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NATIONAL MARINE FISHERIES SERVICE SOUTHWEST FISHERIES SCIENCE CENTER

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WAVE TANK TESTS:
EXTRAPOLATION TO OPEN OCEAN CONDITIONS

by

J. Ian Collins

ADMINISTRATIVE REPORT LJ-93-11C

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WAVE TANK TESTS: EXTRAPOLATION TO OPEN OCEAN CONDITIONS

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1. Introduction.

As part of the Southwest Fisheries Science Center research on the impact of gill net fishing of tuna a series of tests were executed in a wave tank at Arctec Offshore Corporation's facility in Escondido, California. In May of 1991 a series of wave tank tests were performed with a 12 feet deep by 150 feet long piece of a gill net partially loaded with tuna. Instrumentation included wave measurements and sensing of net motions by accelerometer packages tied to the net. The test set-up is illustrated in Figure 1-1. The data report was prepared by Goebel (1991).

Observations of the fish loss for various waves were made. The fish loss data are summarized in Table 1-1 (from Holts, personal communication).

Typical "at sea" wave conditions would be considered as; wave heights up to 2 meters with wave periods from about 6 to 10 seconds. In the test basin the wave heights are restricted to about 0.6 m. and wave periods of 2 to 3 seconds. Normally, the simulation of more realistic seas would suggest the application of a reduced scale model. It was not possible to scale the prototype tuna. Initially, the model study in the tank was planned as one task in a longer range program in which measurements of motions of prototype nets would be made. In the tank tests accelerometers were attached to the net at selected locations and the "fish loss" versus "acceleration" fields were measured. The question remaining was whether the observed data in the test tank could be extrapolated to more realistic open ocean conditions.

To extrapolate the laboratory test data to prototype conditions, three steps are required:

1. Relationship of fish loss rates to the relative acceleration and velocity fields experienced by the fish at various locations on the net,

2. Definition of a procedure for the extrapolation of measured fish loss as a function of velocity and acceleration to sea state and,

3. Definition of the joint occurrence of such velocity and acceleration fields at representative fishing grounds in the North Pacific.

This report presents the results of these investigations.

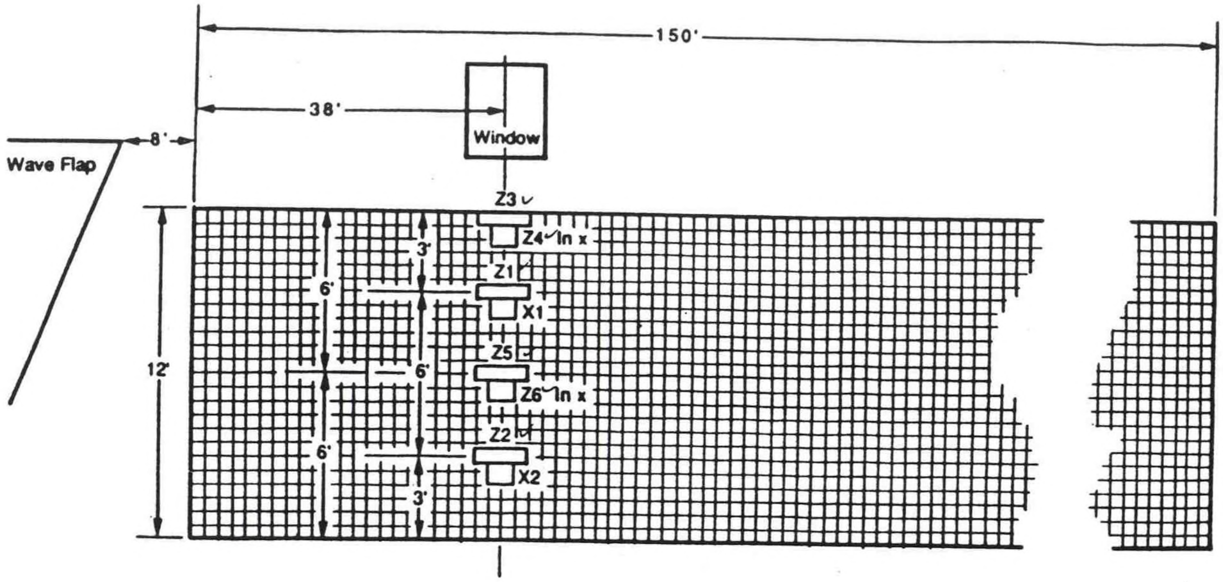


Figure 1-1
General Net Layout and Accelerometer Locations

TEST RUN	WAVE PROPERTIES TYPE	PERIOD (sec)	HEIGHT (in)	TEST TIME (min)	FISH IN NET	DROPOUTS No.	%
201	Regular	4.0	14.6	26	12	0	0
202	Regular	3.0	23.7	34	12	2	17
203	Regular	3.0	23.6	32	12	1	8
205	Regular	2.5	20.1	25	12	9	75
301	Irregular	2.5	23.5	30	10	0	0
303	Irregular	2.5	27.4	30	10	2	10
305	Irregular	2.5	29.3	30	10	1	10
307	Irregular	2.0	20.0	30	10	3	30
309	Irregular	2.0	30.0	30	10	3	30
311	Irregular	2.0	19.0	30	10	1	10
313	Irregular	3.0	23.5	30	10	0	0
315	Irregular	2.0	23.5	30	10	6	60
317	Irregular	3.0	23.5	30	10	2	20

Table 1-1
Summary of Fish Losses Observed During the Tests

2. Hydrodynamic Forces on Gil-Netted Fish

Once a fish is trapped in a net it must be anticipated that the motions of the net and the motions of the water near the net will not be the same. This implies that there will be hydrodynamically induced loads on the fish as it is "jerked around" relative to the water.

The water particle motions can be defined in terms of the wave heights and wave periods. The net would be expected to respond to some "average" property of the hydrodynamic loads on the surface floats and the motion damping induced by the sink weights attached to the net base. This was readily observed, through the glass window in the test tank.

The hydrodynamic loads on any body in a moving fluid are normally considered to consist of two types: drag loads induced by the relative velocity of motion and inertia loads due to relative acceleration. Such loads can be expressed by the so-called "Morison" formula (Morison, O'Brien, Johnson and Schaaf, 1950) as modified to take into account the fact that the body itself may be moving. The relationship can be written;

$$F = 0.5\ \rho\ C_d\ A\ (x_w - x_f)\ |(x_w - x_f)| + \rho\ C_m V\ (x_w - x_f) \qquad \text{(Eq. 1)}$$

where;

F	is the force on the body
ρ	is the density of the fluid
C_d	is the drag coefficient
A	is the projected area normal to the flow
x_w	is the position of the body
x_f	is the position of a fluid
	the dot denotes first time derivative (velocity) and the double dot denotes the second time derivative (acceleration)
m	s the mass of the body
C_m	is the added mass coefficient
V	is the displaced volume of the submerged body

It is noted from an examination of the above equation that if there is no relative motion between the body and the fluid the only net force is that required to accelerate the fish. However, if the fish which is trapped in the net does not follow the water motions in the waves precisely there will be resultant hydrodynamically induced loads on the fish.

The net was supported by floats at the water surface and included weights at the bottom. Visual observation of the net motions in the waves was possible due to the presence of a large glass window in the wave tank. It was observed that, as the waves passed by, the net moved up and down in response to the waves but the floats did not follow the water surface exactly. On the other hand, in the wave trough the surface floats would follow the water surface. This would imply that even if the waves were sinusoidal, the net motions at the top of the net could not be. At deeper positions of the net both the horizontal and vertical motions of the net were generally greater than the water particle motions. At some intermediate depth it would be expected that the net motions (and hence any trapped fish) would follow the water motions fairly closely.

