Considerations for the Design and Testing of Large Models of Fixed Offshore Structures

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INTRODUCTION

Scaled model tests are traditionally used as an aid in the design and engineering of offshore structures. Such models are normally used to validate numerical models or investigate phenomenons that cannot be handled by numerical models alone. Often there are anomalies in the model's response that become apparent only during testing and may not be included in the associated numerical model. Nevertheless, the advent of low cost high speed computers, coupled with advances in numerical hydrodynamics, has reduced the requirement for certain types of tests to be included in a typical test program. For example, testing of fixed jacket structures and semisubmersibles in small amplitude linear waves is not as extensive as it was two decades ago.

However, as exploitation of offshore resources moves further offshore into deeper water and more violent environments, the engineering challenges of minimizing capital costs while ensuring a high standard of safety has prompted the need for more innovative type structures. Consequently the models and associated testing techniques must become more sophisticated. The measurements made during test programs related to large scaled models can be quite varied in scope although they are made simultaneously. Present trends in model testing of fixed offshore structures require a more acute knowledge of localized loading as well as global loads. Global loads are much larger than local ones but generally have to be measured during the same test program.

Simultaneous measurement of local and global loads requires a large physical model, particularly in terms of minimizing scaling effects associated with the local loads measurement. Apart from scaling errors there may be others introduced through instrumentation measurements or the constraints of the test facility itself. Test programs can produce very large quantities of data that must be reduced to useful products for the designers.

The following paper discusses, from a cursory viewpoint, a number of considerations that should be given to the model's design, testing techniques and reduction of data.

WAVE MODELLING

Of the environmental loads of wind, waves and currents, the greatest loads imparted to a fixed offshore structure are those related to waves. Wave testing is normally carried out in regular and irregular waves. Regular waves are usually defined in terms of a "design wave", i.e. the largest wave a structure will be subjected to in a particular return period. Irregular waves are used for a more statistical type analysis where it is assumed that a wave equal to the design wave is contained in the irregular spectrum. Irregular waves present a more authentic representation of the waves that occur in nature.

Quantities that have a linear relationship with waves theoretically respond, for a particular wave contained in the wave spectrum having a particular height and frequency, identically to a single regular wave of equal frequency and height. Comparison of responses measured in regular waves to those measured in irregular waves is a good indicator of the degree of non-linearity contained in the response. However quantities such as impact loads affected above the water line are more susceptible to wave crests than to heights and, in cases where wave diffraction occurs, to wave grouping patterns.

Wave grouping patterns, like the waves that affect them, are statistical in nature. Therefore complex phenomenons such as wave runup or impact loads will have to be estimated statistically. Estimates should be based on measurements made in long sequences of random waves rather than regular waves. Even in regular waves there tends to be considerable variation in impact loads from cycle to cycle. The basis for a structure's design should be a storm spectrum having a very long duration and thus a high probability of containing wave groups as well as individual wave heights near the design wave conditions.

Another consideration to wave modelling, particularly in shallow water, is the asymmetry of the waves. Although the wave heights contained in wave spectrum may be Rayleigh distributed, the crest heights may not. An example of this is shown in Figures 1 and 2. Figure 1 is a Weibull plot of the wave heights found in a wave spectrum modelled at an intermediate water depth. The line fitted through the data represents a Rayleigh distribution. Figure 2 shows the wave crests found from the same spectrum and plotted in the same fashion. The broken line in the plot represents the Weibull model with Rayleigh parameters. In this case the crest heights are not Rayleigh distributed. This difference is due to shallow water effects.

When investigating responses that are affected mainly by crests, such as impact loads or deck clearances, it is critical that the correct heights be attained in the wave spectrum. It is therefore necessary to identify the maximum crest height that will occur in the irregular wave train. The only way to be certain that this maximum crest height occurs in the irregular train is to subject the model to an infinitely long sequence of waves. Since this is not possible a statistical approach must be taken and, as in all statistical estimates, there is always a certain degree of variability. Some authors [1] have used a hybrid model to estimate the maximum crest heights that occur in a particular spectrum. Deciding on a particular crest height is dependent mainly on test requirements. Also it must be acknowledged that the largest responses are not always related to the largest waves. In certain cases the largest local wave runup or local pressure can occur in a group of smaller waves which have non-linear cumulative effects.

Although the objective of modelling waves in a test facility is to provide authentic representations of sea states to which the structure is to be subjected during its term of operation, there a number of constraints related to the confines of the test facility itself that must be considered. Test facilities for modelling waves are normally equipped with a wavemaker device at one end and a wave absorption device at the other. The intention of the wave absorption device or "beach" is to dissipate the wave energy such that a very minimum is reflected back on the wavemakers. When the model being tested is large enough to cause diffraction the result is wave reflection, from the development of diffraction, impinging on the wavemaker and returning to the model.

An example of such an effect is illustrated in Figure 3. The figure shows a wave measurement made near a large model of a fixed structure. The time trace identifies two intervals; the first contains waves that are not affected by reflections from the wavemaker and the second shows a distinctive increase in wave height. In this second interval diffracted waves have reached the wavemakers and returned to the wave gauge measuring the profile near the model. When comparing the results from INTERVAL 1 to those predicted by numerical models there is a distinctive improvement when data used from INTERVAL 1 is used. The two intervals are identified using the wave group velocity. The group velocity of the wave is used to identify the time taken for the wave to travel to the model then to the wavemakers and back to the model again. The technique has been demonstrated to be an effective means of identifying the optimum window for data selection.

The technique of using wave group velocity to identify the time at which the effects of reflected waves reach a model is not applicable in irregular waves because of the number of wave frequency components contained in the spectrum and consequently the range of group velocities. In this case a "snapshot" technique can be used to identify the amount of contamination buildup that occurs during an irregular wave run. The snapshot technique introduced in [2] selects a group of waves from the long sequence representing the full spectrum and runs this selected portion in isolation. A direct comparison between the two will quantify the differences assumed to be caused by wave reflection buildup. An example of a snapshot is given in Figure 4. Here the wave profile from a snapshot is compared to the measurements made during the same sequence of waves run in the full length time sequence. As indicated in the figure, the differences are extremely small suggesting that the contamination buildup is not severe. Similar results are found when comparing wave loading time traces.

The small differences, found between a sequence of waves run as a snapshot or run within the full wave sequence, may be attributed to an averaging effect in the basin caused by the numerous frequency components and random nature of the associated phase. The spectrum considered in the given example contains over 4,000 frequency components.

DATA ANALYSIS TECHNIQUES

The primary objective of data analysis is to reduce and present the test data in a format useful to the designer. Results from regular waves are normally presented in the form of RAO's (Response Amplitude Operators). Here the ratio of amplitudes, or heights, of the input waves and the measured response are presented together with the associated phase. These results can be directly compared to irregular waves in the form of transfer functions to investigate the degree of non-linearity. When selecting data for analysis, the group velocity technique is useful in minimizing the effects from the test facility boundaries.

Responses that are non-linear in nature make the associated analysis techniques best suited to a statistical approach. A useful means of comparing regular wave results to irregular wave results is through a "ranked plot" technique. The ranked plot technique allows a direct comparison of the relationship between statistics of waves and measured quantities. The technique described in [3] can be statistically justified because only the two probability distributions are compared. This assumes that on average the largest responses occur in the largest waves.

