would occur if set-down alone existed. This is the reason such comparisons were not presented in my Paper.

75. Finally, it is pleasing to be able to end on a note of agreement. The need to absorb surf beats at the wave-maker, as described in § 63 of the discussion, has been recognized at HR as well.

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