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THE CORRECT REPRESENTATION OF SET-DOWN BENEATH WAVE GROUPS IN RANDOM WAVE HARBOUR MODELLING

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ABSTRACT

A device to compensate for set-down beneath wave groups in long crested random wave models has been developed and tested with satisfactory results. It is found that, generally, set-down compensation reduces the amount of long period energy in physical models. This is consistent with the theory describing the minimisation of spurious long waves from the wave-maker.

Application to a particular harbour model used in project work has again illustrated the dominance of long period moored vessel responses in controlling berth downtime. This remained true with set-down compensation even though mooring line loads and vessel movements were reduced by up to 30% for some wave conditions. Results obtained with set-down compensation can be expected to provide more realistic estimates of berth downtime.

In the near future it is planned to design and build a short crested wave-maker for use in harbour modelling. It is known that set-down in this more realistic representation of the sea is different from set-down in long crested seas and this can be expected to further influence berth downtime estimates. Research is underway into methods of set-down compensation for short crested wave generators.

The work described in this report also shows how extremes of paddle movement become non-Gaussian when set-down compensation is employed with longer paddle strokes being required. Therefore, further research is also needed to enable extremes to be estimated so that the new wave-maker can be designed with sufficient stroke to be capable of set-down compensation.

CONTENTS

1 INTRODUCTION

This report describes the evaluation of a device to ensure the correct representation of set-down beneath wave groups in harbour models using long crested random waves.

Research has shown (Ref 1) that although set-down is not a true long wave it can excite harbour responses in a way that is similar to free long waves incident on a harbour. Free long wave energy can also appear in coastal areas when the incoming set-down reflects from the shoreline. The resulting seaward going long waves are called surf beats because they were found to be correlated with beats produced by groups of waves breaking in the surf zone. Thus, long waves in harbours can be caused both by set-down, which is bound to groups of incoming incident waves, and by surf beat, the reflection of set-down from the coastline outside the harbour.

Recent examination of site data collected just offshore of Port Talbot with a pressure sensor (Ref 2) indicates that in moderate wave conditions surf beat will dominate over set-down. But in storms the dominant mechanism exciting a long wave response in harbours is likely to be set-down beneath wave groups. This happens because the magnitude of surf beat appears to be linearly related to the wave height whereas set-down is proportional to the square of the wave height. Thus, as wave height increases set-down will gradually become dominant.

From the above it follows that the correct representation of set-down beneath wave groups is crucial in harbour modelling. Research has shown (Ref 3) that the result of not programming the wave generator to produce set-down is to introduce spurious secondary long waves but that this spurious behaviour can be avoided by adding an appropriate long period movement to the wave-maker. Provided this movement exactly compensates for set-down at the generator no unwanted long waves will be produced.

In a previous report (Ref 4) it was shown that a microprocessor can be used to modify the input signal to the wave-maker to produce set-down correctly. While demonstrating the feasibility of this approach it was found that improved filtering in the microprocessor was needed to avoid excessive wave paddle strokes. These improvements have now been made and this report describes an evaluation of the updated microprocessor.

2 EVALUATION METHOD

To compensate for set-down it is necessary to generate the appropriate long period movement of the wave-maker. This is done by first calculating a spectrum for the long period paddle movement which is dependent on the primary wave and paddle spectrum and water depth at the wave-maker. Tests are then carried out using the set-down generator and a gain control on the device is adjusted until the measured long period spectrum of paddle movement matches the calculated one over the frequency range of the device.

Having set-up an appropriate long period movement of the wave generator wave measurements can be made to verify that the long period disturbance in the water is that expected due to set-down beneath wave groups by again checking a measured spectrum against a calculated one.

In this report both of the above steps are described for a number of wave spectra with the disturbance in the water being checked for the case of a uniform water depth. In physical models of harbours seabed contouring appropriate to the site under investigation will exist in front of the wave generator and this precludes checking the spectrum of the disturbance in the water as both surf beat and set-down will be present in a complex pattern of long period energy that defies calculation. This difficulty can be overcome for uniform depths by using the technique described in Reference 3. In this technique a shingle beach is placed at the end of a wave flume to absorb primary waves. However, set-down will still reflect from the beach due to its long wave nature causing surf beats to travel back towards the wave generator. These surf beats will re-reflect from the wave board as it if were a vertical wall giving rise to nodes and antinodes at various distances from the wave board. For each frequency band in the long period spectrum it will therefore be possible to calculate nodel positions and spectral densities measured there with a wave probe should contain a minimum of surf beat energy for that particular frequency. Thus, it is possible to build-up a composite long period spectrum with a minimum of surf beat energy in it by only using spectral densities measured at a nodal point for each frequency band. In this way a number of wave probes placed in strategic positions over an area of uniform water depth can be used to measure a long period spectrum in which set-down is dominant. This allows comparison with a calculated set-down spectrum which is defined in terms of the primary wave spectrum and the water depth. Without the set-down generator operating spurious long wave energy will also exist at the nodal positions causing a mismatch with the calculated set-down spectrum.

2.1 Calculated spectra

In the evaluation method described above two steps were identified. In the first step the gain control on the set-down generator is adjusted by making a comparison with a calculated spectrum for the long period paddle movement. In the second step a check is made on the disturbance in the water by comparing a measured long period spectrum with a calculated set-down spectrum. Here we outline the method used to calculate the paddle and set-down spectra.

The basic equation describing irrotational motion is

$$\nabla^2\phi = 0 \qquad (1)$$

where water particle motion, in the vertical x, z plane of a right handed orthogonal co-ordinate system, with velocity $\underline{v}$ (horizontal component u and vertical component w) is related to the velocity potential ϕ by

$$\underline{v} = (u, o, w) = -\nabla\phi$$

The boundary conditions to be satisfied by surface waves are:

$$w = 0 \qquad (2)$$

on the bottom $z = -d$ and

$$\eta_t + u\eta_x - w = 0 \qquad (3)$$

$$\tfrac{1}{2}v^2 + g\eta - \phi_t = 0 \qquad (4)$$

on the free surface $z = \eta$.

Here, ϕ_t indicates the partial derivative of ϕ with respect to time with corresponding meanings for the other variables with a suffix.

Equation (1) can be solved for wave motion by carrying out a Stokes expansion. This assumes the product terms in (3) and (4) to be small in comparison with the other terms in the equations. Thus, the following set of lowest order equations is obtained:

$$\nabla^2\phi^{(1)} = 0 \qquad (5)$$

where

$$\underline{v}^{(1)} = (u^{(1)}, o\ w^{(1)}) = -\nabla\phi^{(1)},$$

and the boundary conditions are,

$$w^{(1)} = 0 \qquad (6)$$

on $z = -d$ and

$$\eta_t^{(1)} - w^{(1)} = 0 \tag{7}$$

$$g\eta^{(1)} - \phi_t^{(1)} = 0 \tag{8}$$

on $z = 0$.

In the above, variables have a superscript of one to denote quantities that vary linearly with wave amplitude.

In second order, quantities vary with the square of wave amplitude and are therefore denoted by a superscript of two. The basic wave equation is

$$\nabla^2\phi^{(2)} = 0 \tag{9}$$

Expanding (4) to second order gives an expression for the second order correction to the wave elevation,

$$\eta^{(2)} = \frac{1}{g}\left(\phi_t^{(2)} - \eta^{(1)}w_t^{(1)} - \tfrac{1}{2}\left(V^{(1)\,2}\right)\right)_{z=0} \tag{10}$$

where the right hand side is evaluated on $z = 0$. Substituting for $\eta^{(2)}$ in (3) gives the boundary condition to be satisfied by the second order potential on the free surface ($z=0$),

$$\phi_{tt}^{(2)} + g\phi_z^{(2)} = \eta^{(1)}(w_{tt}^{(1)} + gw_z^{(1)}) + 2\underline{v}^{(1)}\cdot\underline{v}_t^{(1)} \tag{11}$$

The boundary condition on the bottom ($z = -d$) is,

$$\phi_z^{(2)} = 0 \tag{12}$$

We see from equation (11) that second order corrections to the velocity potential, amongst them set-down beneath wave groups, are forced by products of first order quantities acting at the free surface (see right hand side of (11)). Assuming a first order spectrum of wave energy (examples are shown in Figs 1, 5, 8, 14 and 17) we can define the first order wave elevation as a sum of frequency components with random phases where the amplitude a_n of a component is related to the spectral density at frequency fn, ie,

$$\tfrac{1}{2}a_n^2 = s(fn)df$$

Substituting first order quantities into the right hand side of (11) then enables a solution to be found for $\phi^{(2)}$ and hence for second order corrections to the wave elevation $\eta^{(2)}$ via (10). This in turn enables definition of the long period part of the spectrum of $\eta^{(2)}$. Examples of set-down spectra calculated in this manner are given in Figures 3, 7 and 10 where the expectation values of spectral density are shown under the theoretical result.

When a wave-maker generates the wave system, a required boundary condition is that the horizontal velocity of the wave board equal the horizontal velocity of water particles at the generator. This can be written as

$$\zeta_t = u$$

where ζ is the horizontal displacement of the wave paddle from its equilibrium position. To first order in wave amplitude this equation allows calculation of the transfer function between wave amplitude and paddle stroke. To second order we find

$$\zeta_t^{(2)} = - \phi_x^{(2)} - \phi_{xx}^{(1)} \zeta^{(1)} \tag{13}$$

where the right hand side of the above equation is evaluated at the equilibrium position of the wave-maker. Substituting for first order quantities and the second order potential in the right hand side of (13) enables an expression to be obtained for the long period paddle movement needed to compensate for set-down. To do this we see from (13) that integration with respect to time is needed which results in very large paddle strokes being required for long period components. In practice there is a limit on the stroke allowed which means that the working range of the set-down generator is bound by a lower frequency. Examples are shown in Figures 2, 15 and 18 of the paddle spectrum required to compensate for set-down according to equation (13) (see theory curves). Also shown is the response of the set-down generator which cannot follow the theory curve for frequencies (at full scale) below about 0.007. This assumes a model scale of about 1 to 100 which is typical for harbour studies and the cut off point corresponds to a period of about 140 seconds which is expected to be adequate for most harbour studies. This is because the resonant periods of horizontal motion of vessels on their moorings normally lie within the range of 20 seconds to 120 seconds. It is emphasised that this limit to the working range of the set-down generator arises purely from the mechanical limitations of the wave-maker. Should a generator with a larger working range be needed then provided an increased stroke is allowed by the mechanical system the response function of the set-down generator can be altered to increase its working range.

2.2 Spurious long waves

In the absence of secondary paddle movement (13) can only be satisfied by introducing free secondary waves. Denoting the velocity potential of these waves by $\phi_L^{(2)}$ and using the suffix s to identify the second order potential of set-down we find (13) gives

$$\phi_{Lx}^{(2)} = - \phi_{sx}^{(2)} - \phi_{xx}^{(1)} \zeta^{(1)}$$

This equation determines the amplitude of the spurious free long waves which also satisfy the usual wave equations, ie, (9), (12) and (11) with the right hand side put to zero.

The presence of spurious long waves has been identified in earlier work carried out as part of the basic research programme of the Hydraulics Research Station (see for example Refs 1 and 3). Their effect in the experiments described here are apparent in Figures 7 and 10 where long wave spectra measured in the absence of the set-down signal to the wave-maker are shown alongside those measured with the set-down signal.

3 EXPERIMENTAL RESULTS

The experiments follow the pattern outlined in the previous Section with the gain on the set-down generator being adjusted first until the required long period spectrum is obtained, with the long period wave motion being investigated subsequently.

When first tried out in a wave basin a fault was identified within the soft wave developed for the updated microprocessor. This prevented tests of sufficient duration being carried out to enable proper definition of long period spectra. The point here is that a sequence of random data lasting about an hour in the model (the equivalent of 10 hours at full scale) is needed to reduce uncertainties in spectral ordinates to reasonable levels. Only then is comparison with calculated spectra justified. Nevertheless, these early results are presented for completeness.

After the fault was corrected tests were carried out in a wave flume with a gently sloping shingle beach at the end to minimise reflections.

Finally, the effect of using the set-down generator in a physical model of a harbour is described.