Data are plotted on linear-linear scales, thus non-linearities and associated degrees and ranges are clearly evident. The technique also facilitates direct comparison between regular and irregular wave responses. Log plots such as Weibull distributions may be useful in predicting long term quantities but tend to over-smooth the data in certain cases.

WAVE LOADING MEASUREMENTS

Figure 5 illustrates the global and local load response of a large caisson fixed structure to a regular wave. The F_x term represents the horizontal global load measured on the structure. The F_z term represents the global vertical load on the caisson caused by a wave breaking over it. M_y is the overturning moment about the base of the structure. The local load shown in the figure is typical of a slam load and although it repeats at a period equal to the wave period there is some variability in the peak values. Such variability is not evident in the measured global loads.

The same time traces for a segment of an irregular wave train are shown in Figure 6. The F_x and M_y values appear to follow the wave pattern shown in the bottom trace of the figure, at least to the extent that the number of higher responses measured for each of these quantities is highly correlated to the same number of high waves contained in a group. However, unlike the responses measured in regular waves, the highest local and vertical loads do not suggest as high a correlation with the high waves contained in the group. In some cases only one large spike will result from a wave group interacting with the structure.

The variability in peak impact loads measured in a regular wave train is usually handled by taking an average over a number of cycles. However this is not possible in irregular wave groups because there is only a single occurrence of a particular wave group and consequently only a single occurrence of the associated pressure. Thus an averaging of the pressures is not possible. One suggested method of investigating the amount of variability in peak pressures occurring in a wave train is to select the sequence of waves causing the largest pressure and run it as a number of repeated snapshots in tandem. Although this technique may be questioned from a statistical point of view, it will provide some indication of the variability without having to run the entire wave train.

A local "slam" or impact load is affected by the momentum of the water being transferred to an impulse acting on the structure, presumably absorbed by an elastic deformation. The load is characterized by a sharp rise to a peak pressure with a more gradual decline as the momentum of the water diminishes.

An expression for this impact load is,

$$F=m\frac{dv}{dt} + v\frac{dm}{dt} \qquad (1)$$

Here, m is effectively the combined mass of the structural component that is responding to the impact including the water that is in contact with the structure at any instant of time. This term can be considered as a lumped mass parameter including structural and added mass of the water in contact. The added mass effect can be quite significant for these impact loads and will affect the natural period of the model structure. If it is further assumed that the velocity of the impinging water is essentially constant, then the primary term affecting the impact load is the change in water mass impinging on the model over time. Even with all these generalizing assumptions the impact loading remains very complicated.

One complication is related to the density of the water on impact. As water from wave crests disintegrates, because of wave instability or the structure itself, air can become entrapped in the water which will result in higher loads being measured. However the disintegration of the wave will cause the water to break into smaller particles which will reduce impact loads due to impact velocity being reduced through air drag and, secondly, smaller water particles will cause a more diffuse impact over smaller areas and over shorter times.

In discussing model stiffness it is necessary to consider the differential equation,

$$M\ddot{X} + B\dot{x} + Kx=F \qquad (2)$$

where, M, is the mass, B, is the damping, K, is the structural stiffness and, F, is the load of interest. The structure's dynamic response is described by the first two terms on the left-hand side of the equation. The mass and damping terms will be contributed to by both the structure and hydrodynamic effects. When the structure responds to an impact load, the inertial and damping effects will be sensed on the measuring transducer. Ideally only the, Kx, term is of interest as a function of time, as measured by the transducer, and the hydrodynamic load, F, can be directly equated to this measurement.

In order to model the correct impact loads on a structural member that include the structure's response a full hydroelastic model will have to be used. Such models are very expensive and prone to complications in instrumentation. The more practical solution is to use a very rigid model such that the natural frequencies of the model are well above those of the full scale structure. The lowest frequency of interest is specific to a particular structure and can depend on the global or local structural dynamics. Higher stiffness in instrumentation will tend to increase the natural frequency but at the expense of sensitivity.

Added mass effects on the model structure can also significantly influence the natural frequency. Figure 7 shows a vertical impact measured on a deck of a model structure. A Fourier transform of this time trace is shown in Figure 8. The time trace of the impact load is comprised of a low frequency component on which is superimposed a higher frequency. The higher frequency is the response of the model deck to the impact load. In this case the natural frequency of the model deck in air was 7 Hz. However the added mass effect during impact increased the effective mass by a factor of 16 and reduced the frequency by a factor of 4.0. Fortunately the lowest frequency of interest was less than 1.0 Hz and the structural response could be filtered off. A sample of the filtered response is also shown in Figure 7. Since the added mass is related to the size of the structural component on which the force is measured, even when the structural component consists of a small mass, the added mass is a physical phenomenon that cannot be controlled. It is sometimes useful to reduce the effective size of the structural member by composing it as a number of smaller members.

Global loads on large models of offshore structures are affected by an averaging of pressures over the structure and are less susceptible to wave crest patterns. A Weibull plot of the global horizontal forces measured on a large caisson structure is given in Figure 9. A ranked plot of the same data is shown in Figure 10. The Weibull plot includes a Rayleigh model of the data but is not distinguishable from the Weibull fit because they are practically identical, indicating that the global wave loads like the wave heights are Rayleigh distributed. This would suggest a linear relationship between the wave heights and the horizontal global loads. Further evidence of this is found in the ranked plot, Figure 10. This plot indicates statically through the straight line relationship that the relationship is linear. Also included in the ranked plot are the results from a number of regular waves having a period close to the peak period of the irregular spectrum and generated over a range of wave heights. As can be seen in this figure there is good agreement between the regular and irregular wave loads.

As mentioned earlier, in the section on wave modelling, it is assumed that a wave having the "design wave" characteristics may not occur in the irregular wave train because of its statistical nature. In this case it may be possible to use a ranked plot such as the one shown in Figure 10 to extrapolate or interpolate the load corresponding to a particular wave height. More confidence would be given to such an estimate if the value were extrapolated from a densely populated part of the curve. As indicated in Figure 10 the upper end of the data are sparse and more scattered. In this case it may be advantageous to enhance the wave heights in the irregular spectrum to attain more points in this upper region.

A sample ranked plot of local pressures measured at a location above the still water line is presented in Figure 11. In this case there is considerable discrepancy between the irregular and regular wave results. This result is expected since the responses are highly localized and, as shown in Figure 6, are not correlated directly to individual waves. Estimating and quantifying such loads from model tests is an area that warrants further development.