The water particle velocities and accelerations as a function of depth of submergence in moderate seas for a wave height, H, and period, T, propagating in the positive x-direction (see Figure 2-1), can be estimated from classical (first order) wave theory (see for example, Lamb,1945):

$$x\ (x_o,\ z,\ t) = H/2 * \exp(kz) * \cos(kx_o - \omega t) \qquad \text{(Eq. 2)}$$

$$x\ (x_o,\ z,\ t) = u\ (x_o,\ z,\ t) = (\pi H/T) * \exp(kz) * \cos(kx_o - \omega t) \qquad \text{(Eq 3)}$$

$$x\ (x_o,\ z,\ t) = a\ (x_o,\ z,\ t) = -(2\pi^2 H/T^2) * \exp(kz) * \sin(kx_o - \omega t) \qquad \text{(Eq 4)}$$

where;

H	is the wave height
k	is the wave number defined as 2π/(wavelength) and is equal to ω^2/g
ω	is the radian frequency defined as 2π/(wave period)
g	is the gravity constant
z	is the mean vertical position measured positive upwards from the surface
x_o	is the mean horizontal position of the water particle
u	is x-component of the particle speed
a	is the x-component of the particle acceleration

A preliminary evaluation of the relative importance of the hydrodynamic forces can be made by assuming that the fish do not move and the maximum values of the two types of forces will be:

1. Drag $= 0.5\,\rho\, C_d\, A\, u\, |u|$ (Eq. 5)

2. Inertia $= \rho\, C_m V a$ (Eq. 6)

It is noted that the maximum drag loads are proportional to the square of the wave height divided by the square of the wave period (H^2/T^2) and the product of the fish diameter and length (broadside area in this case). The dependence on depth of submergence (with this simplified model) is exponential. On the other hand, the maximum inertia loads are proportional to the wave height divided by the square of the wave period (H/T^2) and increase with increasing fish size (volume). This force also decays exponentially with depth of submergence. The apparent decay of loads with depth of submergence will not be

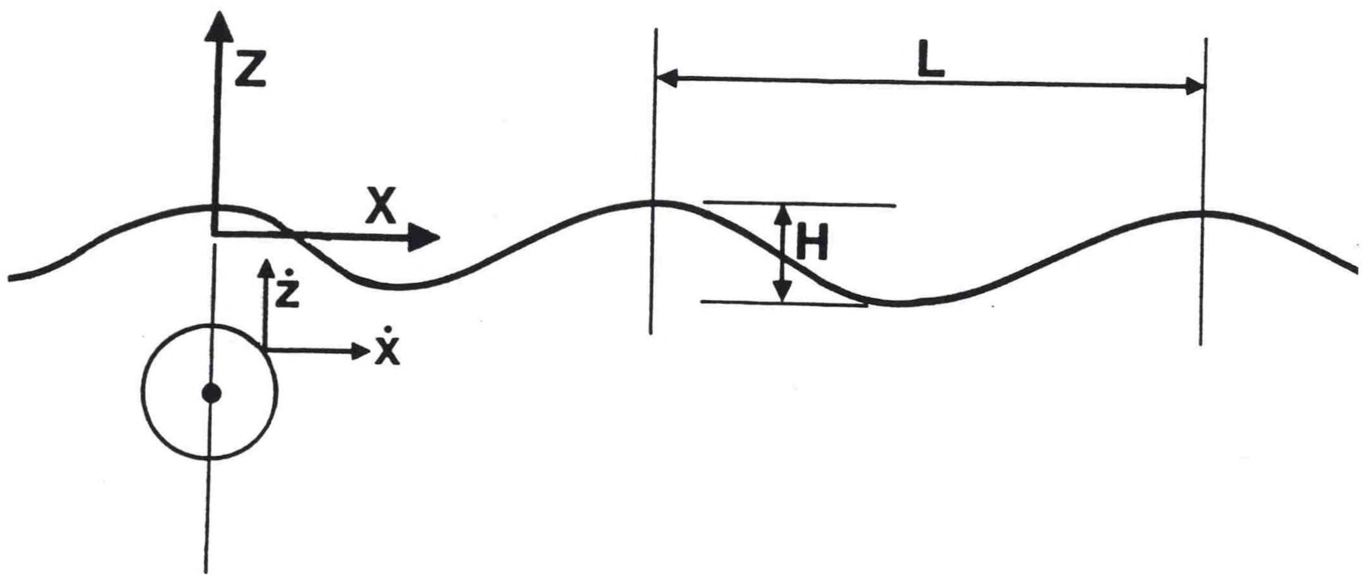


Figure 2-1 Definition of Wave Terminology and Co-Ordinate System

quite correct in practice, since it has been noted during the tests that with deeper submergence the net usually moves more than the water particle motions.

A comparison of the relative magnitude of inertia and drag loads can be made by taking the ratio of maximum Inertia to maximum Drag as:

$$(\rho C_m V a) / (0.5 \rho C_d A u^2) \qquad \text{(Eq. 7)}$$

substituting the values for u and a from Equations 3 and 4 yields;

$$\text{Ratio of Inertia to Drag load} = (4 C_m V) / (C_d A H \exp(kz)). \qquad \text{(Eq. 8)}$$

Now, V/A is the diameter of the fish (about 15 cm.), $C_m \approx 2.0$, $C_d \approx 0.5$ and at a vertical elevations of -2.0 and -3.0 meters, the relative ratio of inertia to drag load will be given by the relationship:

$$\text{Maximum Inertia/ Maximum Drag} = 16 \lambda / (H \exp(kz)) \qquad \text{(Eq. 9)}$$

where, λ is the length of the fish.

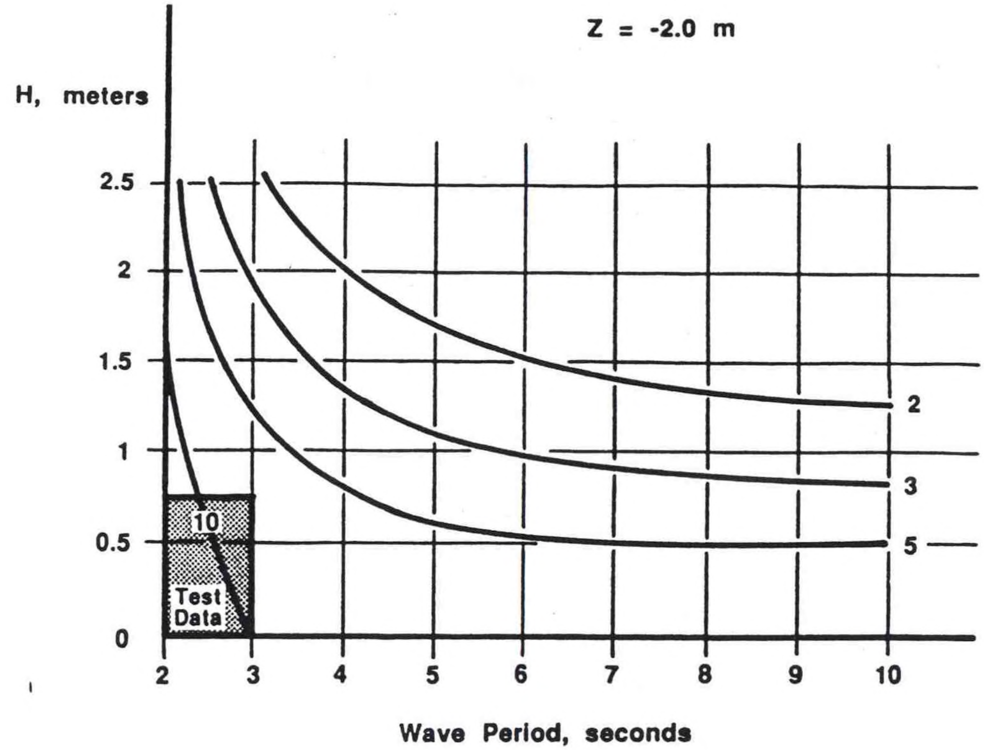
The distribution of the length of the fish appears to follow a tri-modal distribution (see Bartoo et al, 1991 and 1992). The tri-modal distribution is apparently related directly to the age of the fish. For purposes of this report the modal length of 65 cm. will be used.

The relationship of Equation 9 is illustrated in Figure 2.2 for a range of wave heights and wave periods for depths of submergence of 2 and 3 meters. It is seen that in the model tank the loads on the fish were dominated by inertia type loads which were about 10 times the drag components. On the other hand, in open ocean conditions in waves of height 1.0 to 1.5 meters this ratio would be between 2 and 3.