3.1 Wave basin tests

A wave basin about 12m wide and 18m long was used. This has a wedge type wave-maker which is position controlled by an HR Synthesizer. A gently sloping shingle beach was built opposite the wave-maker to absorb the waves.

The primary wave spectrum used for these tests is shown in Figure 1. It is representative of storm conditions in the North Sea with the spectral peak occurring at a period of 14 seconds. The model scale was 1 to 100 which is typical of harbour models. In full scale terms the water depth was 32m. This too is representative of harbour models which normally have seabed contouring out to depths equivalent to 20m to 30m. But for the purposes of these tests the depth was uniform at the model equivalent of 32m.

Having set-up the primary waves and measured the transfer function between wave height and paddle stroke the long period paddle movement required to compensate for set-down was calculated. Its spectrum is shown as the "theory" curve in Figure 2. As explained in 2.1 the very low frequency components in the theoretical paddle spectrum cannot be generated due to limits on the stroke of the wave-maker. This leads to the expected set-down generator spectrum shown in Figure 2. A gain of 85 was found to produce an actual paddle spectrum (denoted by circles in Fig 2) which was a good fit to the calculated one. This good fit is surprising as the limited length of test involved would lead one to expect large uncertainties in the measured spectral ordinates. In subsequent cases where limited cycles of random data were used these uncertainties became more apparent.

Having set the long period paddle movement, attention was turned to measurements in the water. The results are shown in Figure 3 where spectral ordinates were measured at nodal points of the surf beat system expected to arise in the wave basin. This follows the technique described in Section 2. Also shown as a solid line is the expected set-down spectrum. It can be seen that given the uncertainty in measured spectral ordinates due to the short test length the results obtained with the set-down signal to the wave generator (•) are generally in closer agreement with the expected set-down spectrum than the results obtained without the set-down signal (o). This indicates that spurious long waves from the generator are being minimised by use of the additional long period paddle movement.

Figure 4 shows the full long period spectrum of water paddle movement at various points across the width of the wave basin. All four positions were the same distance from the paddle face which means that nodes and antinodes of any surf beats present will occur at the same frequencies in all four spectra. This probably explains the peaks and troughs present in all four spectra. We also see that the effect of the set-down signal is to reduce the overall energy levels in the long period spectra and this is consistent with minimisation of spurious long waves from the wave generator.

3.2 Wave flume tests

These tests were carried out after the fault in the software, which prevented tests of sufficient duration being performed, had been corrected. Two cases, one representing a large swell condition and the other a storm wave condition, were considered. For the swell of spectral peak period 20 seconds (Fig 5) the significant wave height was 4m and for the storm condition (Fig 8) the spectral peak period was 14 seconds with a significant wave height of 5.5m.

The model scale was again 1 to 100 with a uniform water depth equivalent to 26m. The flume used for the tests was 1.4m wide with a piston-type random wave-maker at one end and a gently sloping shingle beach at the other end to minimise wave reflections.

The pattern of testing was the same as that already described with the gain on the set-down generator being adjusted first until the measured long period paddle spectrum matched the calculated one over the frequency range of the device. In the case of the swell condition (Fig 5) the measured values are shown as circles in Figure 6 for a gain of 229. This is a good fit to the set-down generator spectrum shown by the solid line which, in turn, matches the theoretical paddle spectrum required over the frequency range of the device. This range extends down to frequencies of about 0.007 at full scale.

A fully random sequence of data was used to produce the measured paddle spectrum in Figure 6. The circles denote spectral densities that are averages from Fast Fourier Transforms of 6 chunks of data each containing 4096 values. Thus, 24, 576 data values were used from the random sequence to construct the measured paddle spectrum. This is equivalent to a run of random data lasting about an hour in the model. Attempts were made to match to the expected set-down generator spectrum using a repeating sequence of random data containing 4096 values but this gave spectral densities that were often a poor fit to the shape of the response curve. But such runs were useful in establishing a first estimate of the gain required to match to the response curve.

When the measurements of the long period disturbances in the flume were made, again using averages of 6 chunks of data from a random sequence each containing 4096 values, an encouraging match to the expected set-down spectrum, over the frequency range of the device, was obtained with the appropriate gain of 229 (Fig 7). The long wave disturbance measured without set-down compensation produced a poor fit to the expected set-down spectrum. The lower energy levels obtained in this case show that because the measurement positions in the flume were relatively close to the paddle, spurious long waves were tending to cancel set-down.

A similar picture emerged when tests using the storm condition (Fig 8) were performed.

A good fit to the required set-down generator spectrum was obtained with a gain of 158. These results (Fig 9) were again obtained with averages from 6 runs, each containing 4096 values, taken out of a long random sequence of data.

The corresponding long period disturbance in the flume was consistent with the expected set-down spectrum over the frequency range of the device (Fig 10) on the appropriate gain of 158. Without set-down compensation the long period spectrum was a poor fit to the theoretical set-down spectrum indicating that at low frequencies, at least, spurious long waves were tending to cancel set-down. This is again explained by the measurement positions being relatively close to the paddle.

Long period spectra in the flume were formed initially using averages from 2 chunks of data each with 4096 values and then from 4 chunks of data and finally using 6 chunks. This was done for both the swell and storm wave conditions with the appropriate level of set-down compensation. In each case it was found that the fit to the expected set-down spectrum was the least good with an average of 2 runs and consistently improved as the number of runs increased up to the 6 finally used. This shows that relatively long model runs are needed to produce a good estimate of the standard deviation of long period harbour and moored ships responses. Even longer runs would be needed to describe the probability distributions of maximum movements with a significant long period component present.

3.3 Maximum paddle strokes

An example of a probability distribution of maxima appears in Figure 11. This shows the probability of exceedance (p) of paddle movement amplitudes for a 10 minute run in the model. The parameters relate to the swell wave condition with set-down compensation (Figs 5 to 7). A long run was carried out using a truly random sequence of data and maxima extracted for a series of equal length 10 minute batches each containing an average of 270 (zero crossing) oscillations of the paddle. Seventeen of these maxima (one forward and one backward movement from each batch) are plotted to show their probability of exceedance.

Without set-down compensation (no long period component to the paddle movement) the probability of exceedance of maximum paddle movement amplitudes squared would fit a Gumbel distribution, ie, they would fit a straight line in the type of plot shown in Figure 11 where the line can be defined by the standard deviation of paddle movement and the number of zero crossings in the batch. But Figure 11 shows that with set-down compensation the paddle movement amplitudes tend to develop some asymmetry and do not fit the theoretical prediction based on the total standard deviation (including long period movements) and number of zero crossings in the 10 minute batch length. This is not unexpected as set-down is a non-Gaussian asymmetric quantity. Thus, compensation for set-down can be expected to cause the resulting paddle movement to be non-Gaussian.

When the gain on the set-down generator was increased further to make the long period movement dominant (the primary signal was reduced to avoid running out of paddle stroke making the total paddle amplitude smaller) the deviation from the theoretical result expected for a Gaussian variable became very obvious (Fig 12). The asymmetry between forward and backward movements from the mean also increased.

These results obtained for maximum paddle movements show that research is needed to gain a theoretical description of maxima. Without such a description the design of wave-makers with set-down compensation will involve guess work as to the allowance needed for paddle stroke.

3.4 Application to a physical model

A random wave physical model investigation at a scale of 1 to 110 has been carried out into a proposed new harbour on the coast of South East Asia. Both wave height measurements and the movements and mooring loads of model ships were used to evaluate a number of proposals. One of the favoured layouts is given in Figure 13. It shows a 13m deep navigation channel leading into the harbour and making quite a deep cut into the surrounding sea bed.

It is of interest to see the effect of using the set-down generator in such a model. To do this the two wave conditions given in Figures 14 (SW waves) and 17 (S waves) were generated. The required long period paddle movement spectra were produced with appropriate gains on the set-down generator, ie, 190 for SW waves (Fig 15) and 250 for S waves (Fig 18).

The effect of the set-down generator can be gauged by comparing long wave spectra measured at various positions in the model with and without set-down compensation. The positions chosen were 2, the monitor probe, and 3 and 11 near the roundhead tip of the breakwater (Fig 13). The resulting spectra appear in Figures 16 (SW waves) and 19 (S waves). It is immediately clear that set-down compensation has a marked effect for S waves (Fig 19) but a smaller effect for SW waves (Fig 16). In both cases, however, the effect is to reduce the overall energy levels in the long period spectrum for positions at some distance from the wave-maker, eg, positions 3 and 11. This is again consistent with the idea of eliminating spurious long waves from the wave generator. Near the paddle, monitor position 2, the opposite tends to happen because any spurious long waves will be tending to cancel the effect of set-down (they are exactly 180° out of phase with one another at the paddle) so that their elimination through set-down compensation will tend to increase long period energy up to the levels expected due to set-down.

Apart from the effect of set-down compensation, comparison of spectra for positions 3 and 11 in Figures 16 and 19 shows that there is noticeably more long wave energy associated with SW waves in spite of the fact that similar offshore waves were generated from the two directions (Figs 14 and 17). The reason for this may be linked to the strong "reflection" of waves that occurred from the western edge of the navigation channel when SW waves were generated. This happens when waves meet a channel at an angle and it is due to wave refraction which tends to bend the wave crest around more perpendicularly to the channel axis. This happens as the part of the wave crest over the channel speeds up due to the increased water depth. If the cut into the surrounding sea bed is deep enough the waves are refracted so strongly that they are unable to cross the channel, being "reflected" back on the side of incidence. In the case of SW waves in the Map Ta Phut model this strong refraction effect must have resulted in some additional generation of long waves. This would explain why set-down compensation has less effect for SW waves. If a significant part of the long wave energy is generated by strong refraction effects due to the channel any spurious long waves from the wave-maker become relatively less important.

The above example serves to show how complex wave behaviour can be and how necessary realistic physical models are in evaluating proposed harbour developments. It also illustrates how set-down compensation will have varying effects depending on the model configuration and the wave conditions tested.

Returning to S waves we can gauge the effect of set-down compensation on a model of a ship moored inside the harbour. The results are given in Table 1. The first point to notice is the dominant role played by long period movements of the vessel on its moorings. The harbour provides very good shelter from the primary waves but long waves are able to penetrate well into the harbour because of their long wavelengths with the result that most of the vessel movement and mooring load is at periods longer than 30 seconds. In this case set-down compensation reduces movements and mooring loads by some 20 to 30%.

4 CONCLUSIONS

1. A device to compensate for set-down beneath wave groups in long crested random wave models has been developed and tested with satisfactory results.

2. Measurements of the long period part of random wave spectra are consistent with theory describing the minimisation of spurious long waves from the wave-maker. In carrying out this work it has been found that model runs using random sequences of waves lasting about an hour in the model and containing almost 2000 waves are necessary to obtain agreement with the expected theoretical spectrum of set-down.

3. Probability distributions of maximum paddle movements have been obtained experimentally. They show that set-down compensation makes the paddle movement non-Gaussian in its behaviour with longer paddle strokes being required. This will influence the design of the short crested wave generator proposed for future harbour modelling. In particular, as well as researching set-down compensation for such wave-makers, further research will be needed to enable extremes of paddle movement to be accurately estimated so that

the new wave-maker can be designed with sufficient stroke to be capable of set-down compensation.

4. Application to a particular harbour design has again illustrated how dominant are long period moored vessel responses in controlling berth downtime. This remains true with set-down compensation even though the amount of long period wave energy is reduced. The reduction can be significant or slight depending on the harbour configuration and the wave condition tested.