CONCLUSIONS

This paper has described and discussed a number of considerations that may be given to the design and testing of large models of fixed offshore structures. Although a cursory viewpoint has been taken, the concepts discussed should be useful as a preamble to a test program. On the basis of what was discussed the following conclusions and recommendations are made:

- group velocity is an effective means of identifying optimum data selection in regular waves

- the snapshot technique can be used to demonstrate the amount of contamination buildup during an irregular test

- ranked plots directly show relationship between statistics of waves and measured quantities

- since ranked plots are plotted on linear-linear scales they show non-linearities and associated degrees and ranges

- ranked plots facilitate comparison between regular and irregular wave responses

- artificially enhance spectrum amplitude to obtain a more data points on top end of ranked plot for extrapolation purposes

- run snapshots of wave groups to average extreme responses in irregular waves

- further develop techniques to quantify local loads in wave groups

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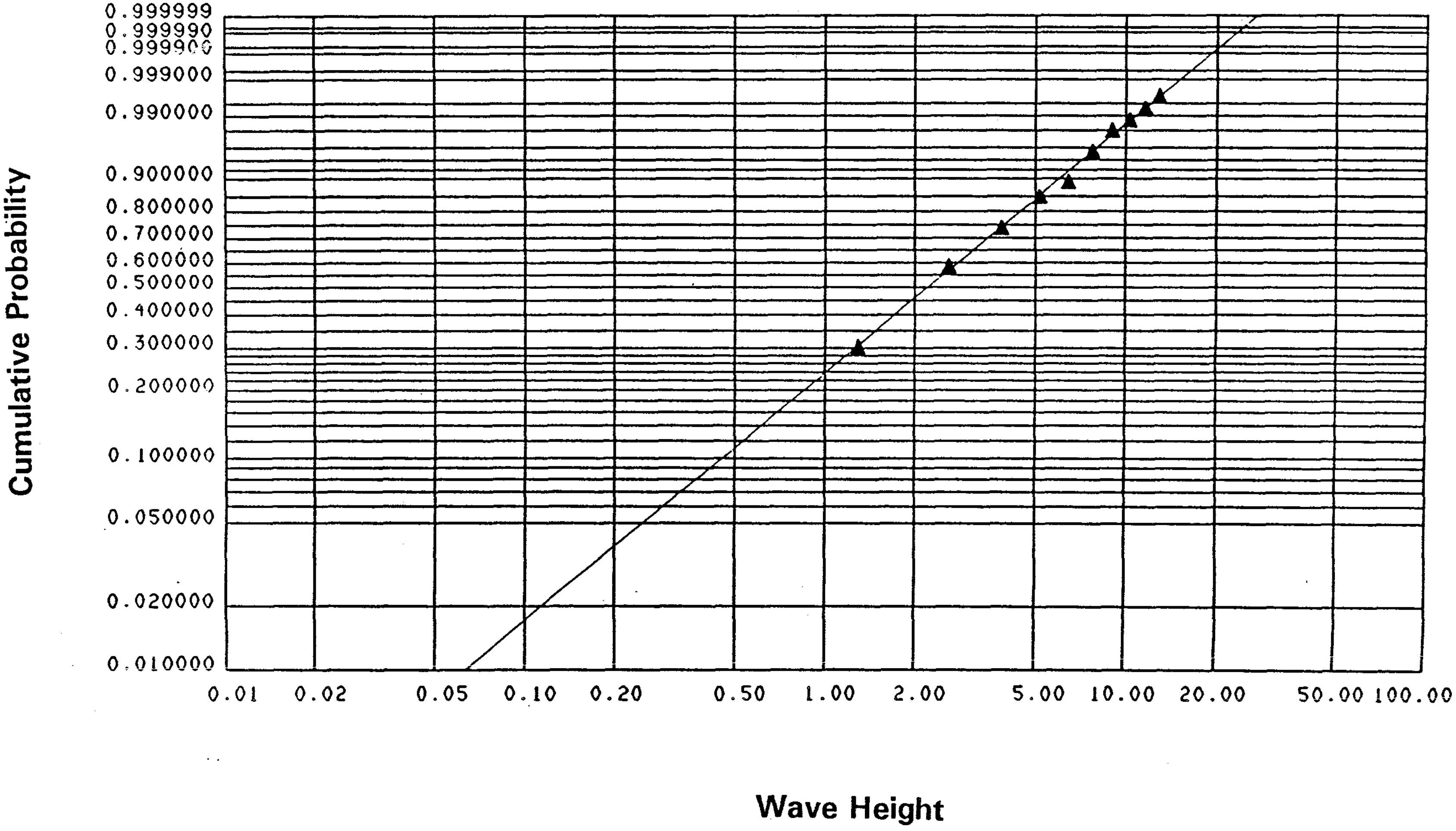