Equations 5 and 6 can be used to estimate the actual magnitudes of the forces. It must be remembered that these maxima are out of phase by 90° and the resultant maximum load magnitude would be given (approximately) by;

$$F_{max} = \sqrt{(\text{Inertia}_{max}{}^2 + \text{Drag}_{max}{}^2)} \qquad \text{(Eq. 10)}$$

Figures 2-3 and 2-4 present the estimated maximum hydrodynamic loads on a trapped fish for the case of an immobile net in various wave heights and wave periods. In the real case the net will respond to the waves but may not always be in phase. For the purposes of the estimation of the wave induced loads on trapped fish the theoretical values given by Equation 10 will be assumed. Actual loads could be greater or smaller than those indicated in Figures 2-3 and 2-4. For example, Figures 2-5 through 2-8



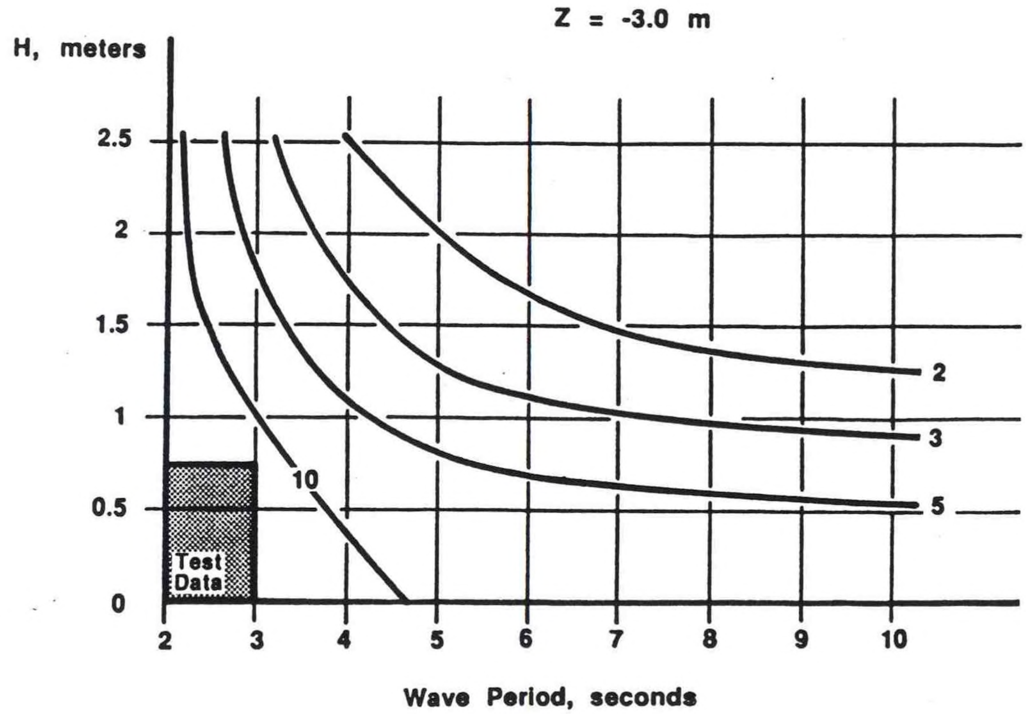


Figure 2-2 Ratio of Inertia to Drag Forces for 2 and 3 meter Mean Submergence Depth

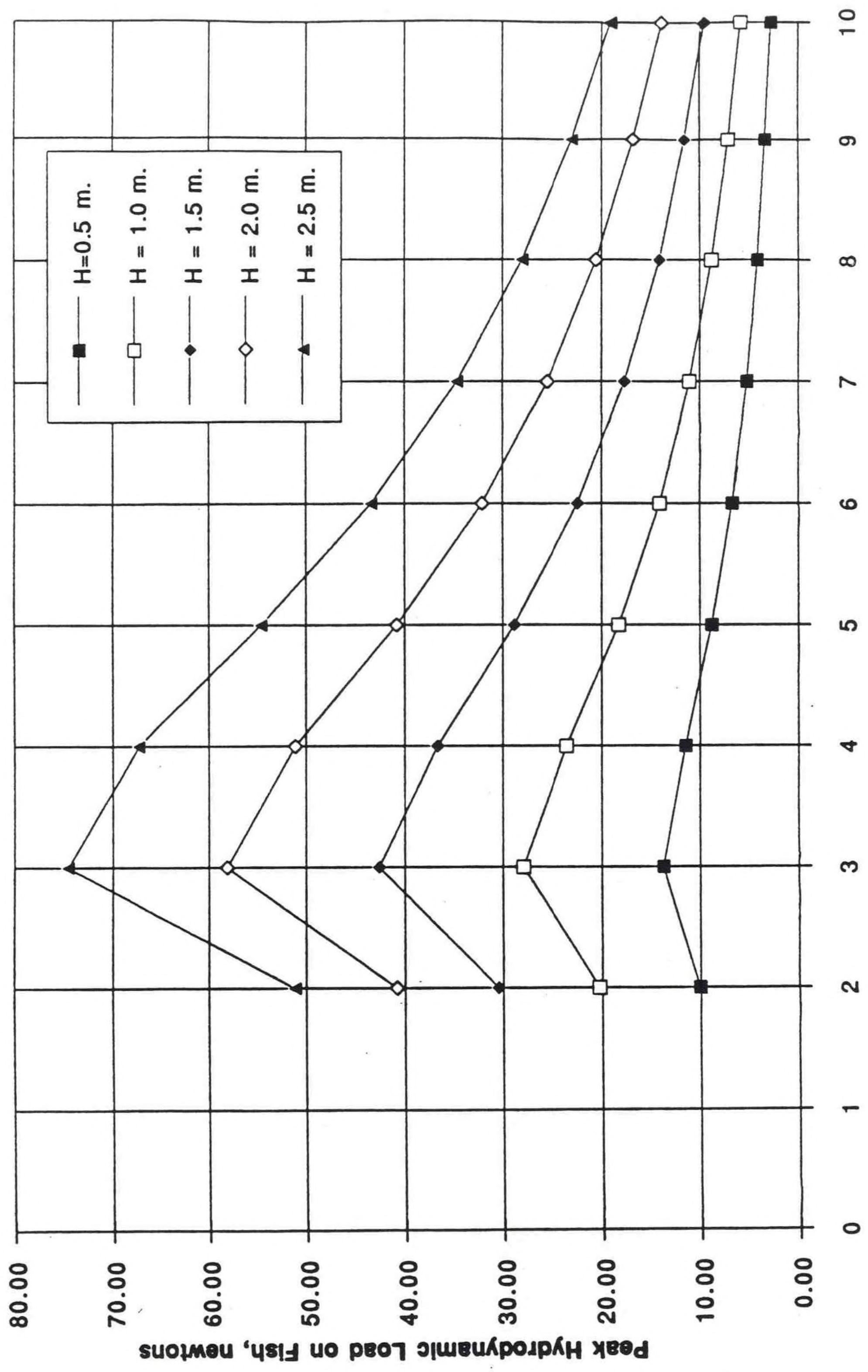


Figure 2-3 Peak Wave Force as a Function of Wave Height and Period at Elevation -2.0 meters