5 REFERENCES

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TABLE

Table 1 **Effect of set-down compensation on model of a ship moored inside a harbour (S waves - see Figs 13 and 17 to 19)**

		With set-down generator		Without set-down generator	
	*Storm part	*Low freq. part	Total	Low freq. part	Total
Load in mooring line 1(t)	2.8	20.0	20.2	24.0	24.2
2	5.3	19.5	20.2	26.4	26.9
3	51.4	127.7	137.7	179.0	186.2
4	44.7	107.8	116.7	152.0	158.4
5	11.9	40.9	42.6	51.7	53.0
6	2.3	20.6	20.7	27.1	27.2
Surge (m)	0.3	2.83	2.85	3.57	3.58
Sway	0.3	2.34	2.36	2.85	2.87
Yaw (°)	0.1	1.38	1.38	2.08	2.09
Heave (m)	0.15	0.25	0.29	0.38	0.41
Pitch (°)	0.16	0.10	0.19	0.11	0.19
Roll	1.06	0.15	1.07	0.19	1.08

* "Storm" and "low frequency" refer to parts of the total record with $f > 0.03$ Hz (periods shorter than 33s) and $f < 0.03$ Hz, respectively

FIGURES

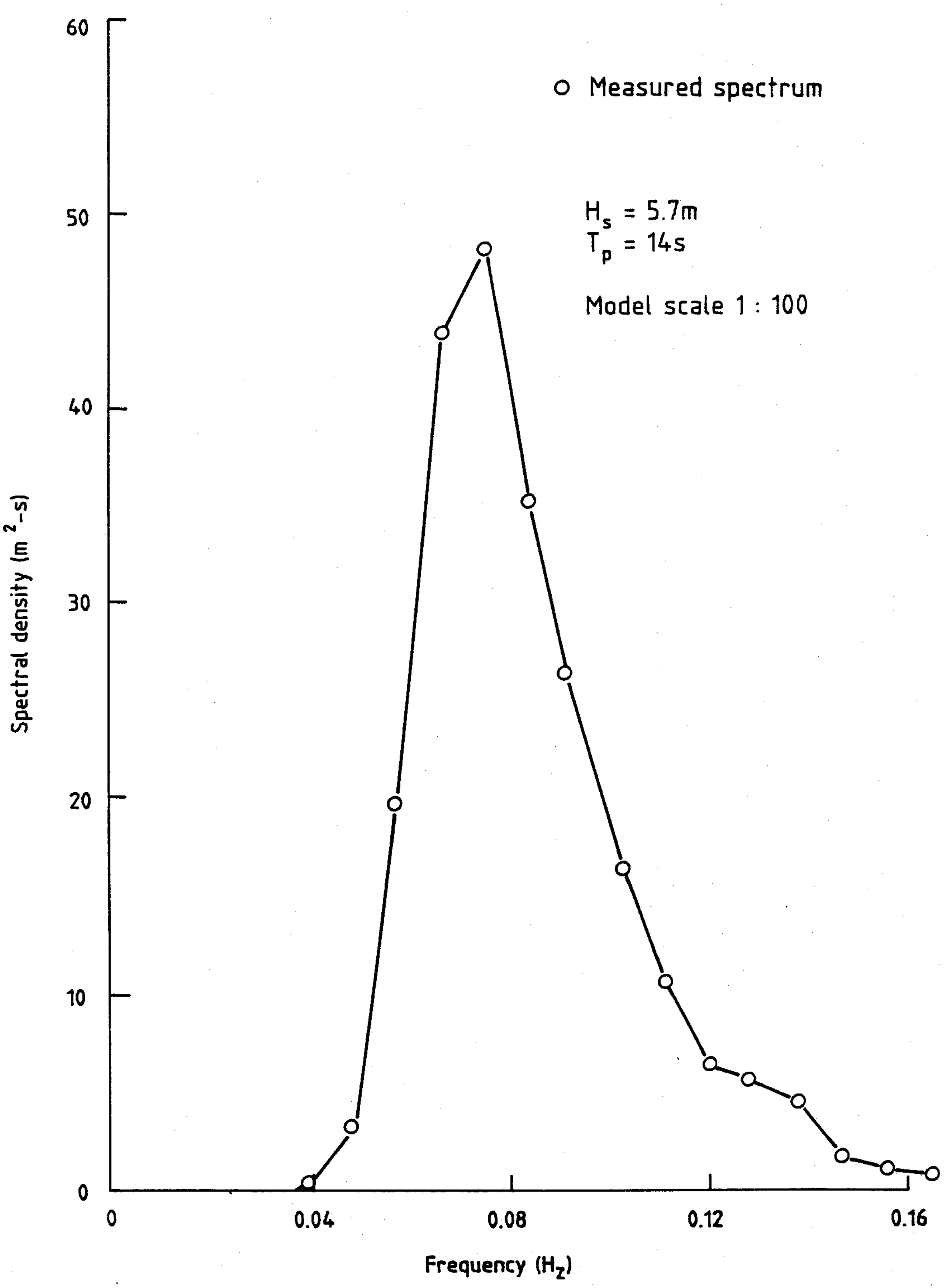

Fig 1 Primary wave spectrum (Case 1)

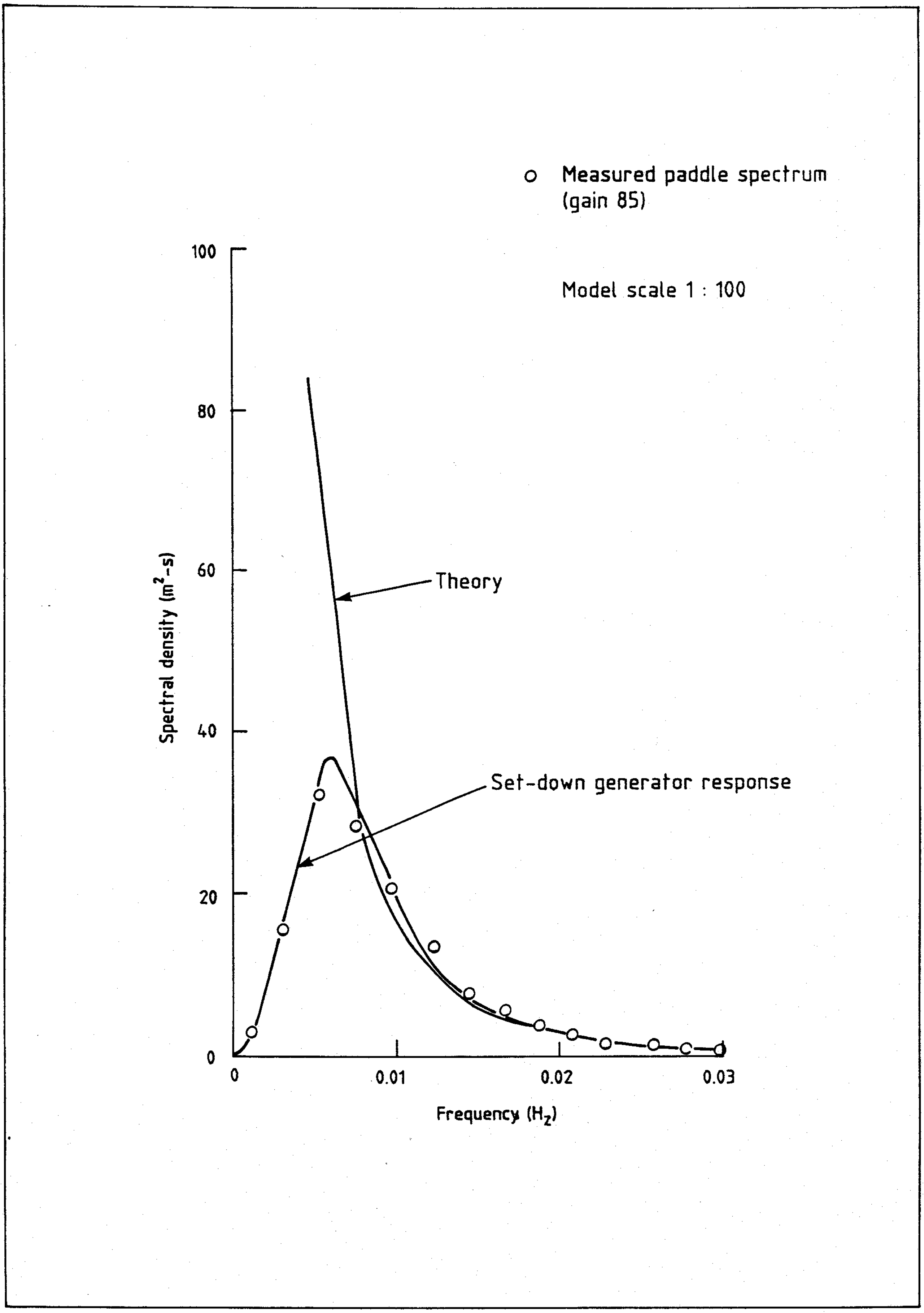

Fig 2 Low frequency paddle spectrum (Case 1)

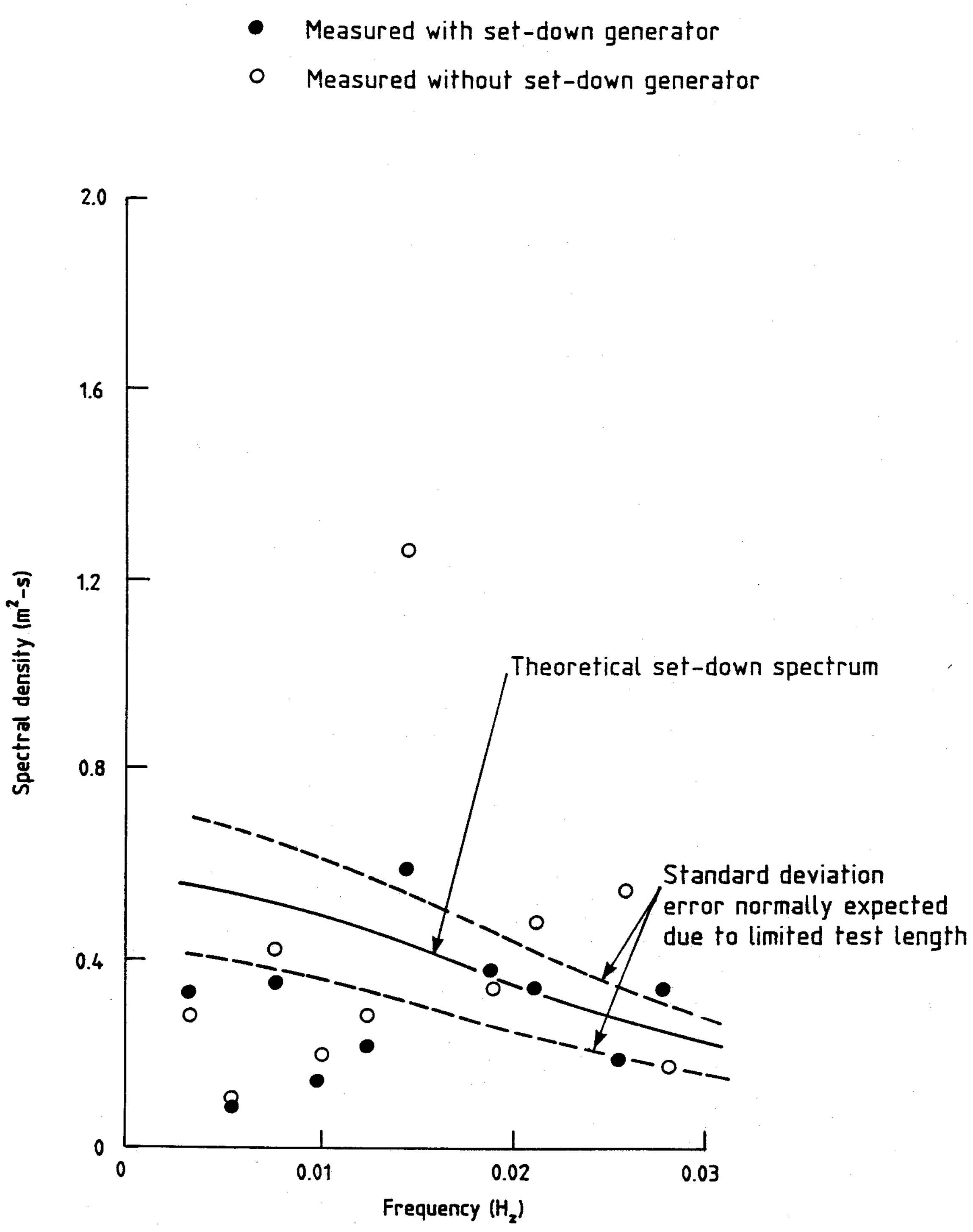

Fig 3 Long wave spectra without surf beat (Case 1)