FIGURE 1 WEIBULL MODEL OF WAVE HEIGHTS

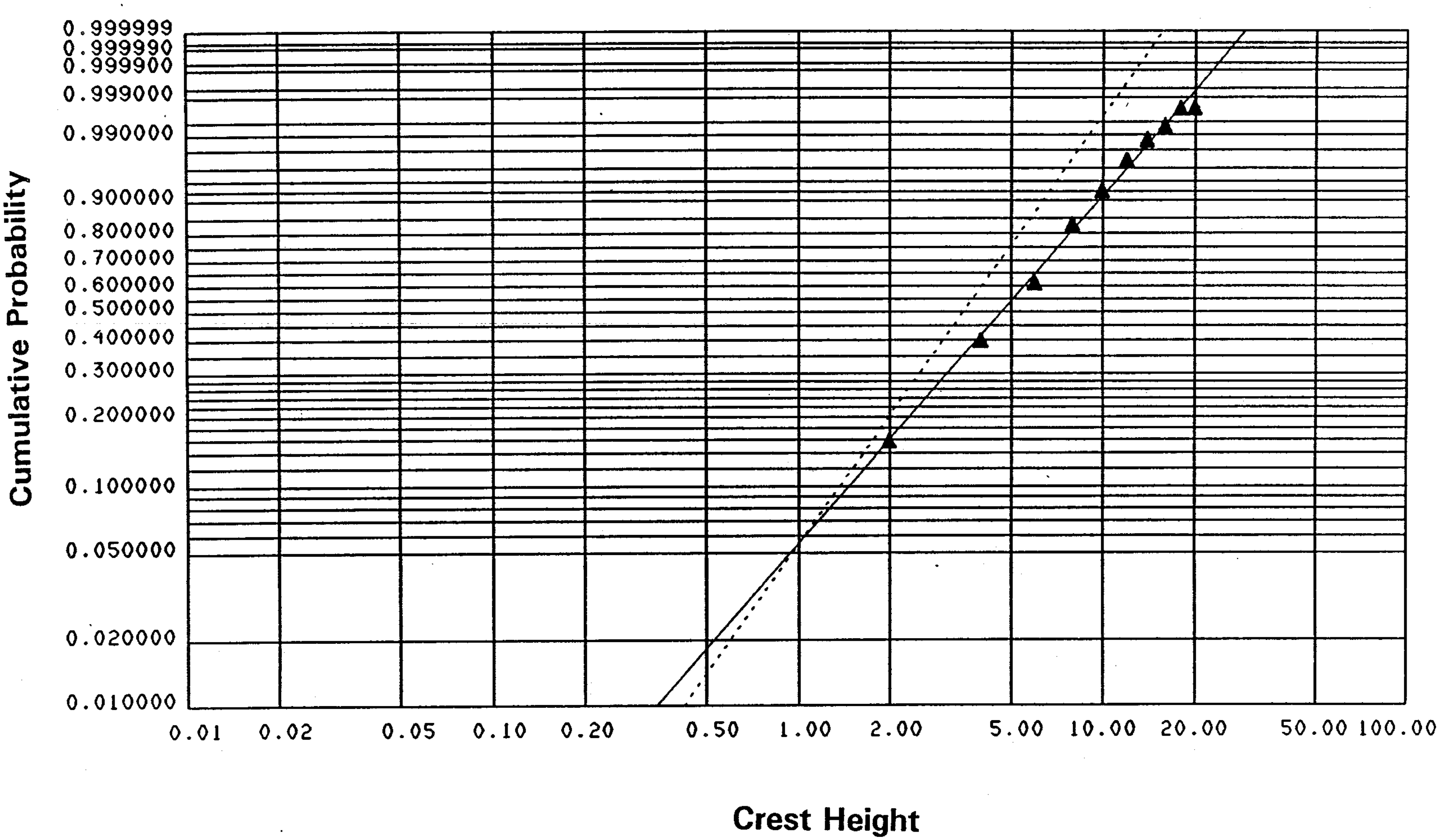

FIGURE 2 WEIBULL MODEL OF CREST HEIGHTS

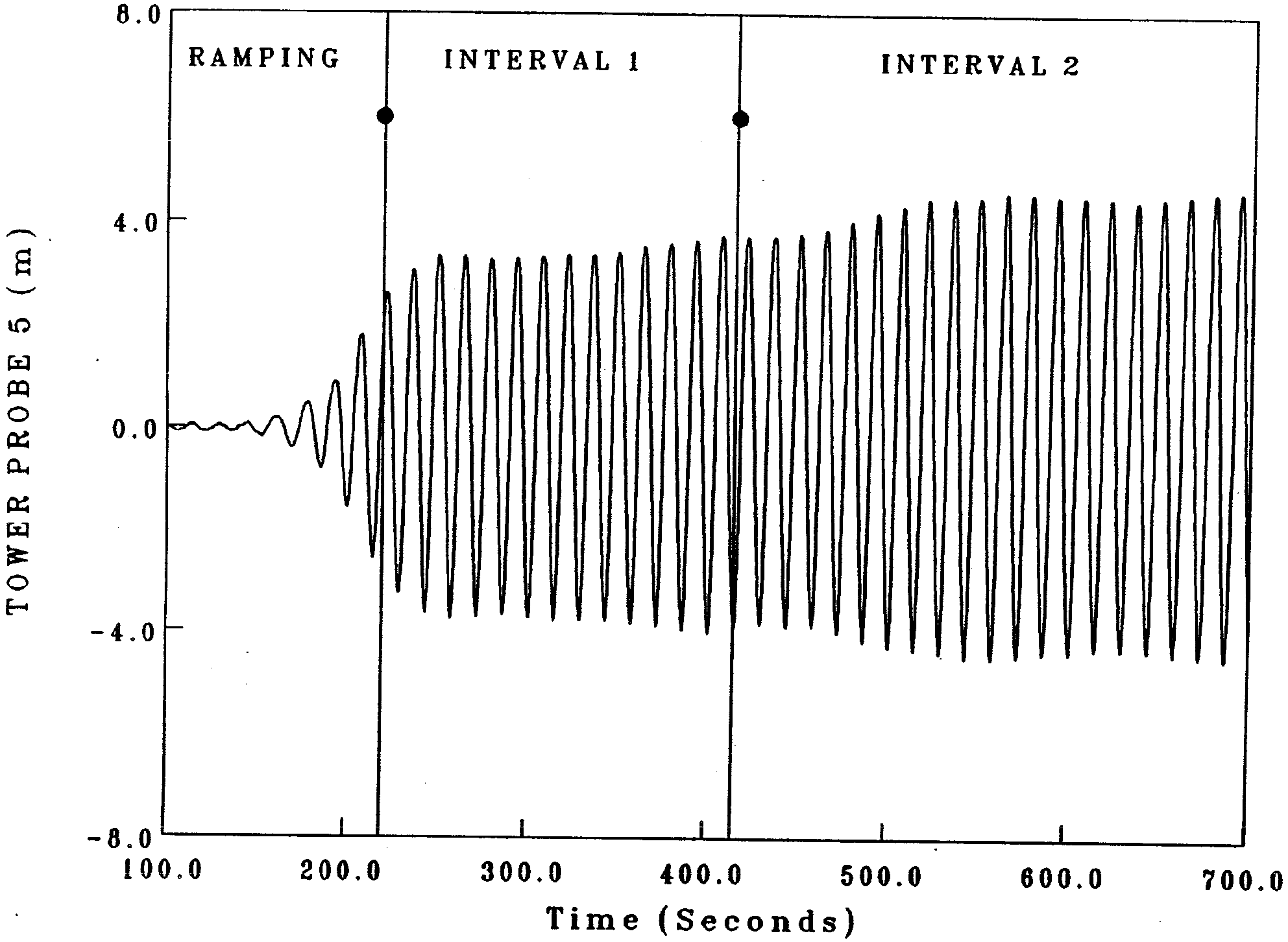