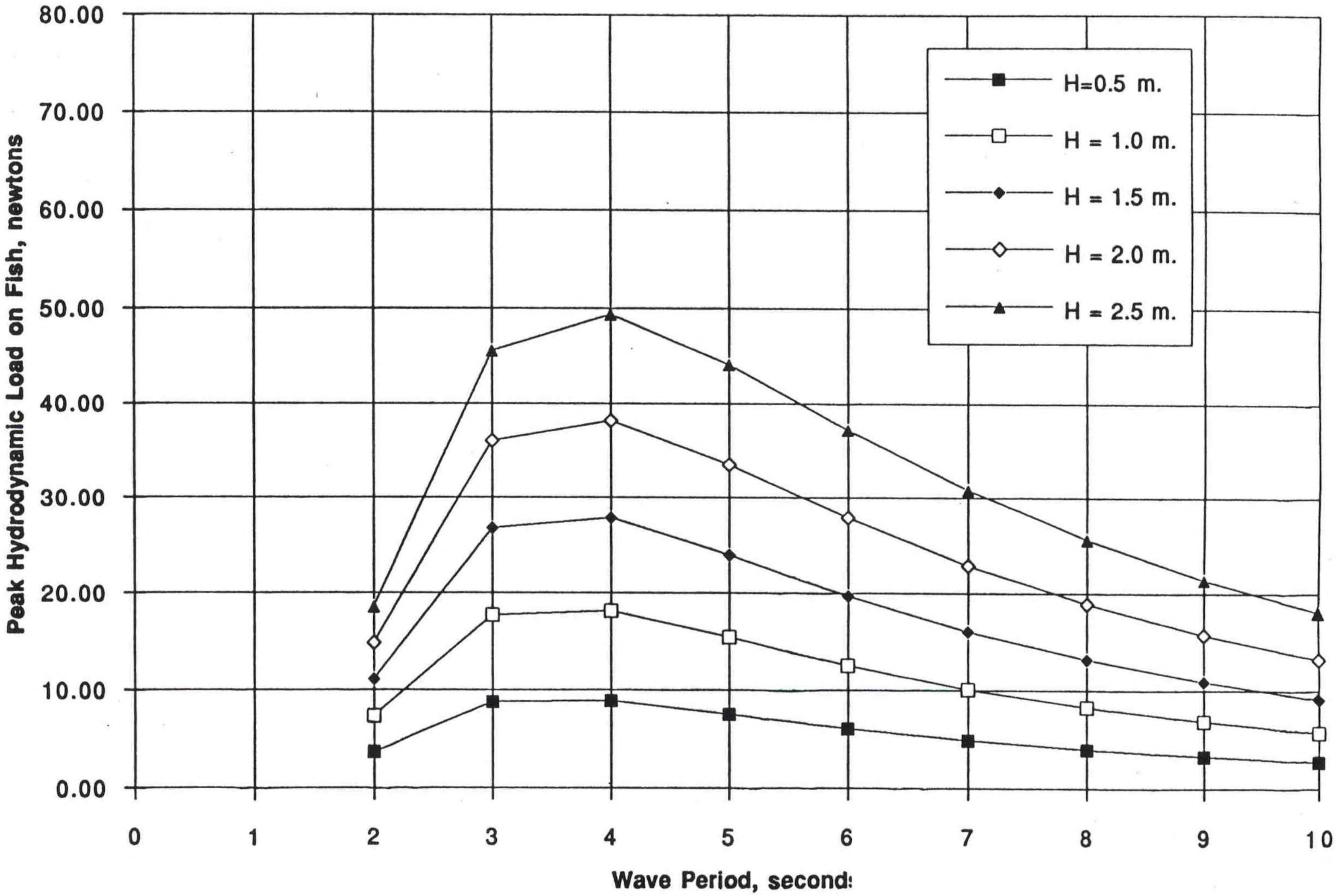


Figure 2-4 Peak Wave Force as a Function of Wave Height and Period at Elevation -3.0 meters

show measured (from the test program) and theoretical response ratios for wave amplitude versus acceleration amplitude.

The "theoretical" lines in Figures 2-5 through 2-8 have been derived according to Equation 4. The "observed" data was taken from the results obtained during a series of tests in which the accelerometers were relocated and distributed over the vertical through Stations 1 and 2 of Figure 1-1. The response amplitude operators (RAO's) were derived using standard cross spectral analysis techniques from the random wave tests.

It is seen that at all elevations the x and z accelerations of the net are greater than the water particle accelerations for low frequencies (wave periods longer than 4 seconds). At higher frequencies (shorter periods) the net accelerations tend to be less than the theoretical particle accelerations near the surface and greater at a depth of 9 feet (2.74 m.).

Co-incident with the development of the so-called, Response Amplitude Operators (RAO's) of the net accelerations, the phase relationships between the accelerations and the wave motions were derived. Theoretically, the vertical accelerations should be 180° out of phase with the surface motion (i.e. the vertical acceleration is directed downwards under a wave crest and upwards under a trough). The horizontal accelerations should be zero under a crest and under a trough. These relationships were found to be true.

The net has vertical and horizontal compressibility so the gradients of the loads may be important. If the net is being stretched at the time of maximum loads the fish will stay trapped as "the noose" is tightened. On the other hand, if the gradients are such that the net slackens at the time of maximum loads the fish may fall out. The practical case is that the vertical acceleration gradients are "in phase" with the vertical acceleration whereas the horizontal acceleration gradients are 90° out of phase with the horizontal acceleration. It is not clear what would be the relative importance of the two modes but it would be expected that having the vertical and horizontal accelerations and acceleration gradients with differing phses would imply tight nooses under most conditions.

An additional consideration is that all of the test data were collected with the waves propagating along the line of the net. It is not clear that the results can be applied directly for other relative angles of wave propagation.

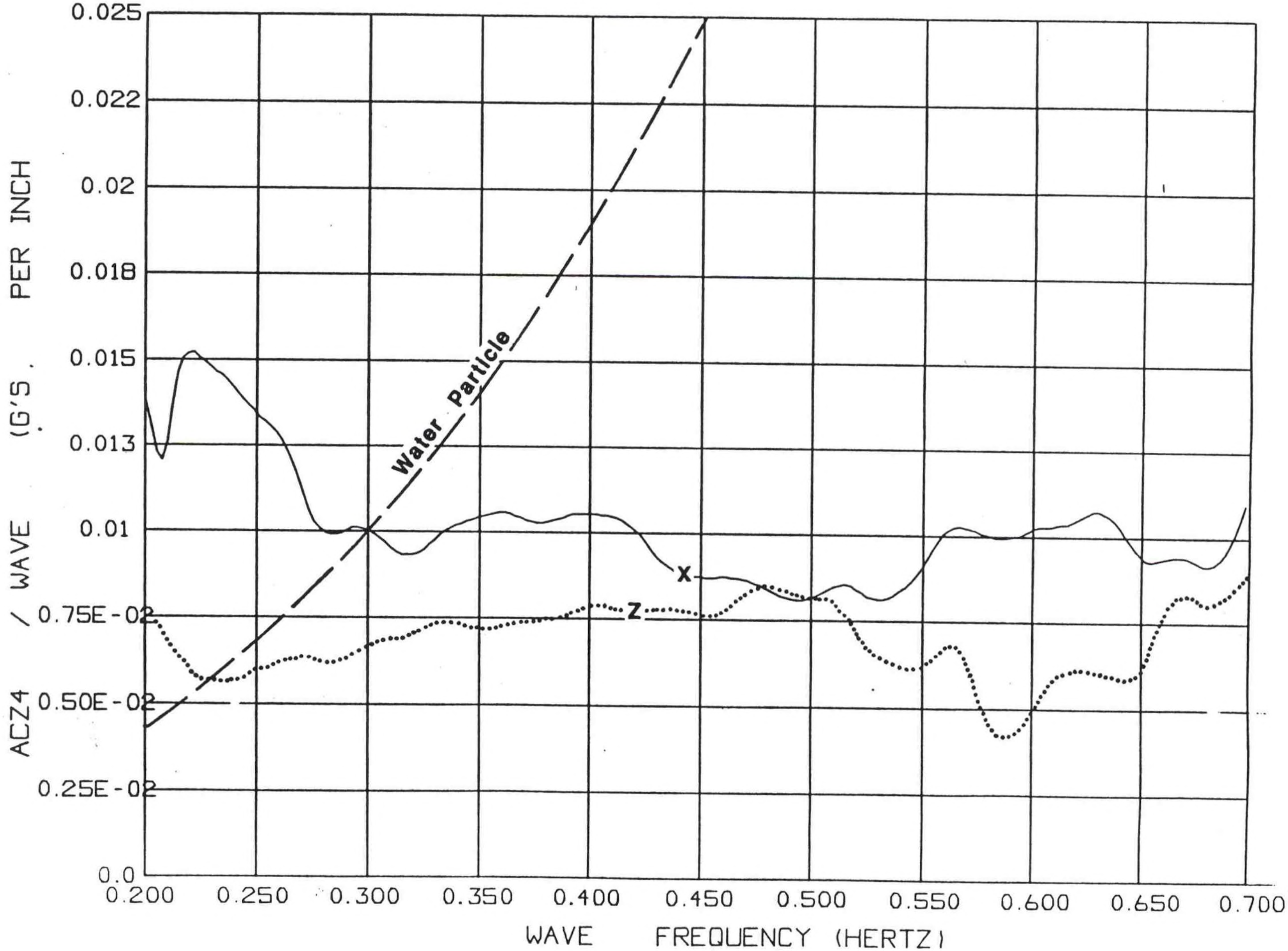


Figure 2-5 Observed Response Amplitude Operators for Horizontal and Vertical Accelerations of the Net at the Water Surface