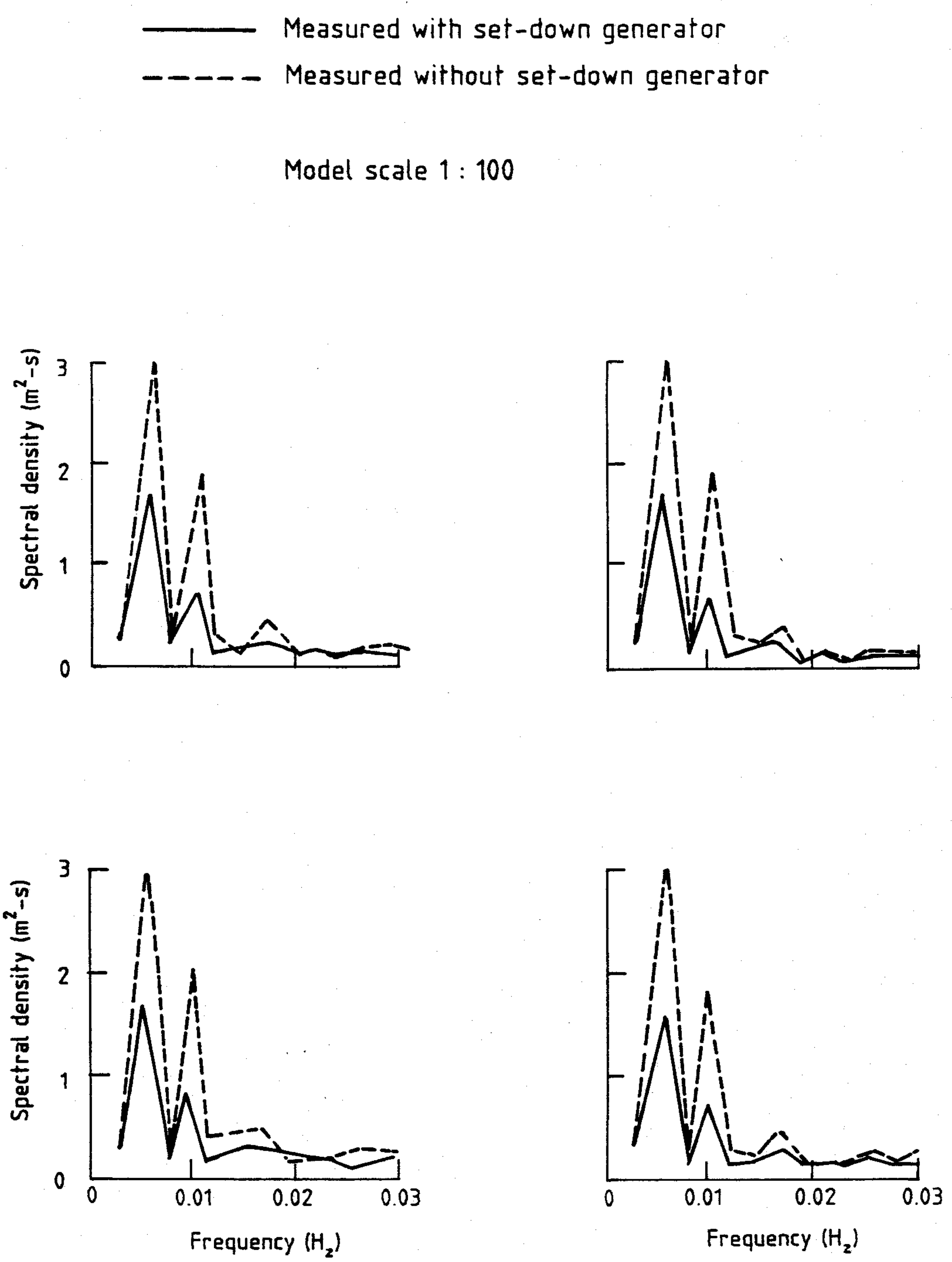

Fig 4 Long wave spectra with surf beat (Case 1)

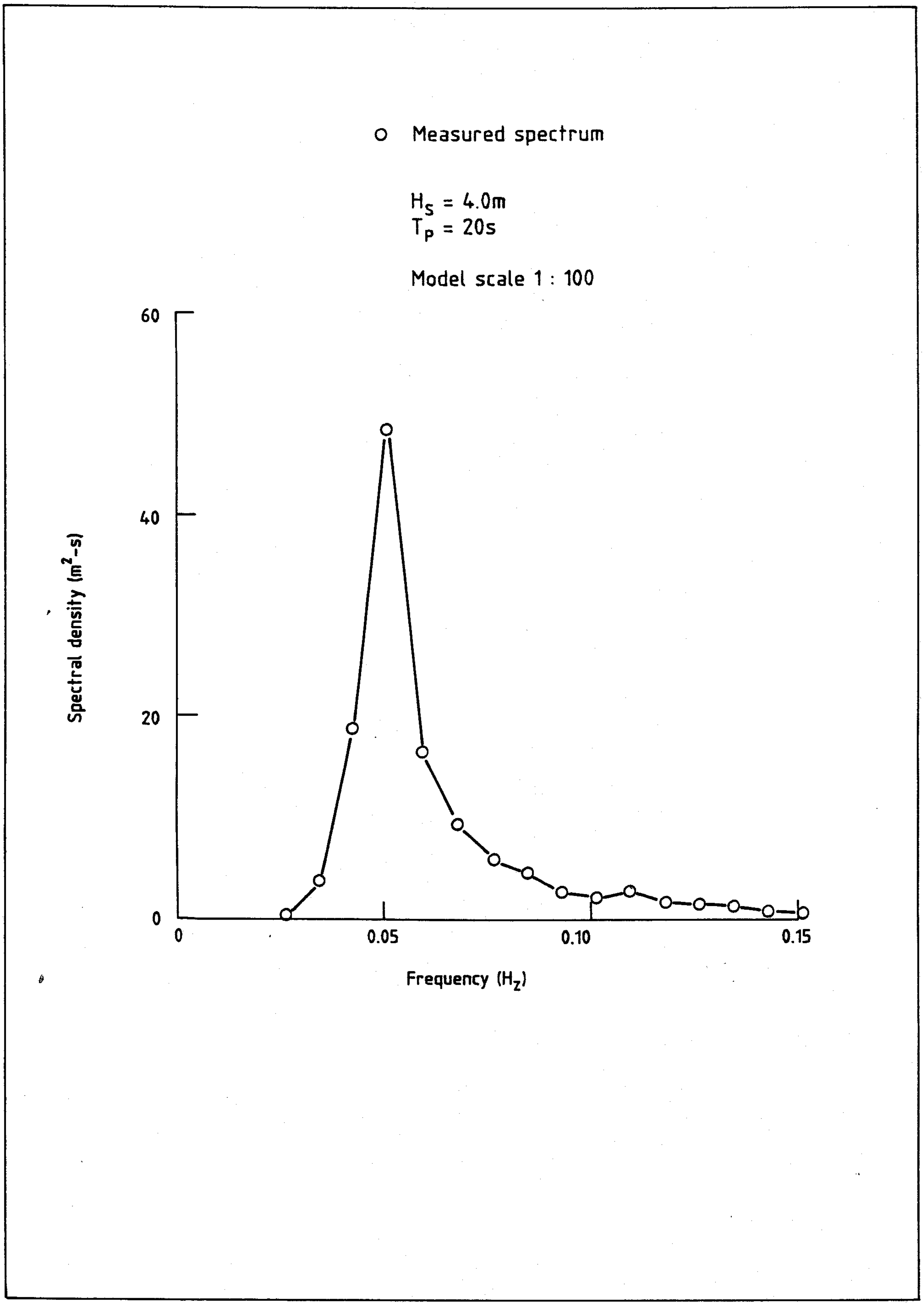

Fig 5 Primary wave spectrum (Case 2)

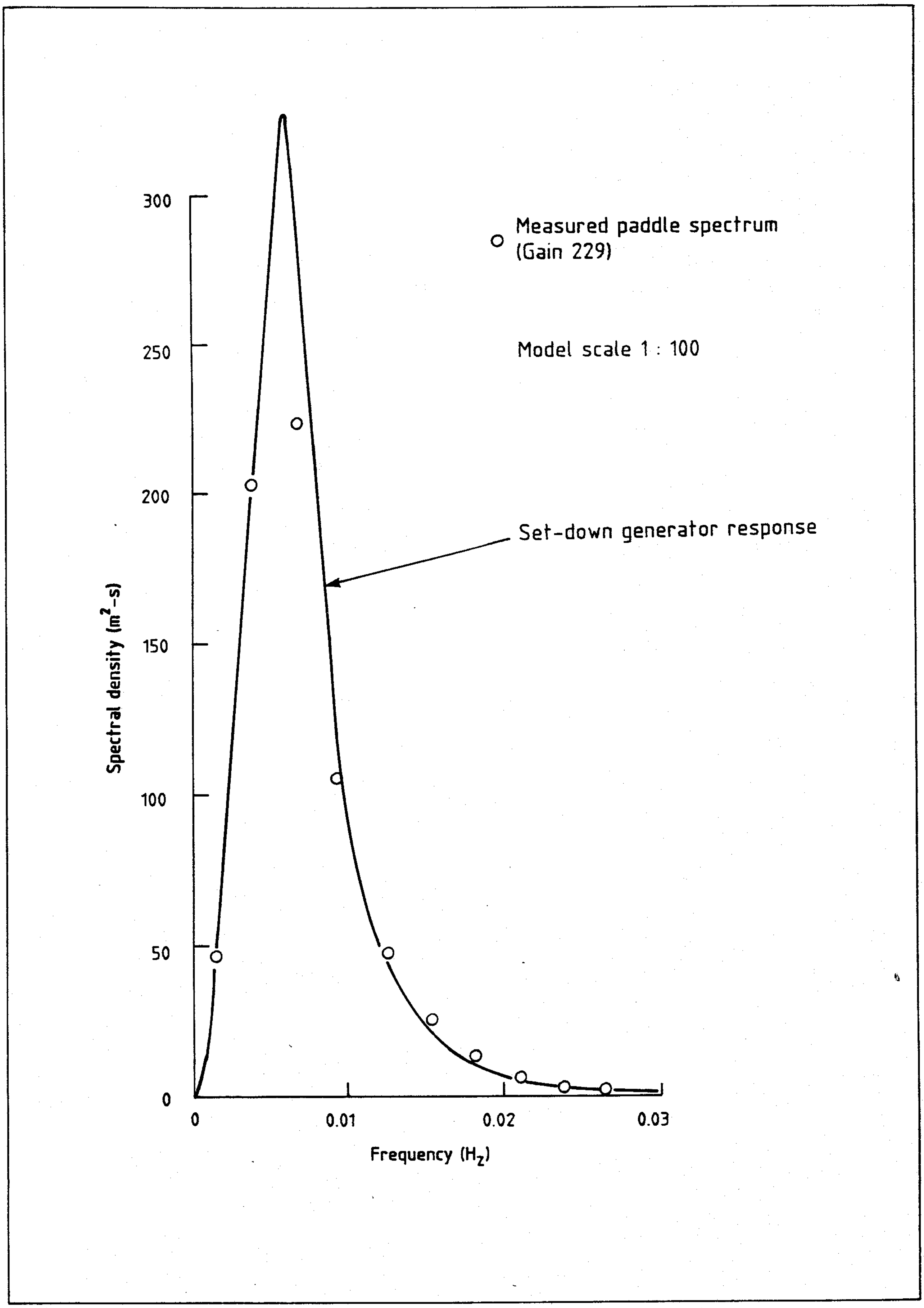

Fig 6 Low frequency paddle spectrum (Case 2).