FIGURE 3 EFFECT OF WAVE DIFFRACTION

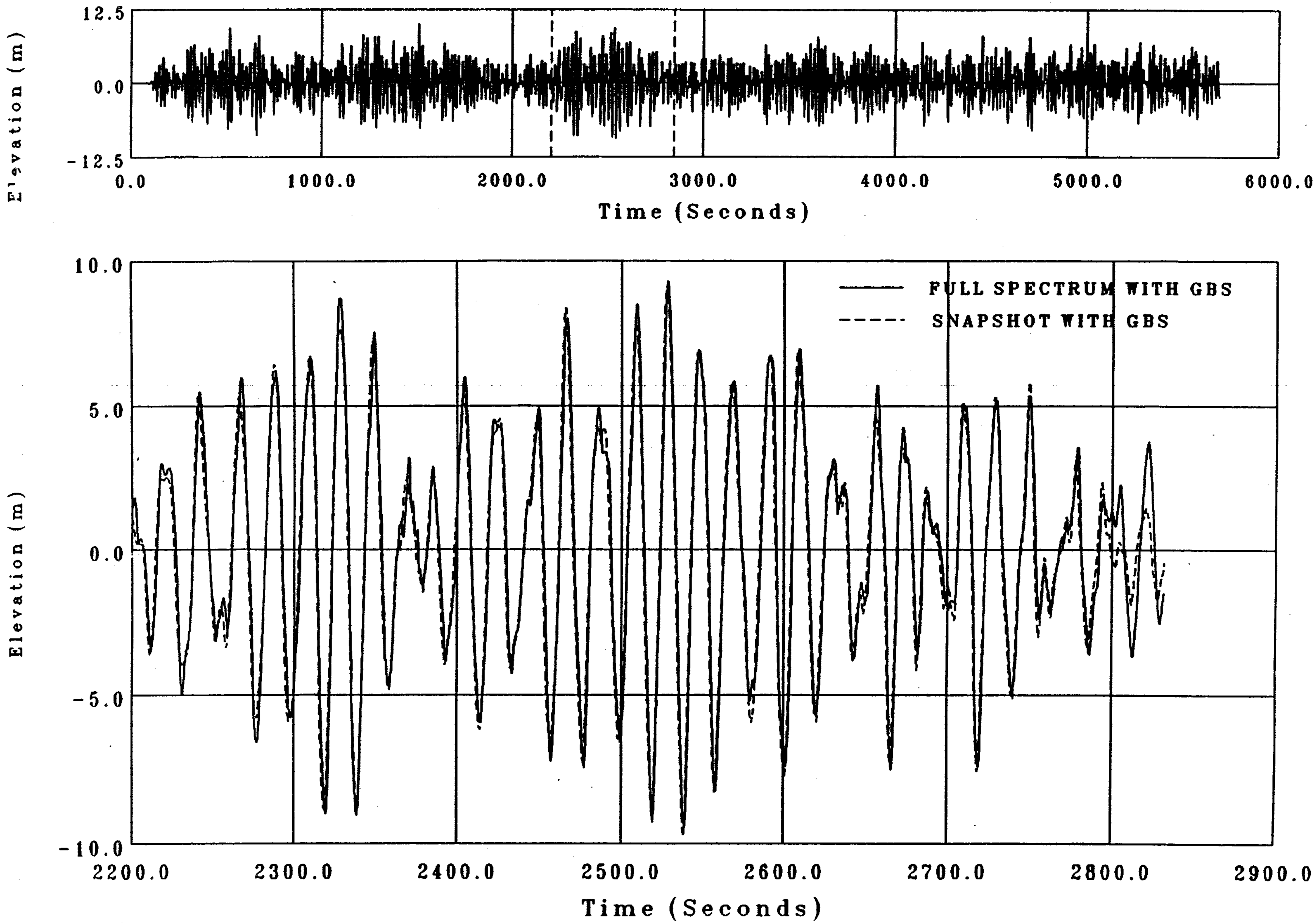

FIGURE 4 SAMPLE OF A SNAPSHOT

REGULAR WAVE TEST

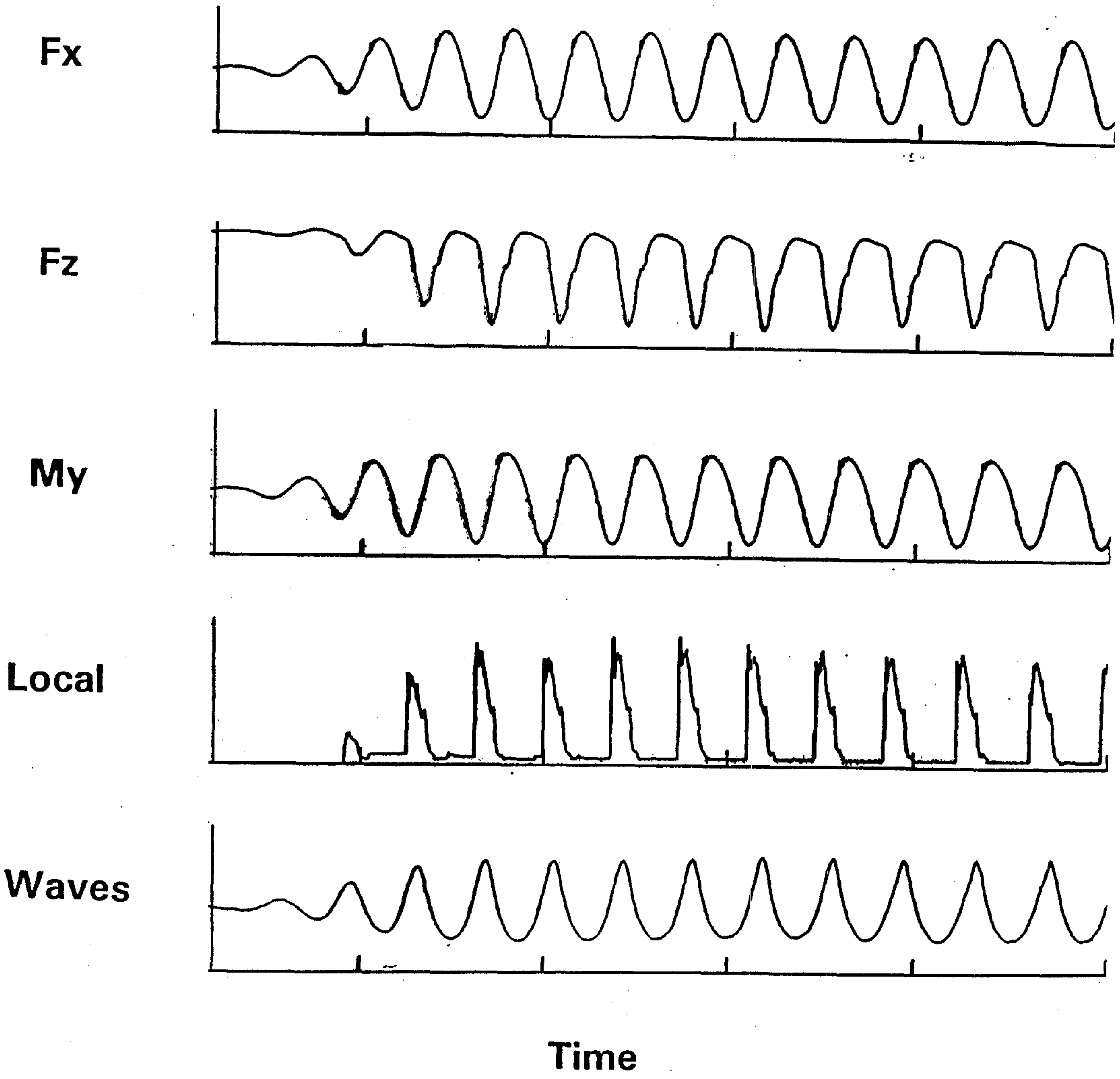

FIGURE 5 RESPONSES IN A REGULAR WAVE