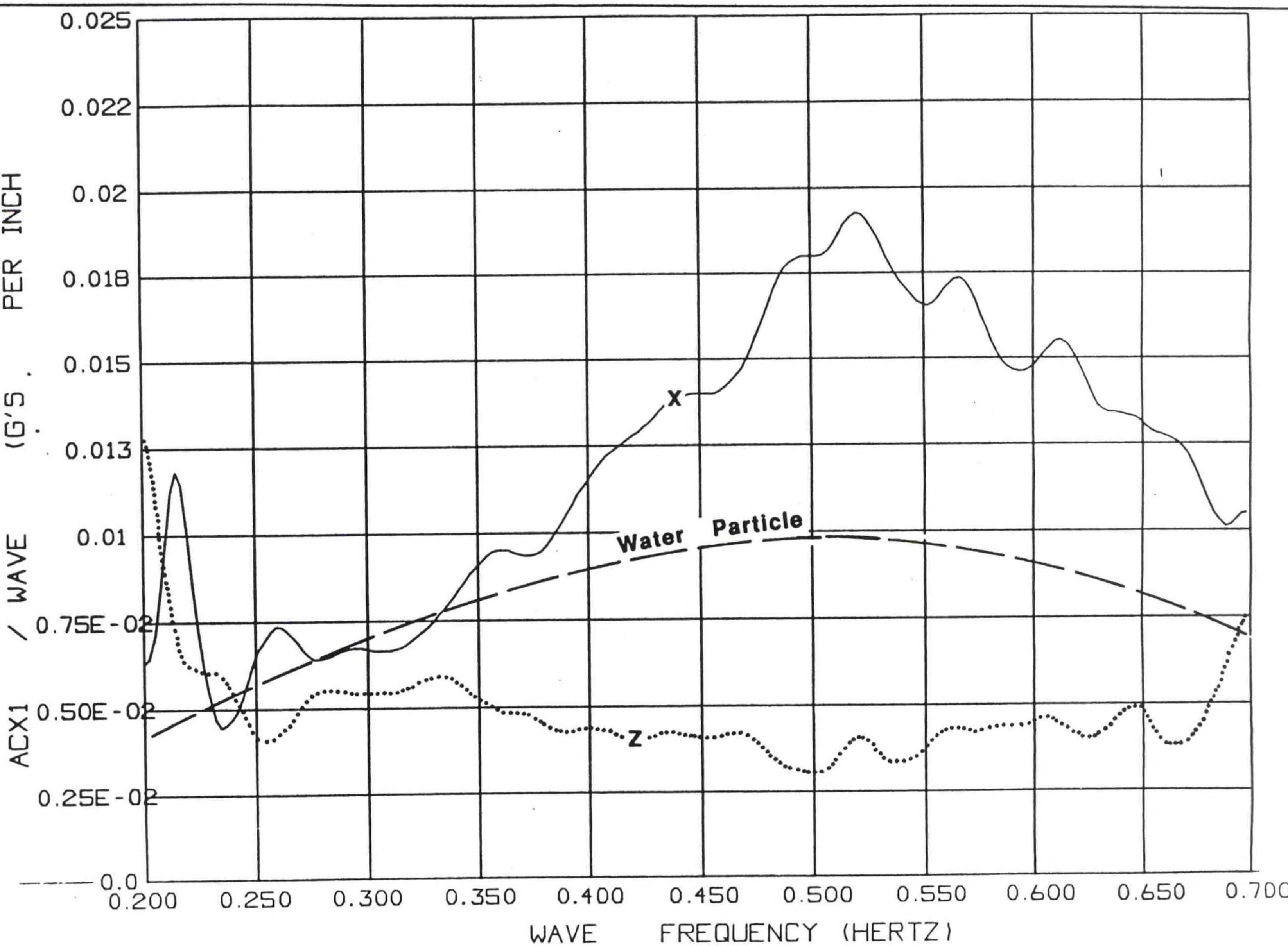


Figure 2-6 Observed Response Amplitude Operators for Horizontal and Vertical Accelerations of the Net at Elevation - 3 feet (-0.91 m.)

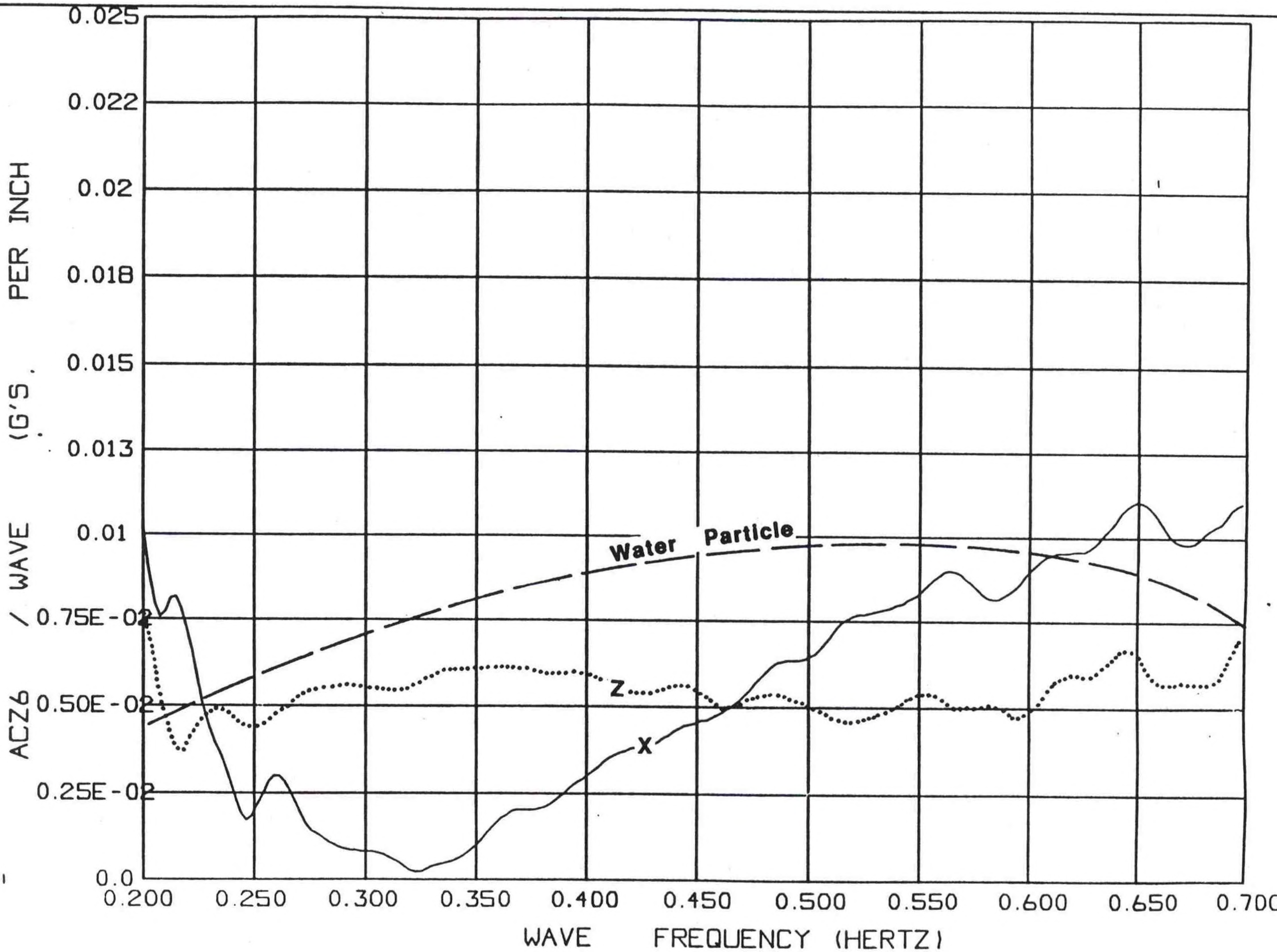


Figure 2-7 Observed Response Amplitude Operators for Horizontal and Vertical Accelerations of the Net at Elevation - 6 feet (-1.83 m.)