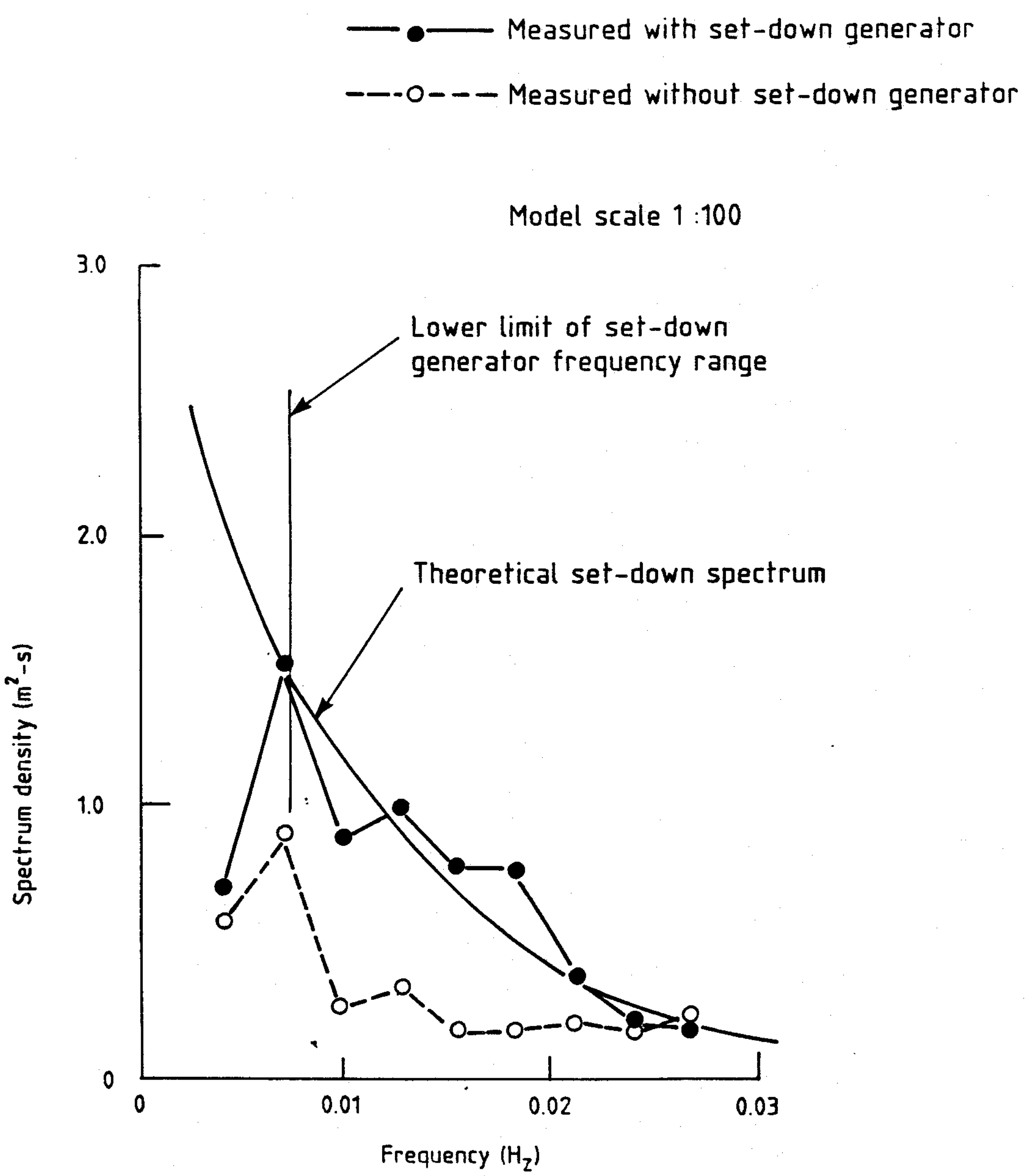

Fig 7 Long wave spectra without surf beat (Case 2)

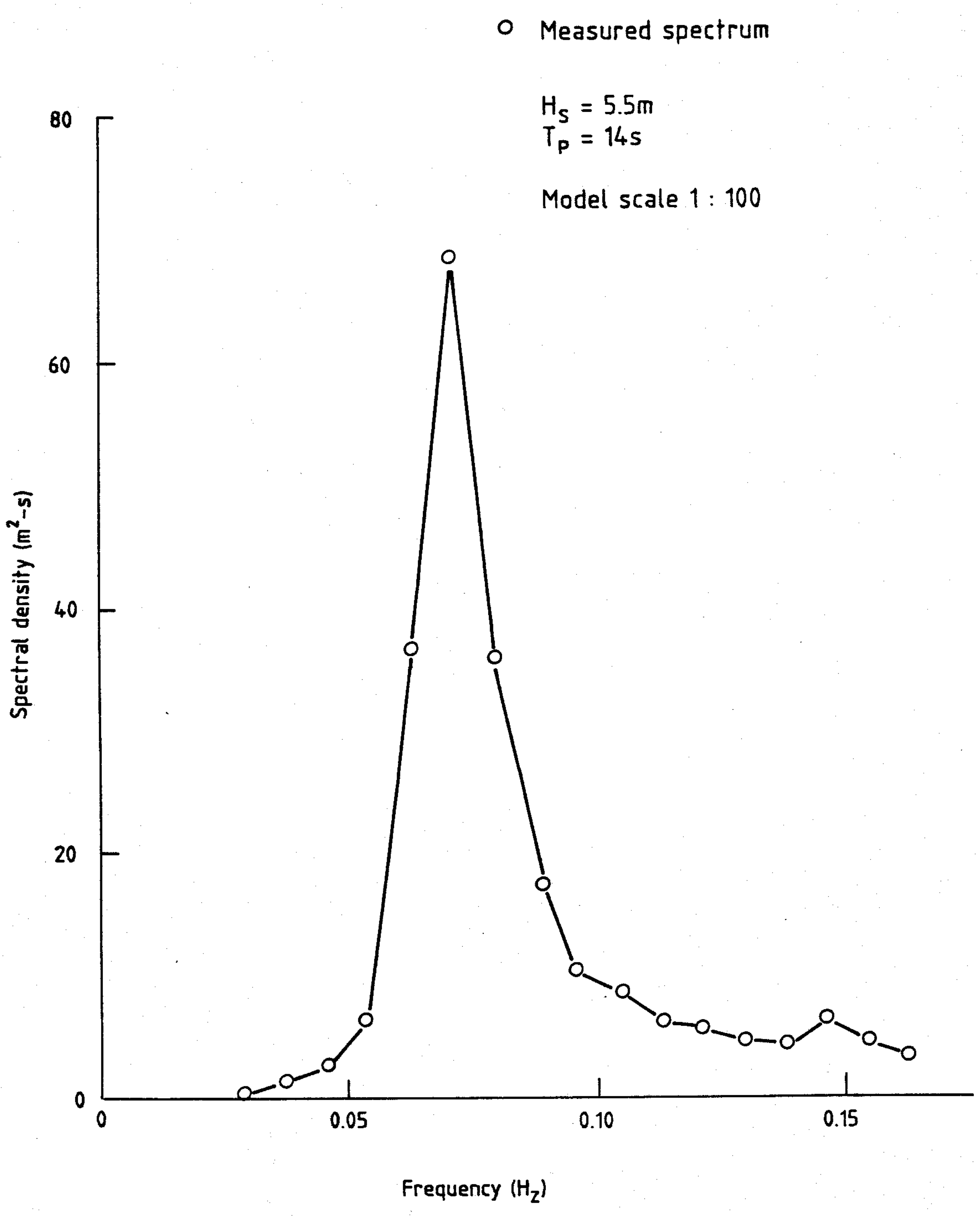

Fig 8 Primary wave spectrum (Case 3)

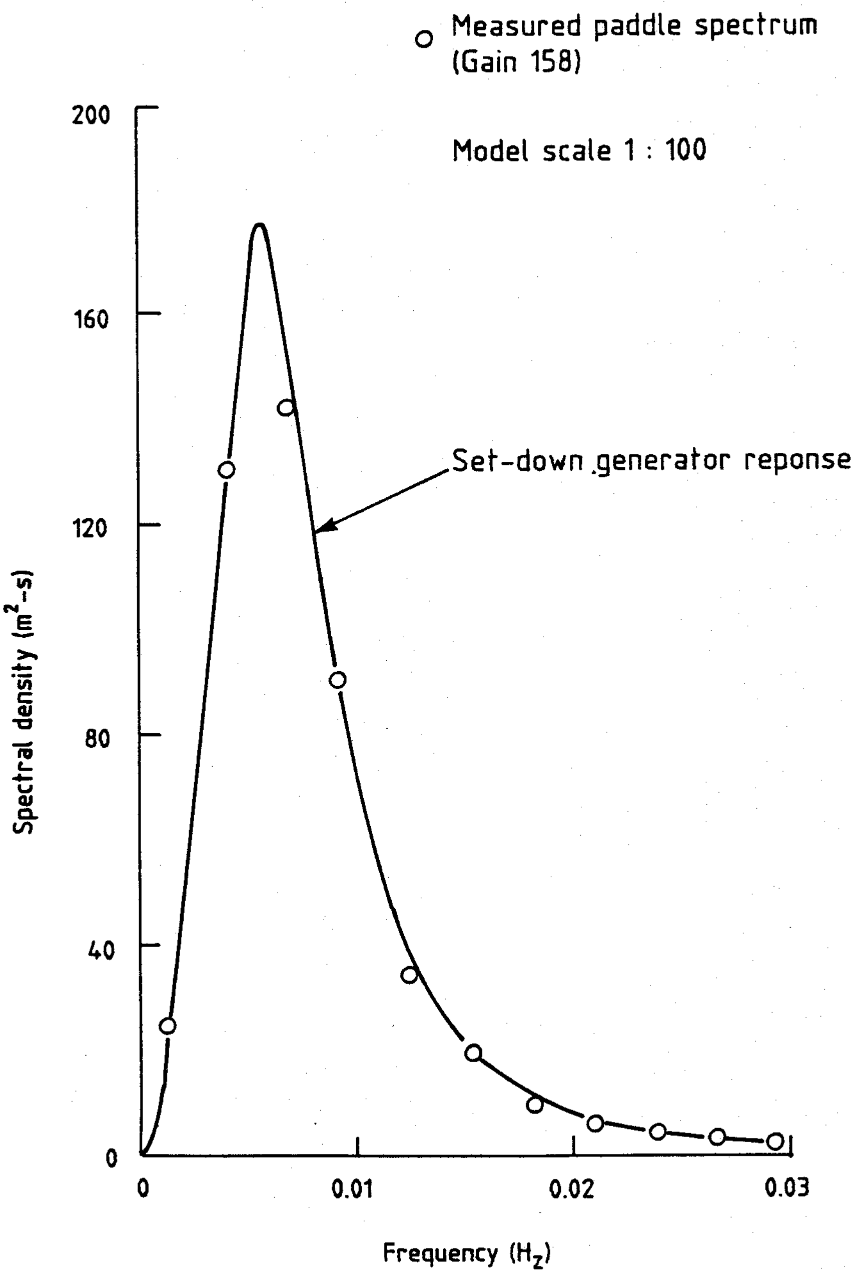

Fig 9   Low frequency paddle spectrum (Case 3)