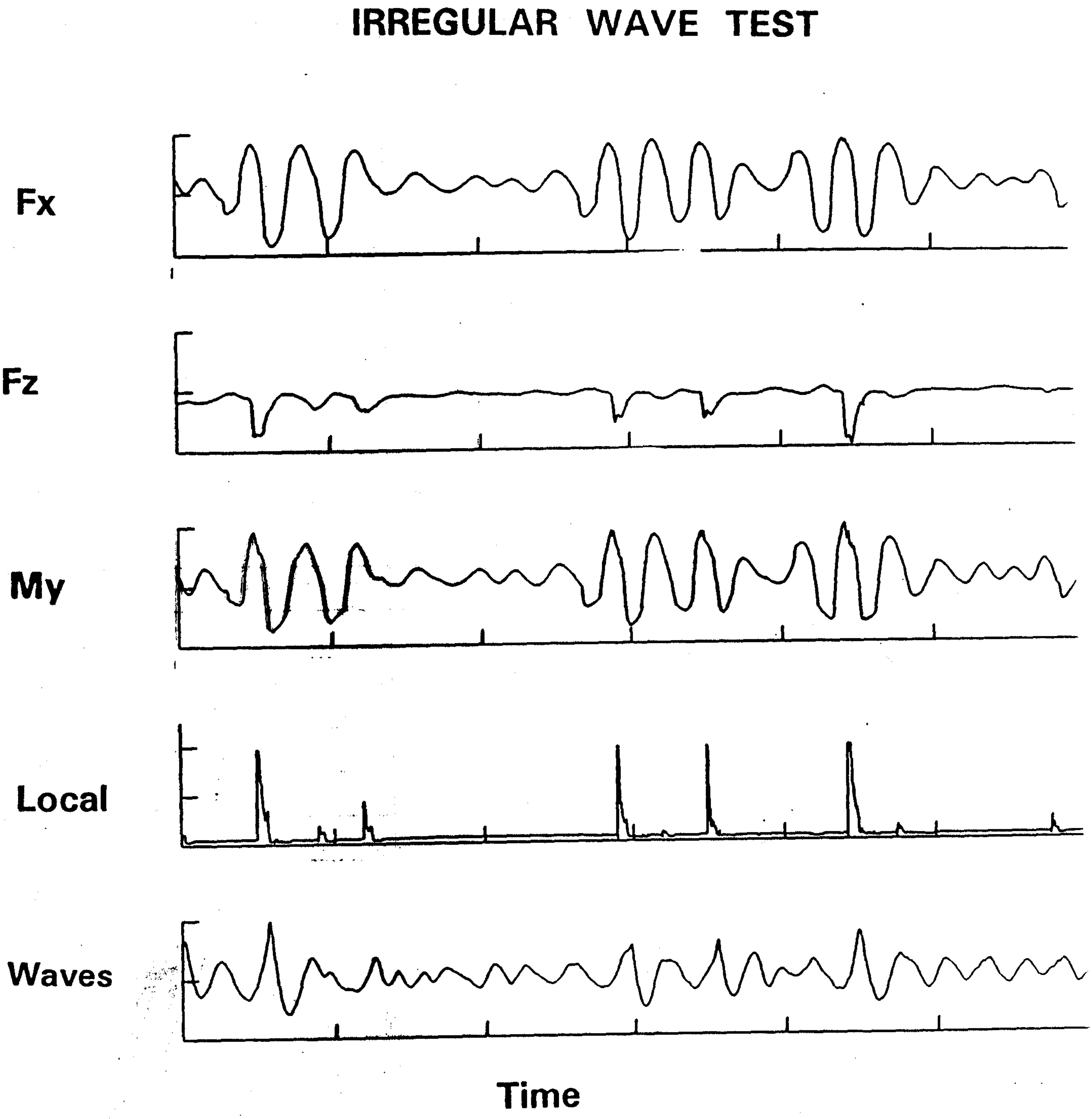

FIGURE 6 RESPONSES IN AN IRREGULAR WAVE

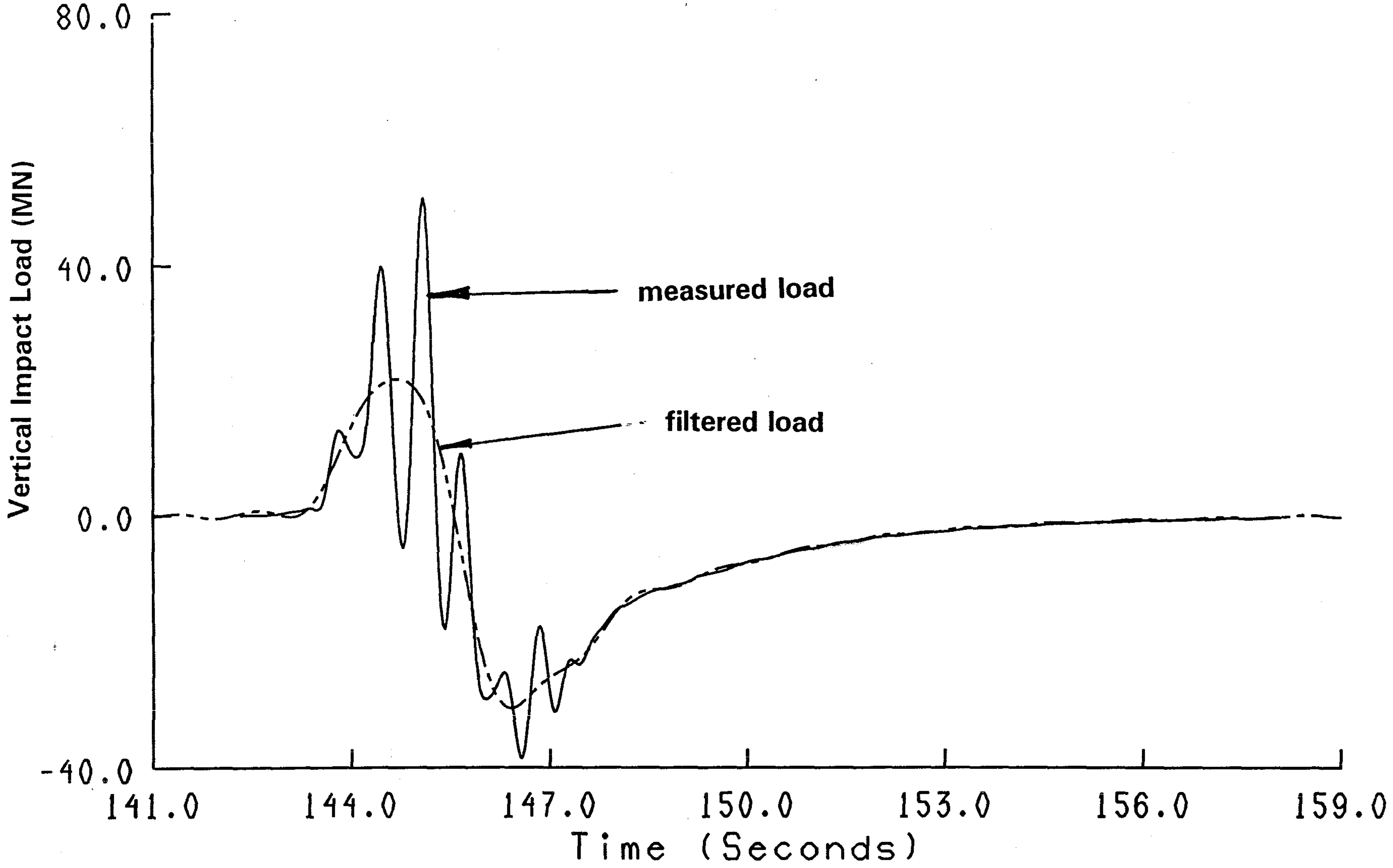

FIGURE 7 VERTICAL SLAM LOAD ON JACKET DECK