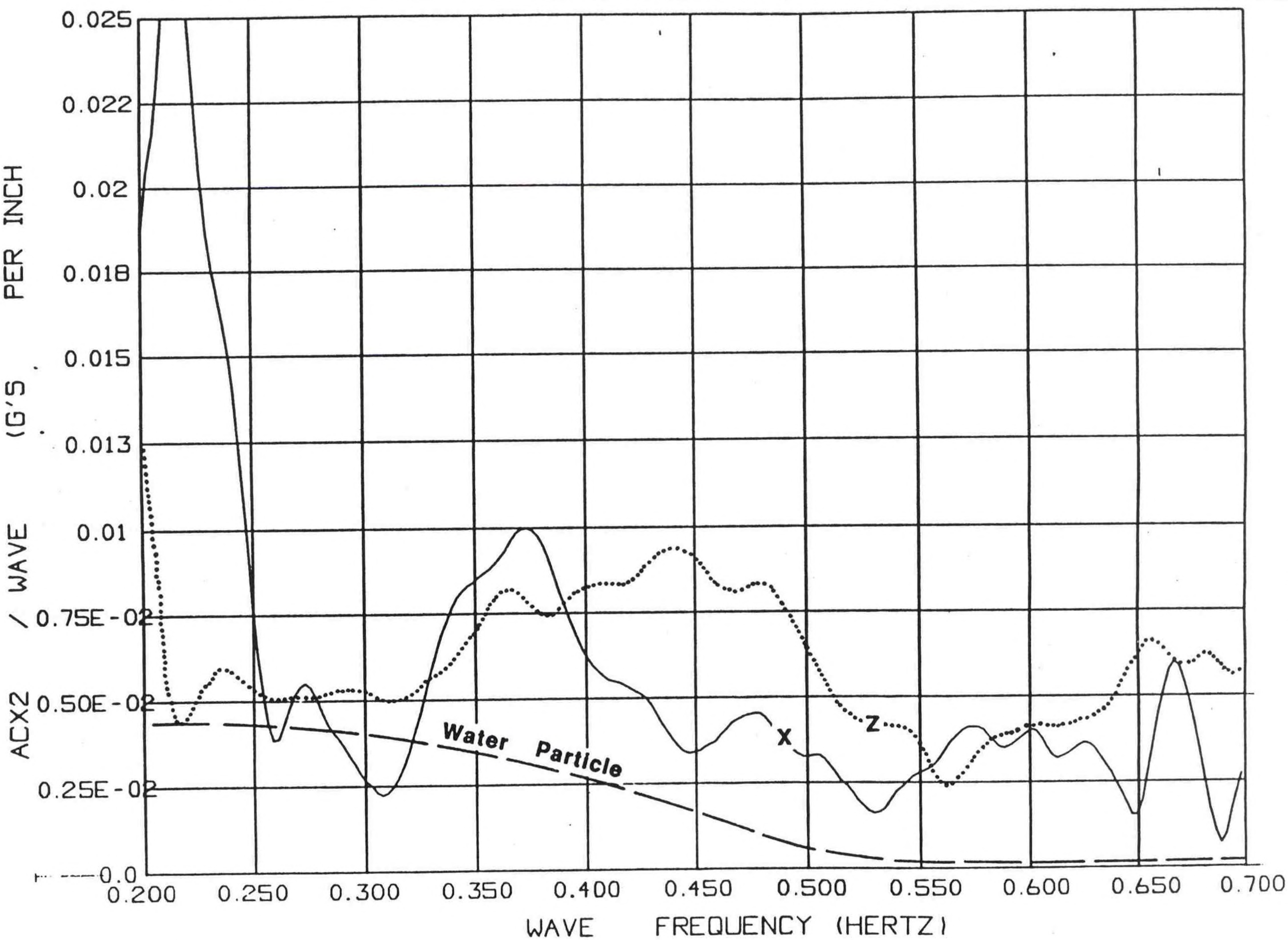


Figure 2-8 Observed Response Amplitude Operators for Horizontal and Vertical Accelerations of the Net at Elevation - 9 feet (-2.74 m.)

3 Extrapolation to Open Ocean Conditions.

Figures 2-3 and 2-4 have presented estimates of the expected range of hydrodynamic loads on a trapped fish. It is seen that the general magnitudes of the loads generated in the test range (typically 5 to 15 newtons) would not be vastly different from the computed loads induced by wave heights up to 1.5 meters with periods of 6 to 10 seconds at a depth of submergence of 2 to 3 meters. The extrapolation of the measured data in the tank to ocean conditions would appear reasonable for such a range.

It is noted from the test data that when the peak hydrodynamic loads were less than 10 newtons no fish loss was observed. There was considerable scatter in the fish loss data (see Table 1-1) as might be expected due to the range of fish sizes, method of attachment to the net, location with depth, "natural" variability, etc. and the loss data do not clearly show an expected trend with greater losses as the hydrodynamic forces increased. Nevertheless, it would be expected that such would be the case. From the present data, a mean loss ratio of slightly more than 20% was observed for all cases when the estimated peak hydrodynamic forces exceeded 10 newtons. This is proposed as the critical criterion.

4 Summary of Characteristic North Pacific Wave Conditions.

The general tuna fishing areas are shown on Figure 4-1 (from Bartoo, Holts and Halko, 1992). Gill net fishing is apparently performed in weather up to Beaufort Force 5. Table 4-1 presents a summary review of the Beaufort Scale (from Bowditch, 1966). Wave heights up to about 2 meters can occur. Bretschneider (1956) has proposed a relationship between significant wave height height and mean wave period given (in feet, second units) by;

$H / T^2 = 0.22$
or $T = 2.13 \sqrt{H}$ if H is in feet
or $T = 3.86 \sqrt{H}$ if H is in meters.

Generally, it has been noted by more recent studies that the mean wave periods are slightly greater than this relationship would imply. According to Bales (1983) from a review of North Pacific wave observations the relationship between mean wave height and modal wave period is given by Table 4-2. This table indicates much longer wave periods.

It would be expected that in a rising sea in a fresh breeze a relationship similar to that of Bretschneider's would be expected from the point of view of the physics of air-sea energy transfer. Coefficients between 4.0 and 5.0 have been reported from analysis of meteorological summaries.

$$T = 5.0 \sqrt{H}$$

will be adopted. The various H vs. T relationships are illustrated in Figure 4-2. This figure also illustrates the region of test data and the expected region of open ocean conditions with the above criteria for the wave period.

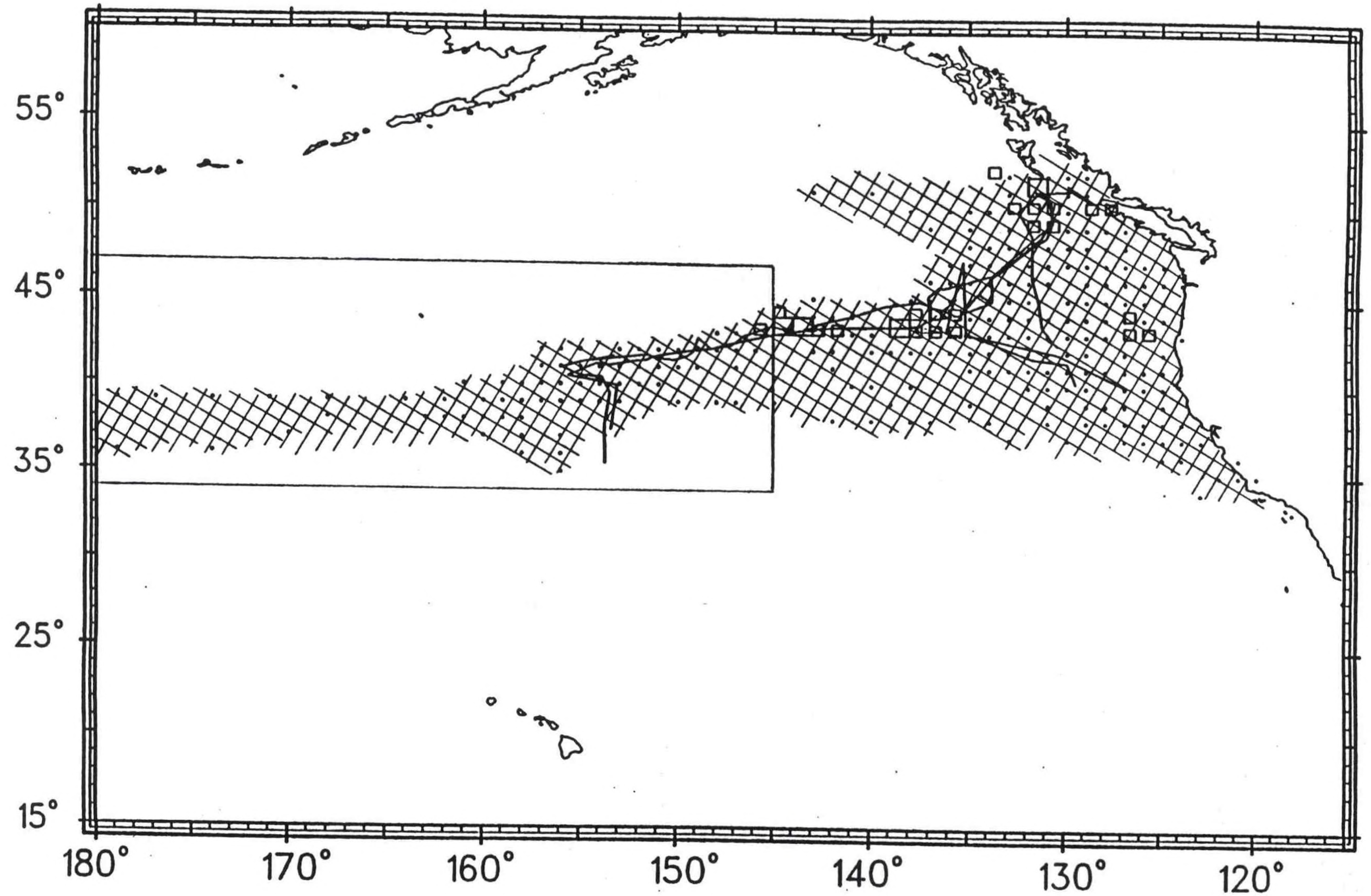


Figure 4-1 General area for U.S. Albacore Fishery (cross hatched) and
Japanese Squid Drift Net Fishery (box outline) for 1990.
Track Lines Represent U.S. Observed trips Onboard Troll Vessels.