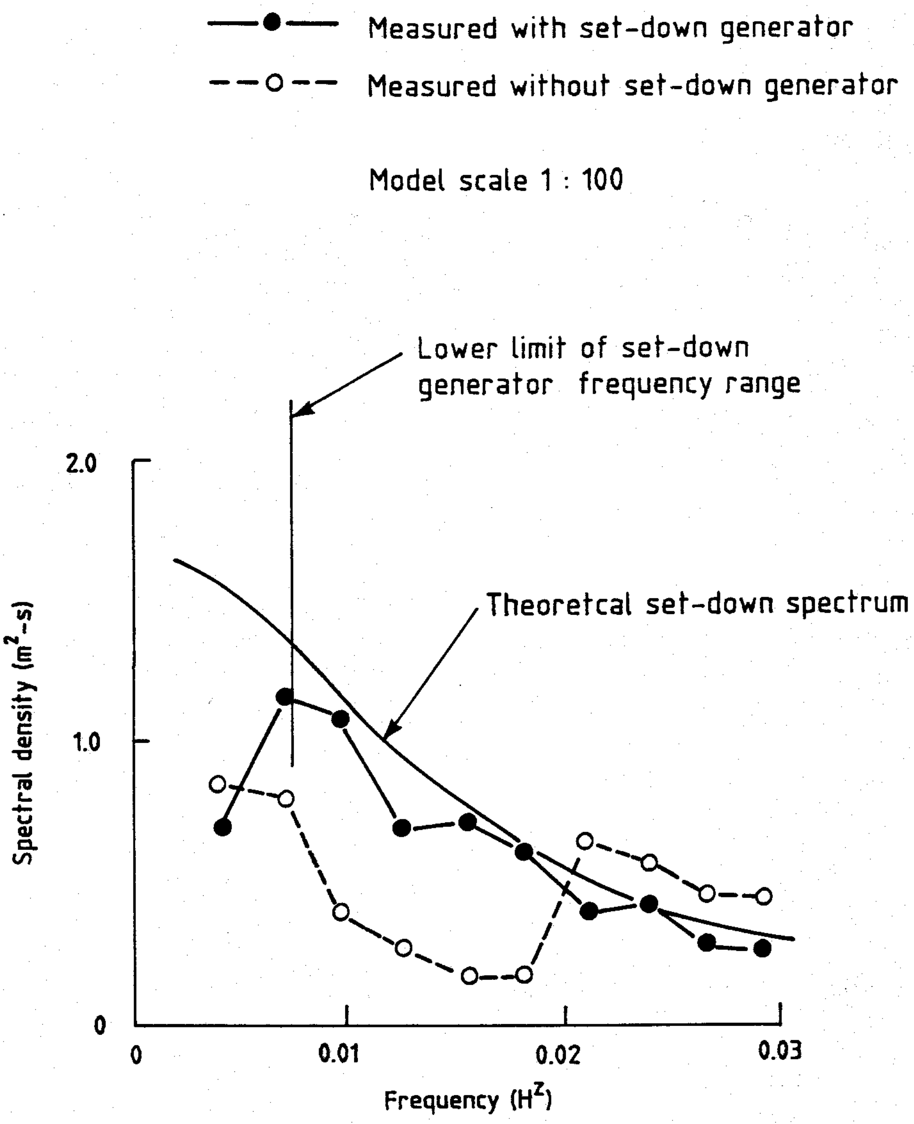

Fig 10 Long wave spectra without surf beat (Case 3)

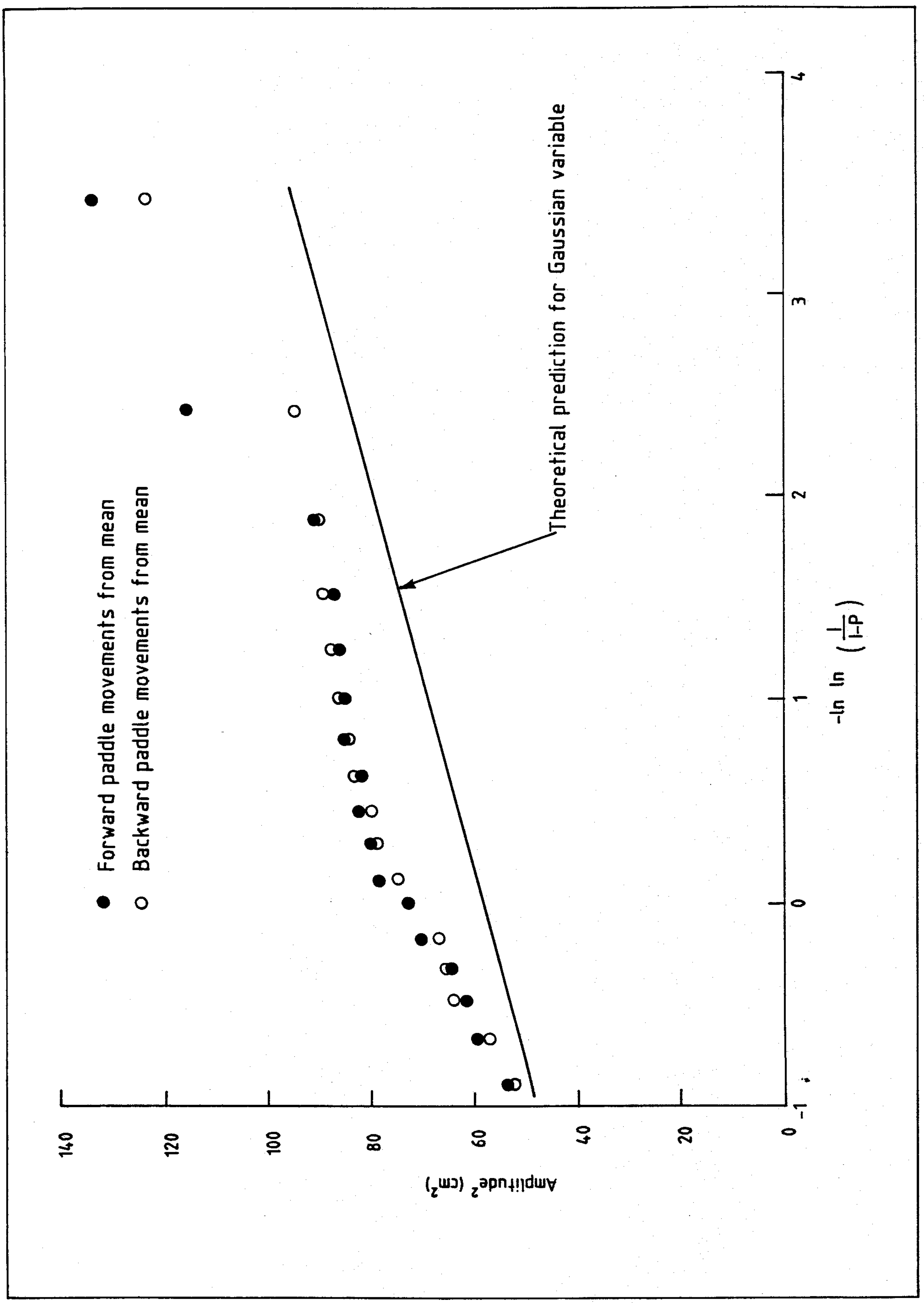

Fig 11 Amplitudes of paddle movement with set-down compensation (Case 2)