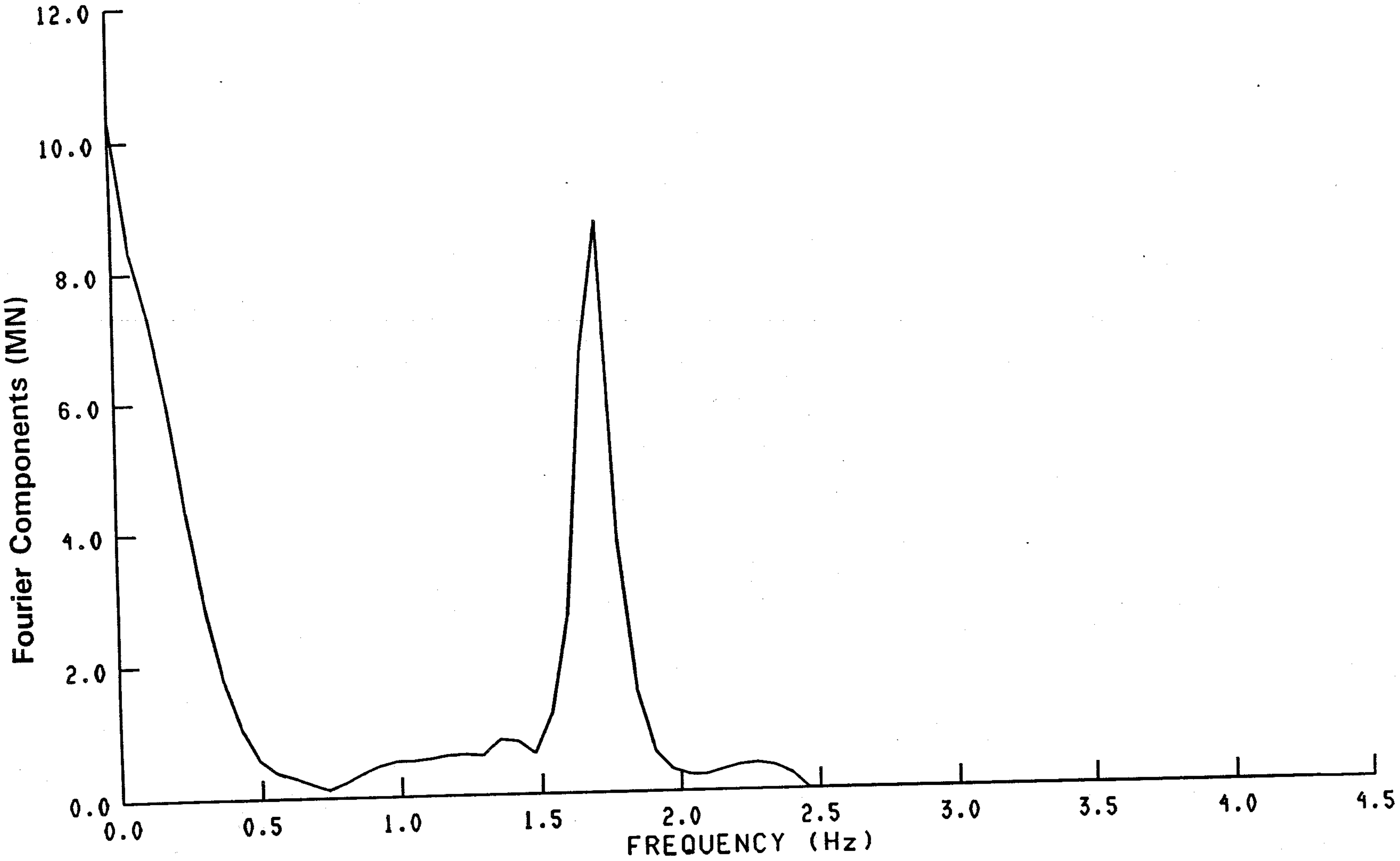

FIGURE 8   FOURIER TRANSFORM OF VERTICAL LOAD IN FIGURE 7

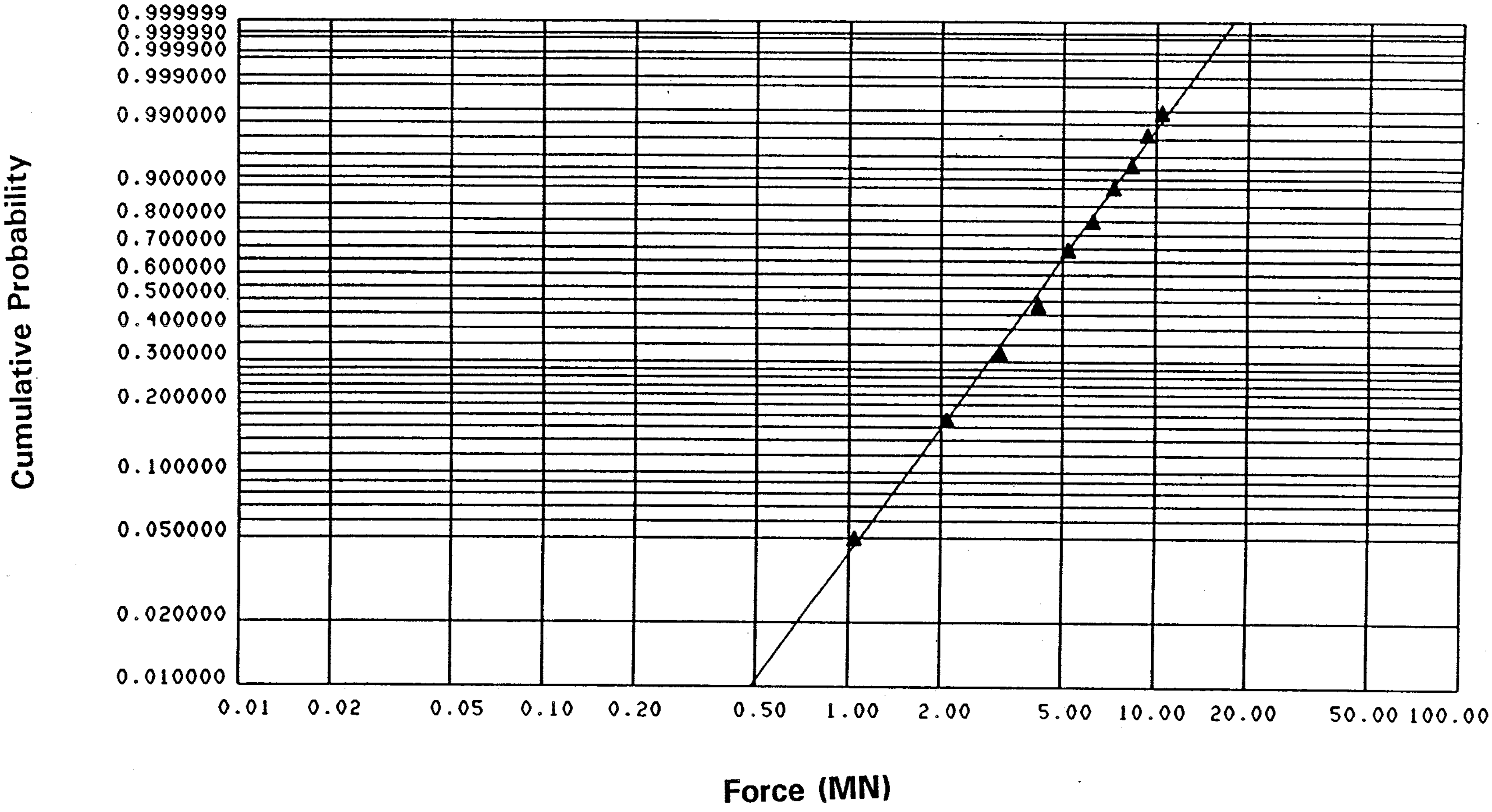

FIGURE 9 WEIBULL MODEL OF HORIZONTAL GLOBAL FORCES