Table 4-1
Summary of Beaufort Scale Definition (after Bowditch, 1966)

BEAUFORT SCALE
WITH CORRESPONDING SEA STATE CODES

Beaufort number	Wind speed: knots	Wind speed: mph	Wind speed: meters per second	Wind speed: km per hour	Seaman's term	World Meteorological Organization (1964)	Estimating wind speed: Effects observed at sea	Estimating wind speed: Effects observed on land	Hydrographic Office: Term and height of waves, in feet	Hydrographic Office: Code	World Meteorological Organization: Term and height of waves, in feet	World Meteorological Organization: Code
0	under 1	under 1	0.0-0.2	under 1	Calm	Calm	Sea like mirror.	Calm; smoke rises vertically.	Calm, 0	0		
1	1-3	1-3	0.3-1.5	1-5	Light air	Light air	Ripples with appearance of scales; no foam crests.	Smoke drift indicates wind direction; vanes do not move.	Smooth, less than 1	1	Calm, glassy, 0	0
2	4-6	4-7	1.6-3.3	6-11	Light breeze	Light breeze	Small wavelets; crests of glassy appearance, not breaking.	Wind felt on face; leaves rustle; vanes begin to move.	Slight, 1-3	2	Calm, rippled, 0-⅓	1
3	7-10	8-12	3.4-5.4	12-19	Gentle breeze	Gentle breeze	Large wavelets; crests begin to break; scattered whitecaps.	Leaves, small twigs in constant motion; light flags extended.	Moderate, 3-5	3	Smooth, wavelets, ⅓-1⅔	2
4	11-16	13-18	5.5-7.9	20-28	Moderate breeze	Moderate breeze	Small waves, becoming longer; numerous whitecaps.	Dust, leaves, and loose paper raised up; small branches move.			Slight, 2-4	3
5	17-21	19-24	8.0-10.7	29-38	Fresh breeze	Fresh breeze	Moderate waves, taking longer form; many whitecaps; some spray.	Small trees in leaf begin to sway.	Rough, 5-8	4	Moderate, 4-8	4
6	22-27	25-31	10.8-13.8	39-49	Strong breeze	Strong breeze	Larger waves forming; whitecaps everywhere; more spray.	Larger branches of trees in motion; whistling heard in wires.			Rough, 8-13	5
7	28-33	32-38	13.9-17.1	50-61	Moderate gale	Near gale	Sea heaps up; white foam from breaking waves begins to be blown in streaks.	Whole trees in motion; resistance felt in walking against wind.				
8	34-40	39-46	17.2-20.7	62-74	Fresh gale	Gale	Moderately high waves of greater length; edges of crests begin to break into spindrift; foam is blown in well-marked streaks.	Twigs and small branches broken off trees; progress generally impeded.	Very rough, 8-12	5	Very rough, 13-20	6
9	41-47	47-54	20.8-24.4	75-88	Strong gale	Strong gale	High waves; sea begins to roll; dense streaks of foam; spray may reduce visibility.	Slight structural damage occurs; slate blown from roofs.	High, 12-20	6		
10	48-55	55-63	24.5-28.4	89-102	Whole gale	Storm	Very high waves with overhanging crests; sea takes white appearance as foam is blown in very dense streaks; rolling is heavy and visibility reduced.	Seldom experienced on land; trees broken or uprooted; considerable structural damage occurs.	Very high, 20-40	7	High, 20-30	7
11	56-63	64-72	28.5-32.6	103-117	Storm	Violent storm	Exceptionally high waves; sea covered with white foam patches; visibility still more reduced.		Mountainous, 40 and higher	8	Very high, 30-45	8
12 13 14 15 16 17	64-71 72-80 81-89 90-99 100-108 109-118	73-82 83-92 93-103 104-114 115-125 126-136	32.7-36.9 37.0-41.4 41.5-46.1 46.2-50.9 51.0-56.0 56.1-61.2	118-133 134-149 150-166 167-183 184-201 202-220	Hurricane	Hurricane	Air filled with foam; sea completely white with driving spray; visibility greatly reduced.	Very rarely experienced on land; usually accompanied by widespread damage.	Confused	9	Phenomenal, over 45	9

Note: Since January 1, 1955, weather map symbols have been based upon wind speed in knots, at five-knot intervals, rather than upon Beaufort number.

Table 4-2
Annual Sea State Occurrences in the Open Ocean North Pacific (After Bales, 1983)

Sea State Number	Significant Wave Height (m)		Sustained Wind Speed (Knots)*		Percentage Probability of Sea State	Modal Wave Period (Sec)	
	Range	Mean	Range	Mean		Range**	Most Probable***
0 - 1	0 - 0.1	0.05	0 - 6	3	0	—	—
2	0.1 - 0.5	0.3	7 - 10	8.5	4.1	3.0 - 15.0	7.5
3	0.5 - 1.25	0.88	11 - 16	13.5	16.9	5.2 - 15.5	7.5
4	1.25 - 2.5	1.88	17 - 21	19	27.8	5.9 - 15.5	8.8
5	2.5 - 4	3.25	22 - 27	24.5	23.5	7.2 - 16.5	9.7
6	4 - 6	5	28 - 47	37.5	16.3	9.3 - 16.5	13.8
7	6 - 9	7.5	48 - 55	51.5	9.1	10.0 - 17.2	13.8
8	9 - 14	11.5	56 - 63	59.5	2.2	13.0 - 18.4	18.0
>8	>14	>14	>63	>63	0.1	20.0	20.0

*Ambient wind sustained at 19.5 m above surface to generate fully-developed seas. To convert to another altitude, H_2, apply $V_2 = V_1(H_2/19.5)^{1/7}$