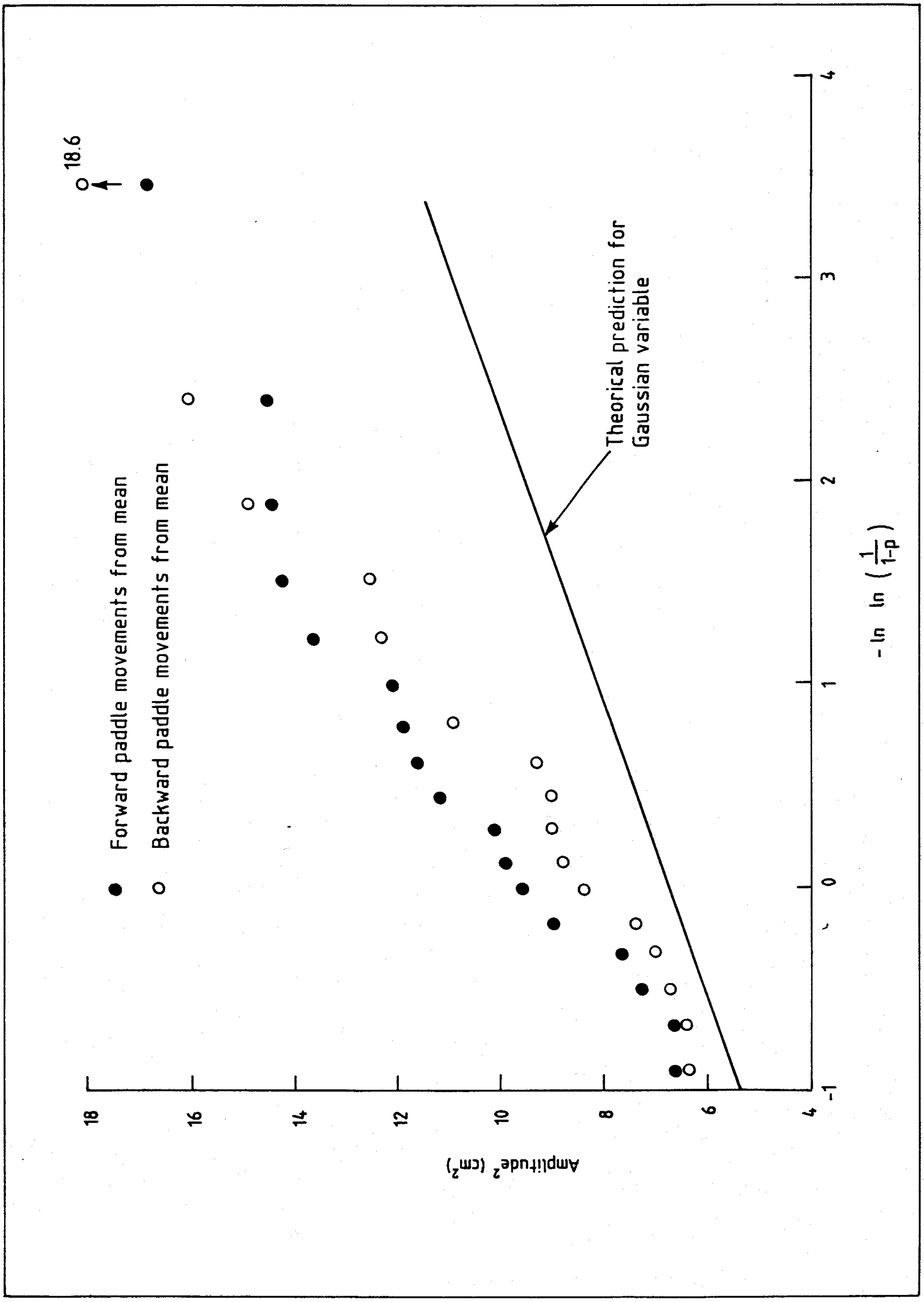

Fig 12 Amplitudes of paddle movement with large set-down signal

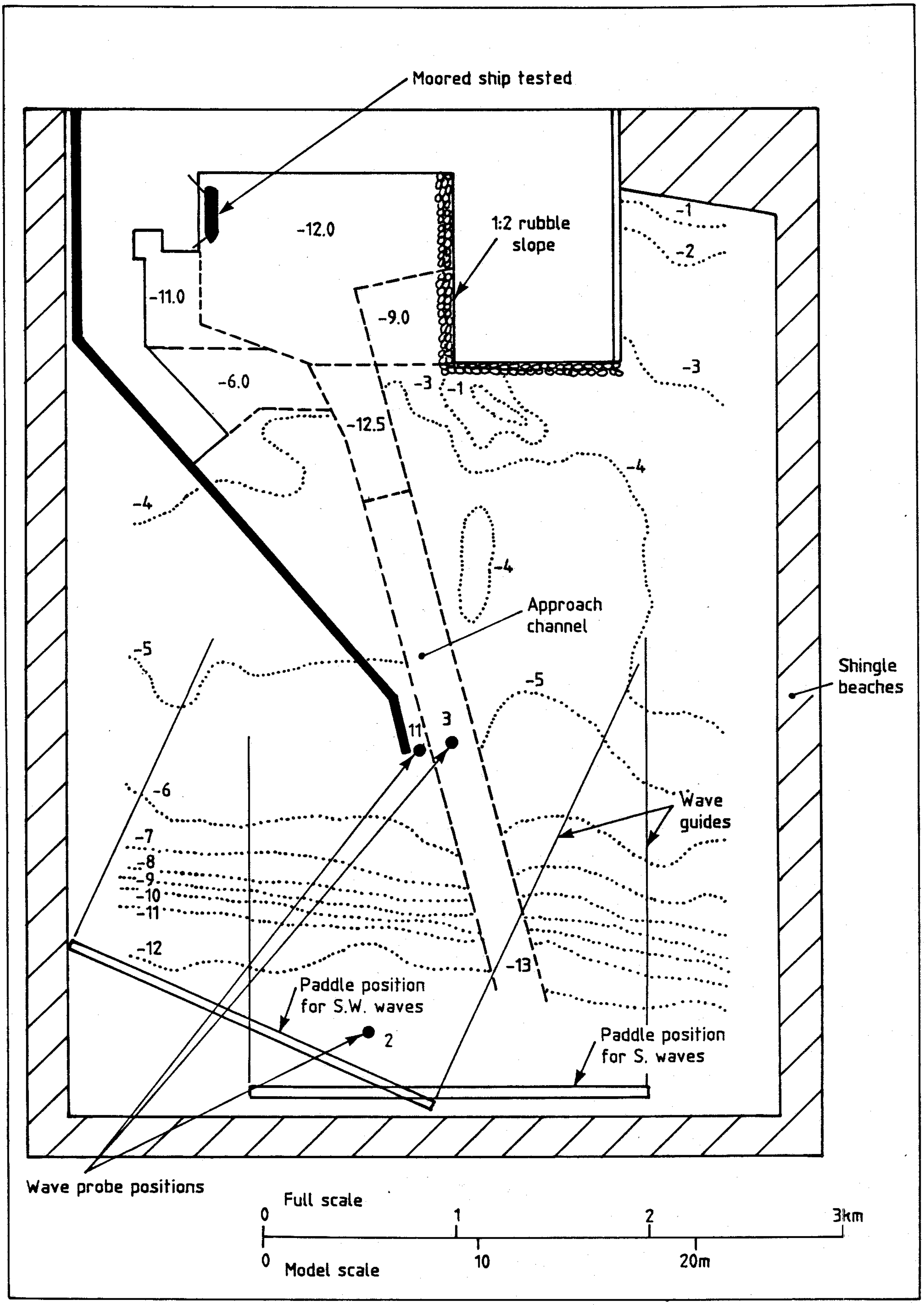

Fig 13 Wave basin layout for harbour study

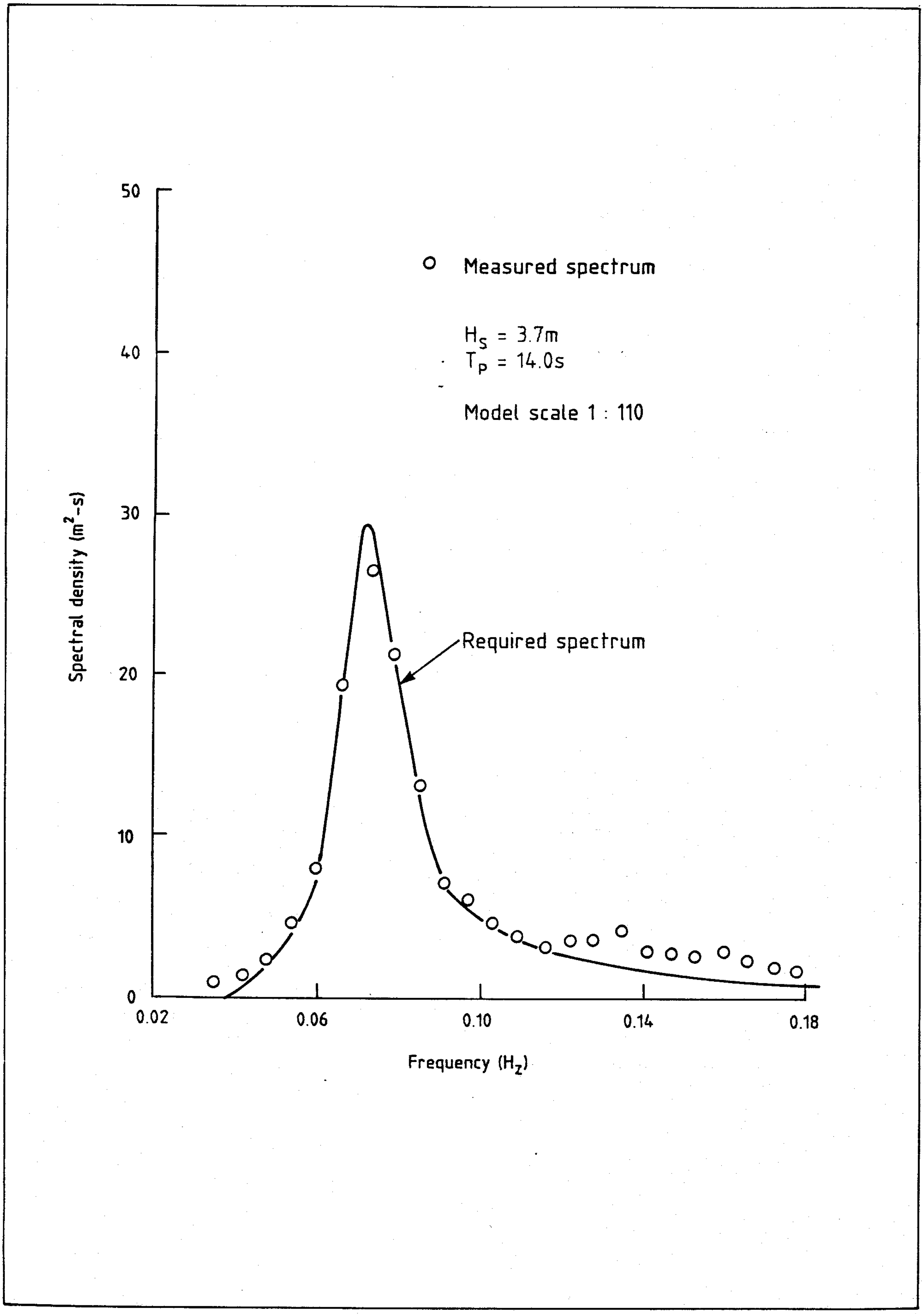

Fig 14 Primary wave spectrum (S.W. waves)

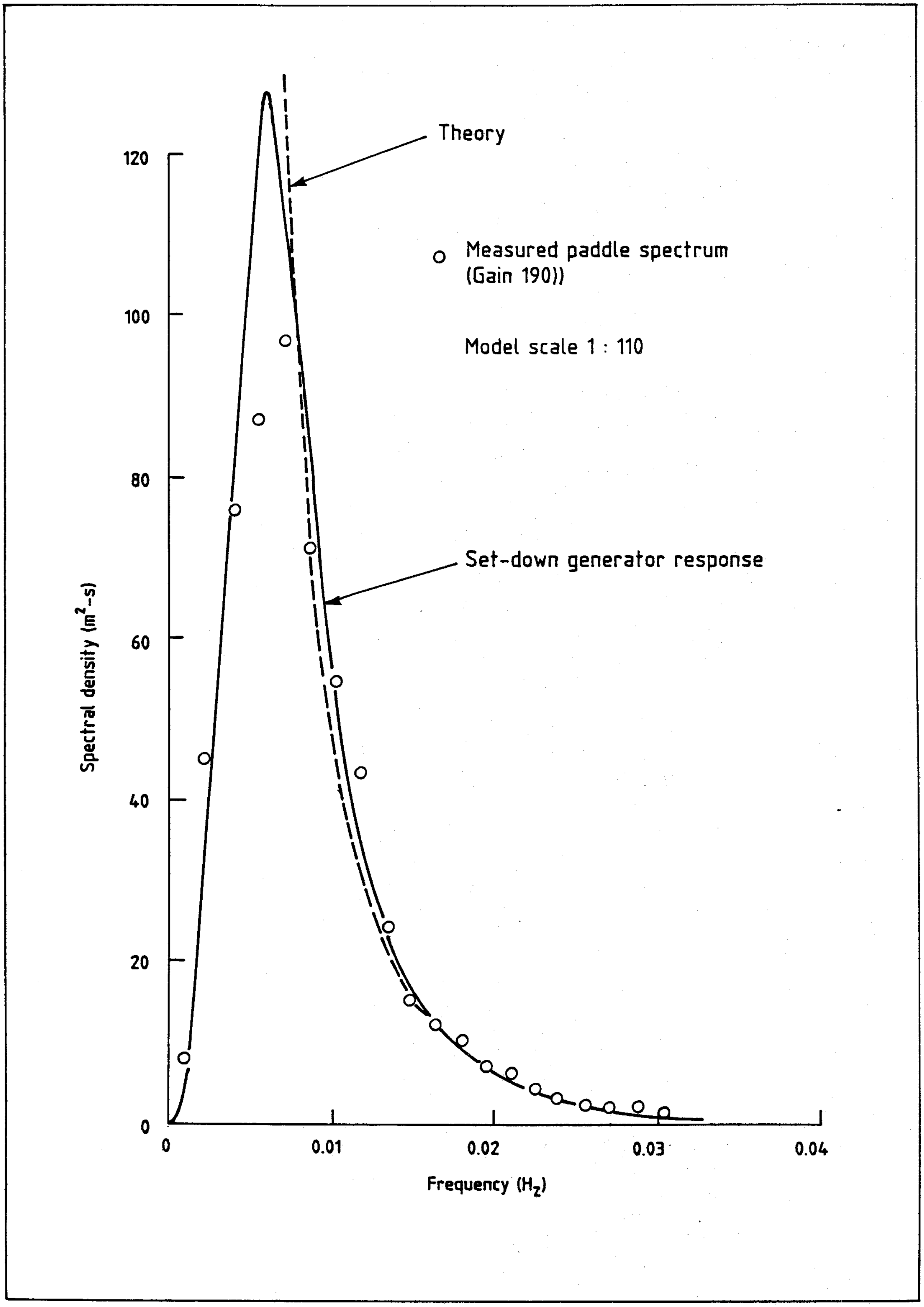

Fig 15 Low frequency paddle spectrum (S.W. waves)

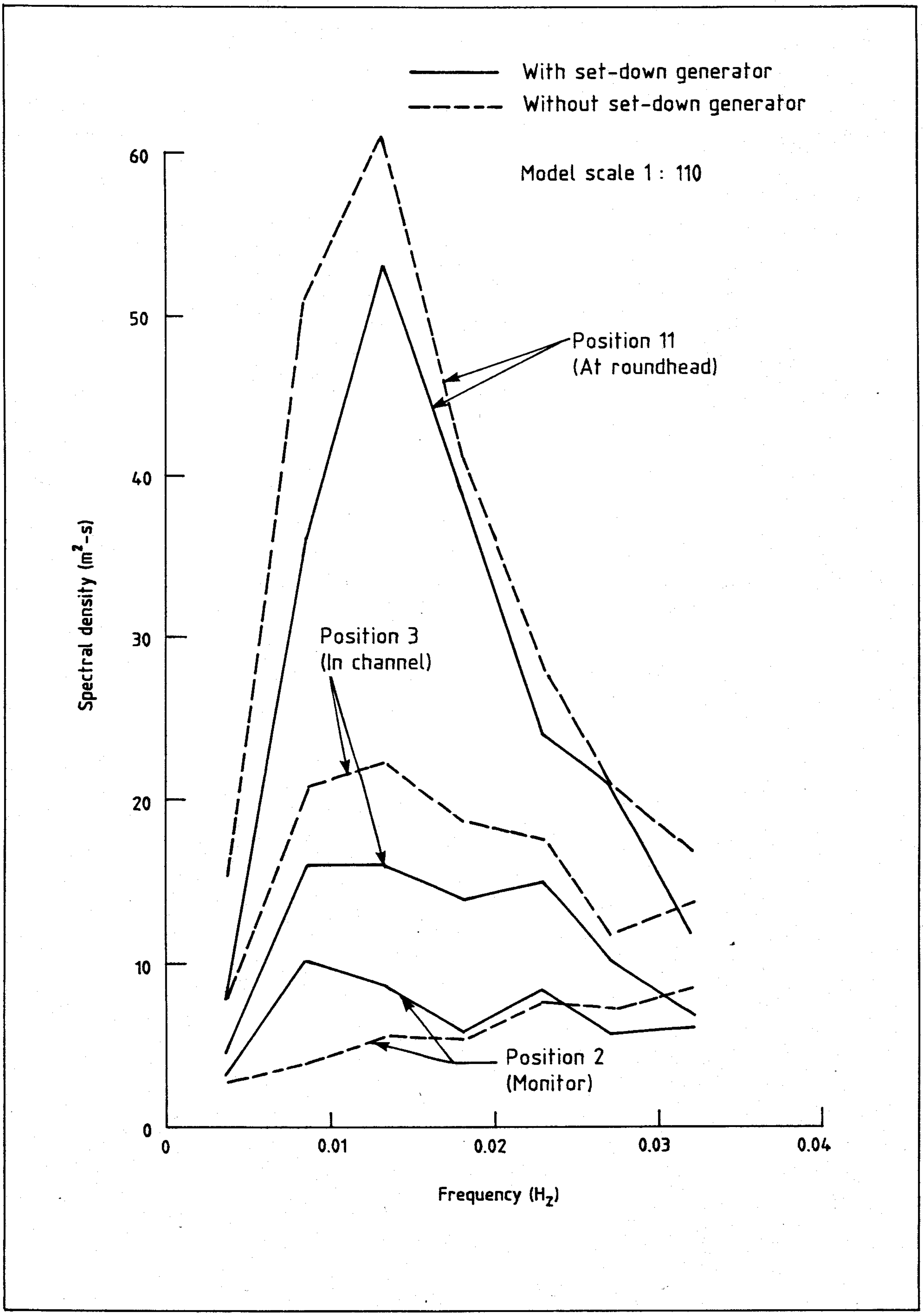

Fig 16 Long wave spectra with and without set-down generator (S.W. waves)