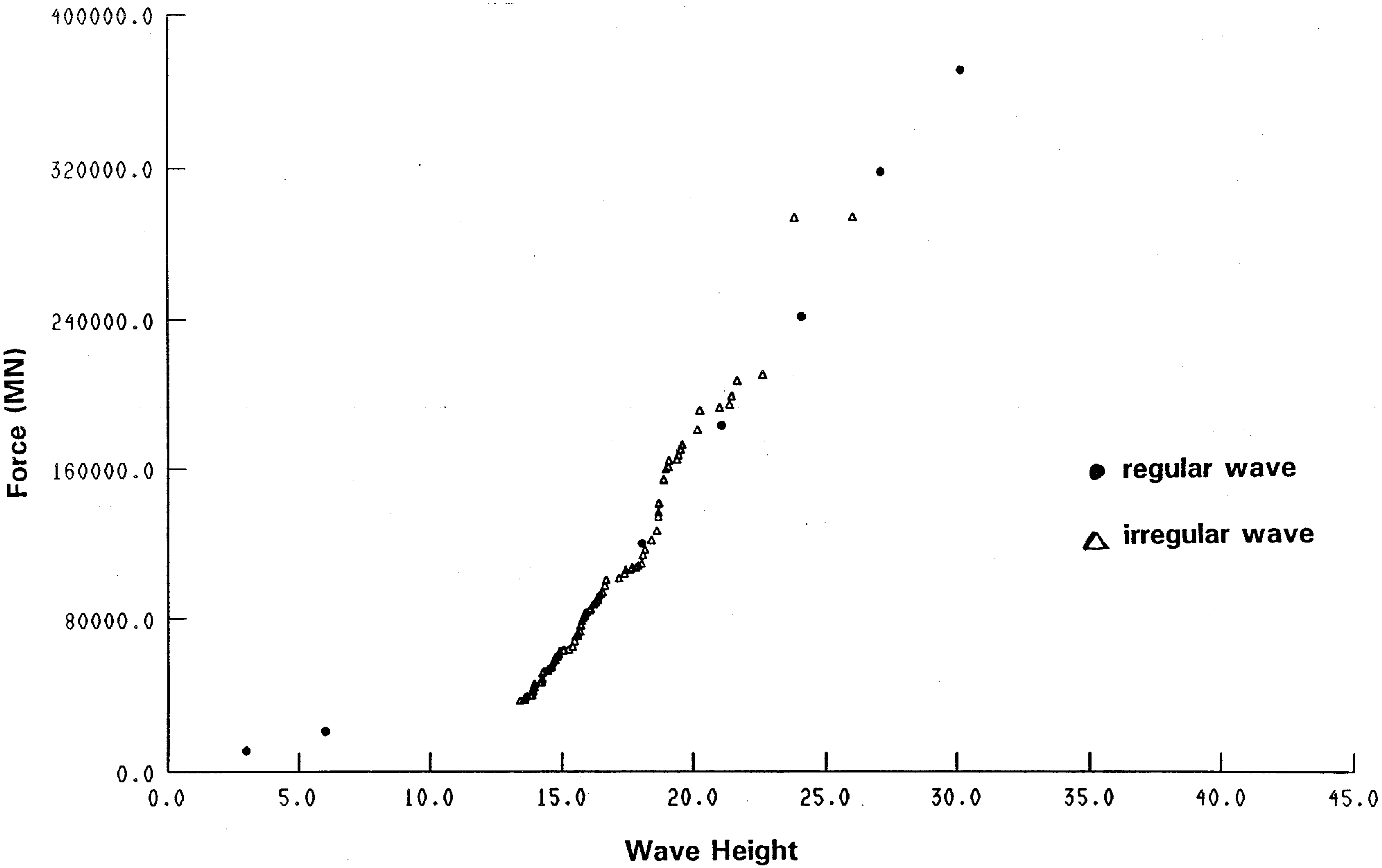

FIGURE 10 RANKED PLOT OF HORIZONTAL GLOBAL FORCES

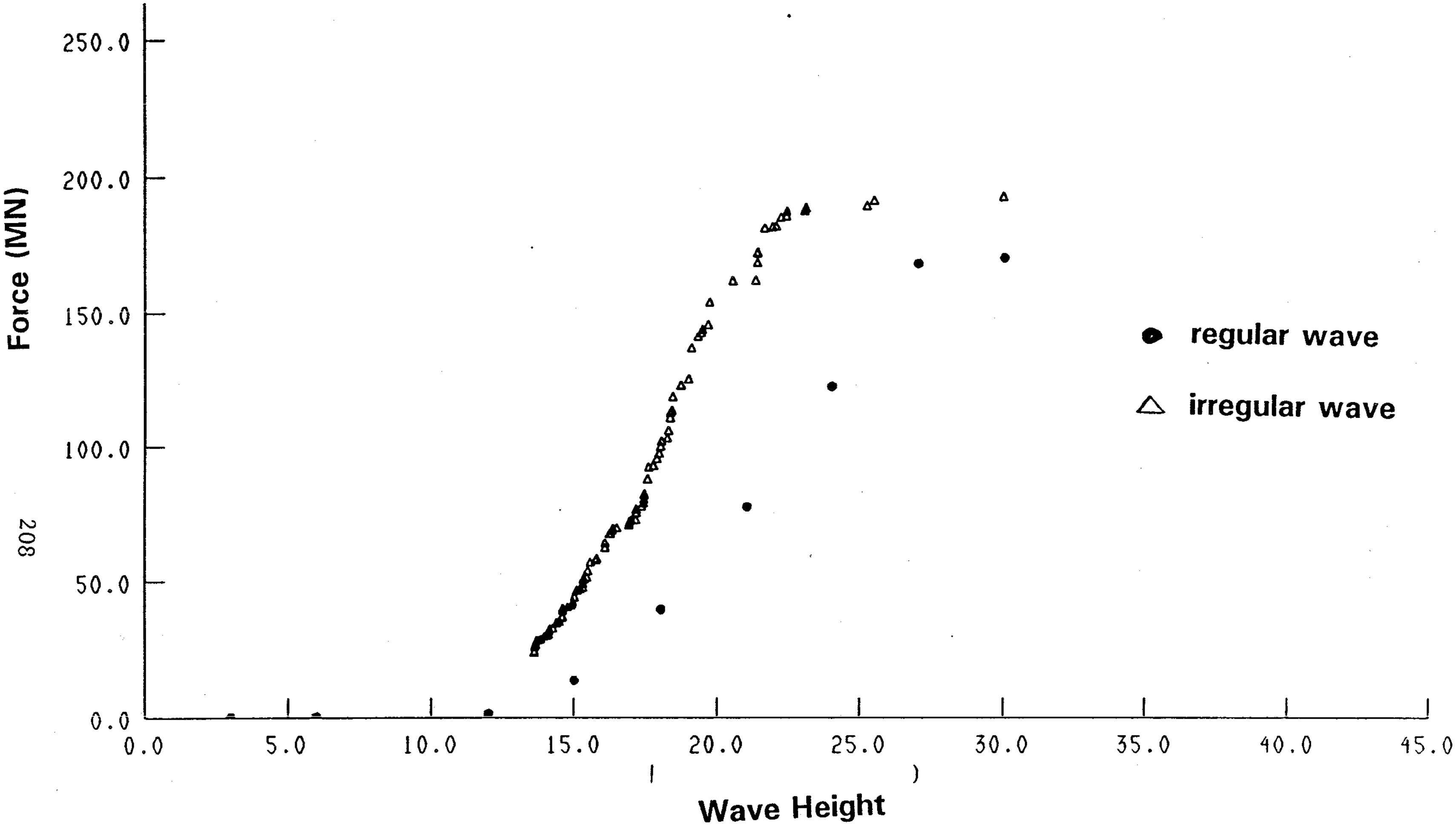

FIGURE 11 RANKED PLOT OF LOCAL IMPACT LOADS