**Minimum is 5 percentile and maximum is 95 percentile for periods given wave height range.

***Based on periods associated with central frequencies included in Hindcast Climatology.

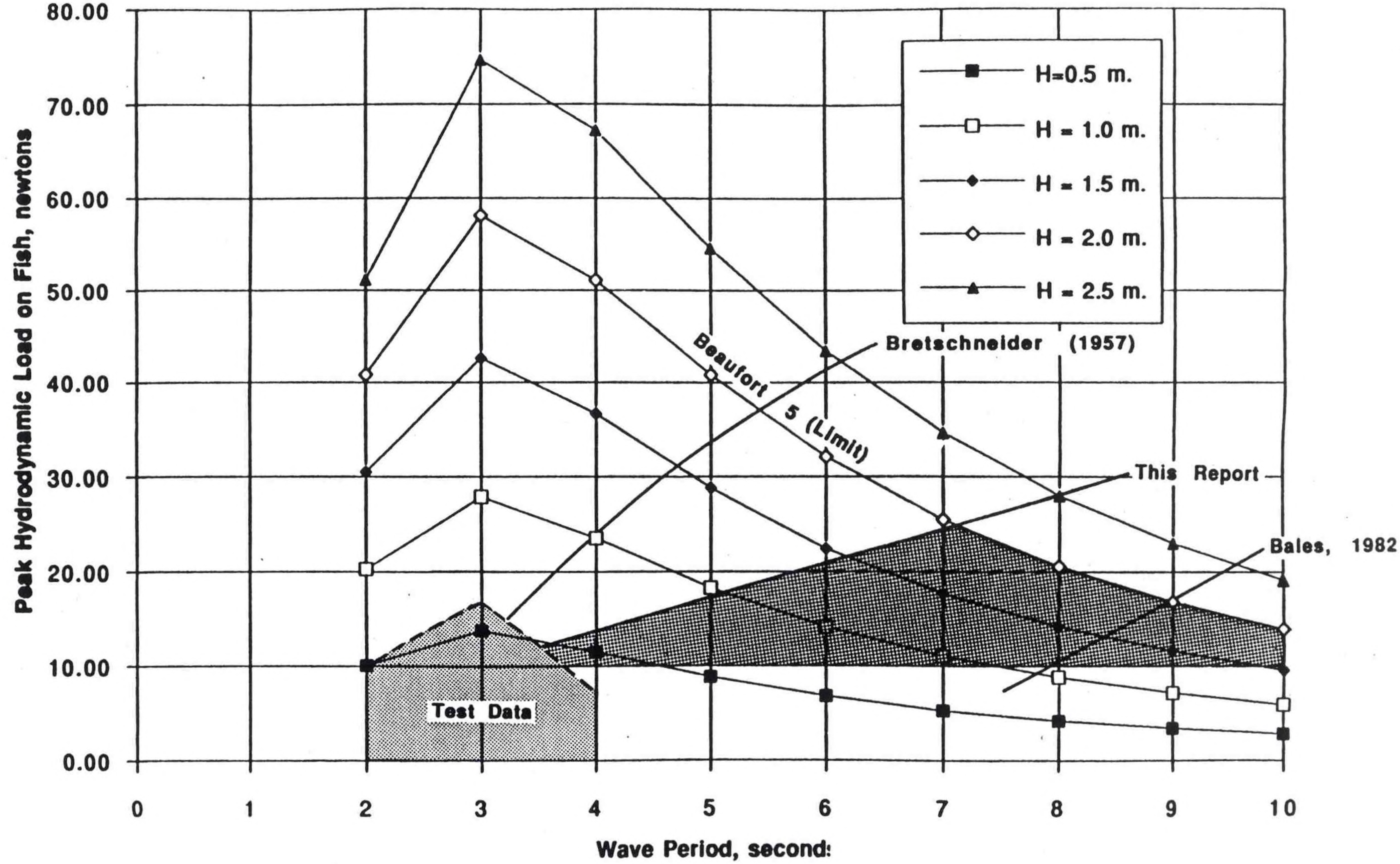


Figure 4-2 Estimated Peak Hydrodynamically Induced Loads on Netted Fish in Various Waves
Showing Test Basin Region and Expected "At Sea" Region
(Diagonally rising lines represent average wave height/period relationships)

5. Estimated Fish Losses.

It is assumed that gill net fishing will take place whenever the waves are less than 2.0 meters high. This corresponds to Beaufort 5 which in turn corresponds to Sea-State 4. It is also assumed based on the test data summarized in this report that for peak hydrodynamic loads of less than 10 newtons there will be minimal fish loss. Hence, a 20% (approximately) loss is estimated for the period of occurrence of waves between this lower limit and 2 meters.

Figure 5-1 from Bales (1983) indicates that a 2.0 meter (Seastate 4) or greater significant wave (corresponding to Beaufort Force 5) occurs about 45% of the time in the North Pacific and a 0.75 meter (seastate 2.5) is exceeded about 90% of the time. The waves will be between 0.75 m. and 2.0 m. for 45% of the time. Hence as a first approximation it is concluded that fishing can take place 55% of the time and the fish loss would be 20% for about 80% of the time that gill net fishing can be performed.

Such an estimate of fish losses from a gill net in the open ocean appears to be consistent with observations by Bartoo, Holts and Brown (1991) and Bartoo, Holts and Halko (1992). These observations were taken by observing apparent net induced scars on tuna caught by trolling.

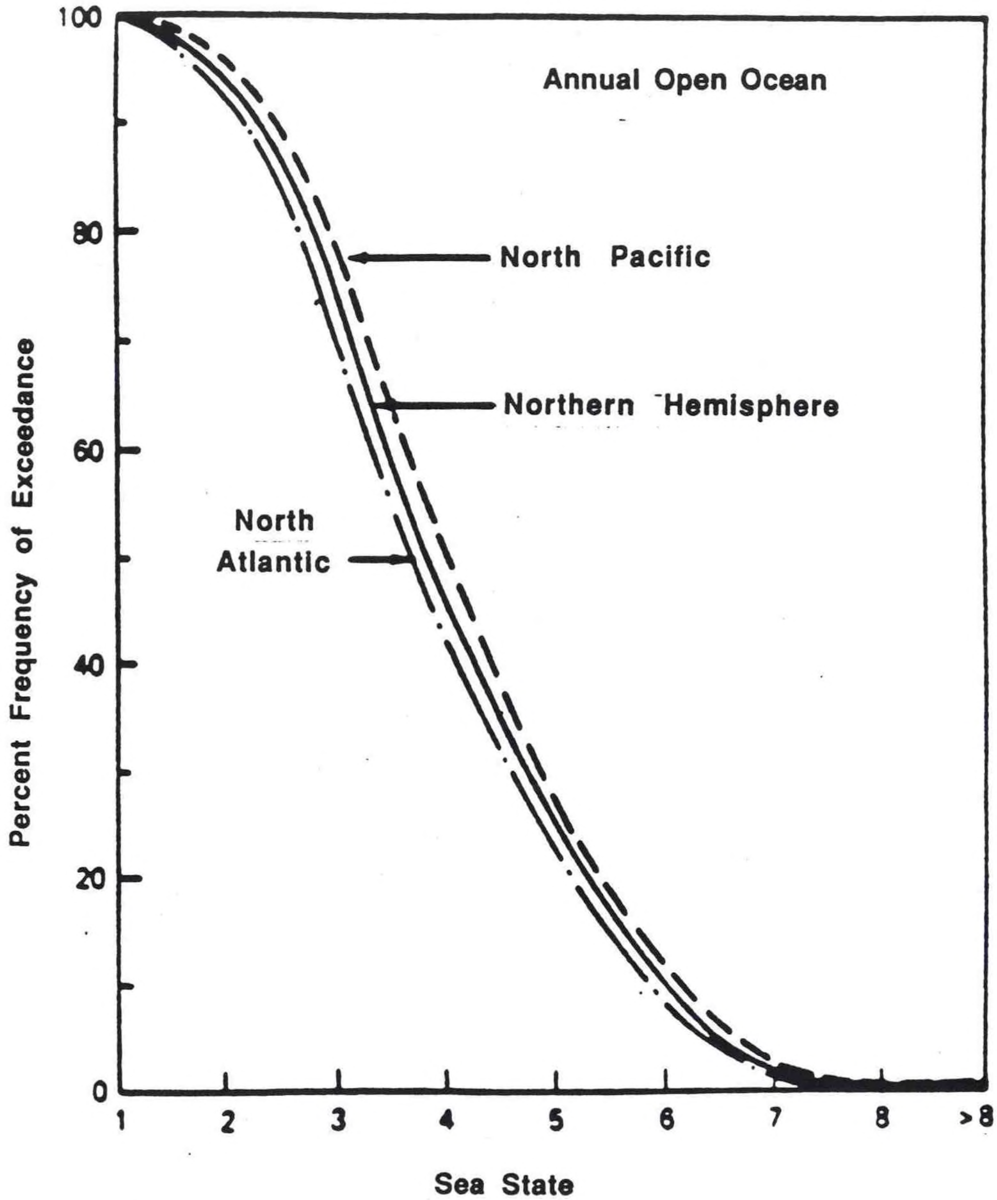


Figure 5-1 Sea State Percent frequencies of Exceedance for North Atlantic, North Pacific and Northern Hemisphere (after Bales, 1983)

6. Summary Discussion and Recommendations

The preceding sections have presented a proposed method for the extrapolation of the observed tank test data to a range of open ocean conditions. The total magnitude of forces induced in an open ocean environment were shown to be similar to those present in the test basin if the relative motions of the net to the water particles are similar. Verification of this similarity should be confirmed by field measurements of net motions and waves.

The hydrodynamically induced loads on trapped fish in the laboratory tank data have been shown to be dominated by forces induced by acceleration (inertia forces). This is less true for prototype waves which would have stronger velocity fields and weaker acceleration fields.

If further investigations of the physical interaction of gill nets on trapped fish are considered, three principal recommendations are offered:

1. Obtain measurements of drift net motions in the open ocean at the same time as waves are being measured
2. Measure the forces required to "break" a trapped fish loose by direct measurement or the performance of "forced oscillation tests" in controlled laboratory conditions.
3. Develop a numerical simulation of drift net motions in waves.

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