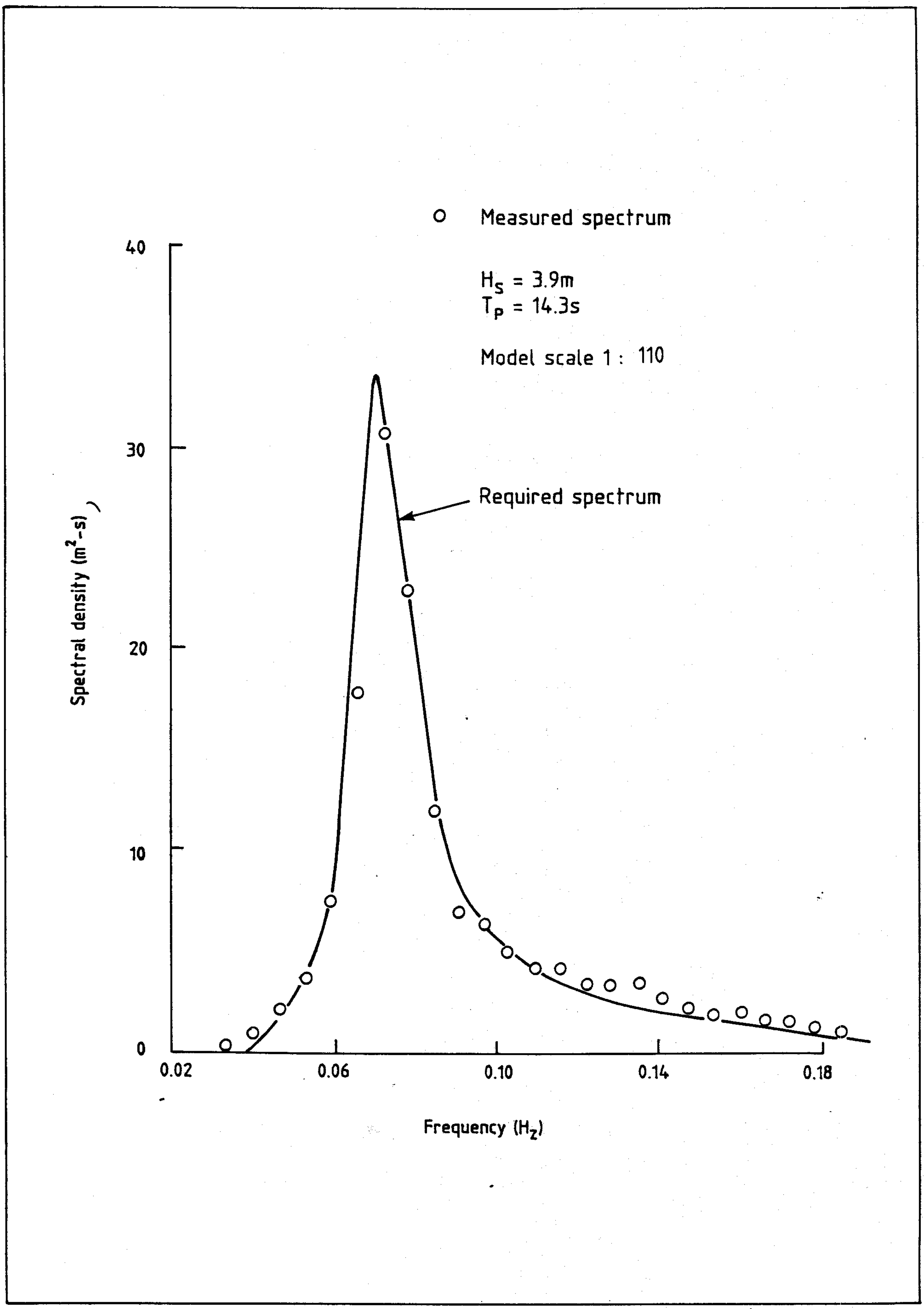

Fig 17 Primary wave spectrum (S waves)

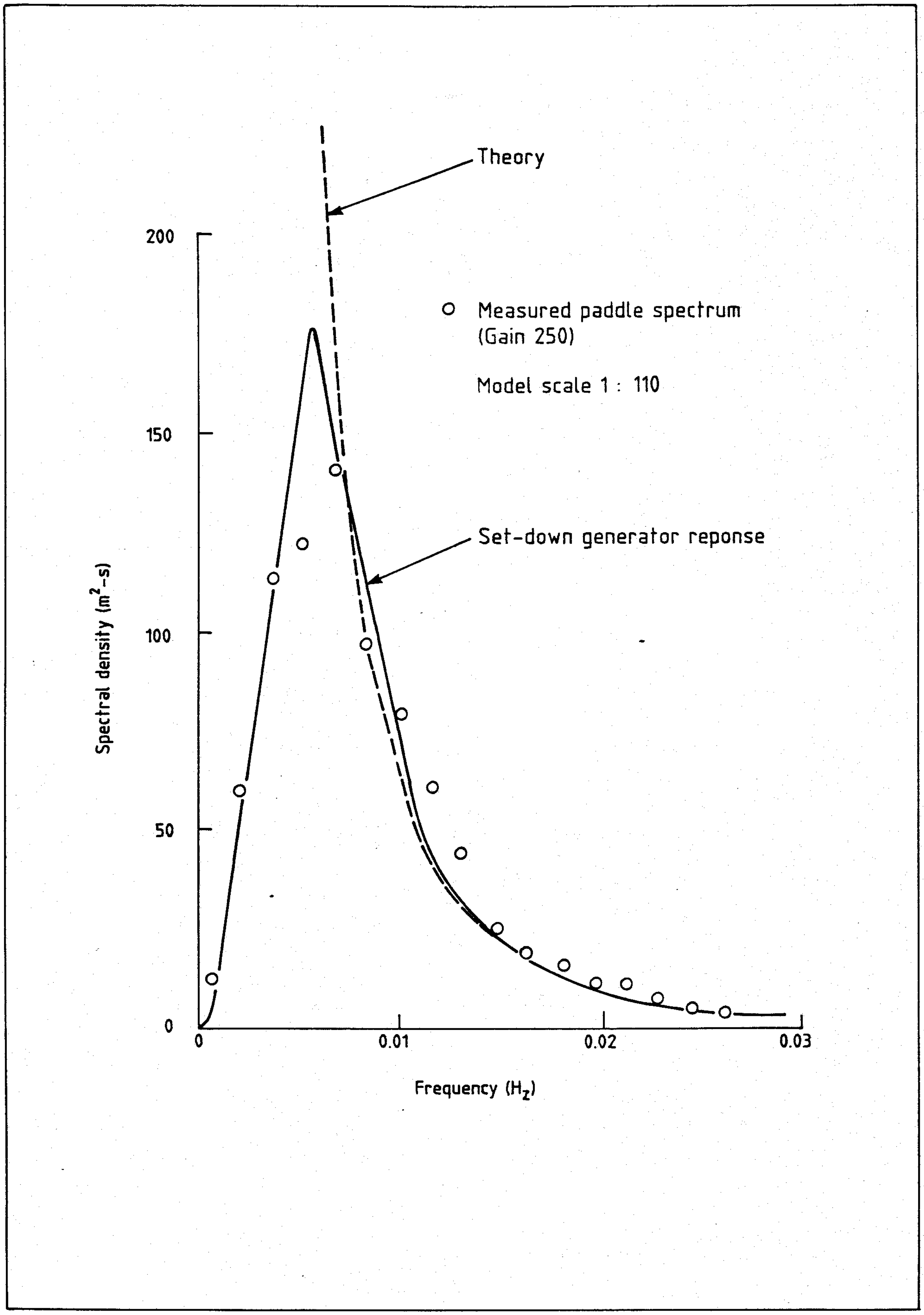

Fig 18 Low frequency paddle spectrum (S. waves)

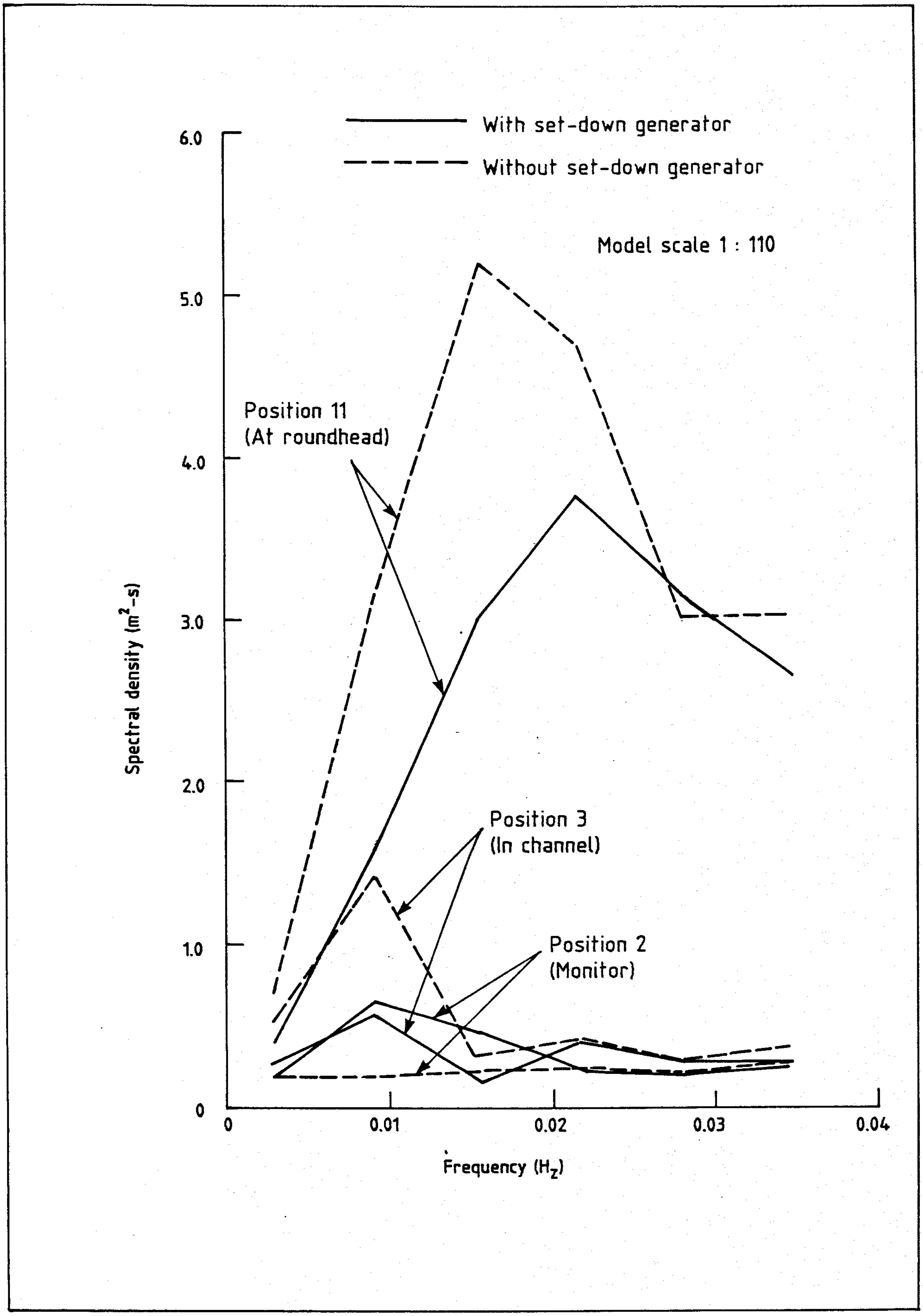

Fig 19 Long wave spectra with and without set-down generator (S. waves)