# OCEAN SWELL WAVE GROUPS FROM WAVE RECORD ANALYSIS

Raymond C. Smith

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# NAVAL POSTGRADUATE SCHOOL
## Monterey, California

# THESIS

OCEAN SWELL WAVE GROUPS
FROM WAVE RECORD ANALYSIS

by

Raymond C. Smith, Jr.

March 1974

Thesis Advisor: W.C. Thompson

Prepared for:
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# Ocean Swell Wave Groups
# From Wave Record Analysis

by

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Submitted in partial fulfillment of the
requirements for the degree of

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# I. BACKGROUND AND OBJECTIVES

Ocean swell is frequently observed visually and in analog strip charts to occur in groups of quasi-periodic waves. Preliminary work by Thompson (1973) has shown that the average period of the waves in swell groups appearing in twenty-minute records is equivalent to the period of maximum energy density derived from spectrum analysis. Only a few other empirical studies of wave group occurrence or properties appear to have been made; e.g. Ewing (1973). There are also studies related to group phenomena by Putz (1952), and Longuet-Higgins (1952). This investigation is an effort to further illuminate this area.

The first objective of this study is to establish a set of criteria that define a wave group. The second objective is to define measures of height, period, and other properties of wave groups. The third objective is to compare wave group properties with the spectral properties of swell. The fourth objective is to examine time changes in the wave group properties of a swell train observed to arrive at a fixed location, and to determine if different swell trains exhibit similar group properties or characteristics. The final objective is to examine interrelationships between wave group measures.

The term swell train as used here refers to a continuous series of waves that is produced by a single weather event such as a cyclonic storm. Five such swell trains generated in the North Pacific Ocean were analyzed from wave records made at Monterey, California.

## II. SELECTION AND ANALYSIS OF WAVE RECORDS

The records used in this study were obtained from the Naval Postgraduate School wave sensor located 700 feet offshore in a mean depth of 25 feet in southern Monterey Bay (Figure 1). The site is sufficiently sheltered that it receives principally low swell. The data were recorded on a strip chart in analog form. The recorder was programmed to give a fast trace (two inches per minute) of approximately 20 minutes duration every six hours, and a slow trace (three inches per hour) the remainder of the time.

The records of five swell trains, each generated by a distinct synoptic weather event, were examined. Identification of the cyclonic storm producing each swell train and the characteristics of the storms, including wind speed, storm speed, and storm track, have been determined by Austin (1972). These records were selected because they contained essentially pure swell trains in the sense that few other waves were present except low background wind noise. These North Pacific storms and swell trains, all occurring in 1971, are indicated as follows:

| Storm/Swell Train Number | Storm Occurrence | Swell Arrival at Monterey |
|---|---|---|
| 1 | 22-29 Nov | 28 Nov - 1 Dec |
| 2 | 19-24 Nov | 25-26 Nov |
| 3 | 31 Oct - 5 Nov | 8-9 Nov |
| 4 | 25-26 Oct | 31 Oct - 2 Nov |
| 5 | 11-14 Dec | 16-18 Dec |

The analysis for wave group measures was a manual procedure using the 20 minute fast traces only. The same 20 minute records were spectrally analyzed by Austin (unpublished). The spectral data were used herein to provide a comparison with the wave group properties.

## III. DEFINITION OF WAVE GROUPS

Before wave group measures can be made, it is necessary to define what is meant by a wave group. After some effort directed to defining, testing, and redefining, a definition emerged that is best described by the sequence of steps detailed below. The definition provides for the variability of both period and height that is ordinarily observed among the individual waves forming a wave group. Simply stated, a wave group is defined in this study as a sequence of three or more successive crests having approximately the same period, the group terminating at either end whenever a 180° phase change occurs, or whenever waves less than one-third the significant height are encountered.

The first step in isolating a wave group is to scan the wave record visually and identify every series of successive crests that displays some uniformity of period. The use of ten-point dividers was found to be of help in this procedure. Three or more successive crests (two waves) are considered as a possible group. Two successive crests, encompassing one wave, are not considered to constitute a group. This first step is partially subjective, and to those unacquainted with wave records, might appear difficult. With a little practice, however, the analyst improves rapidly, and can isolate all wave groups in a 20-minute fast trace in less than 10 minutes.

The second step is to mark the center of mass of each crest near the estimated mean water line (Figure 2). The sea level disturbance between adjacent centers of mass was considered to define a wave. Waves have also been defined by successive upcrossings or downcrossings of the wave record zero line, or by successive crest-to-crest, or trough-to-trough locations. These definitions were not used in this study. When the wave shape is irregular, which is frequently the case, both up and downcrossings and crest-to-crest or trough-to-trough measurements are generally more irregular. In addition, long waves are sometimes present which cause the mean water line to deviate from the zero line on the wave record. These kinds of difficulties may be seen in Figure 3.

The third and most important step in the identification process is the location of the wave group's beginning and end. To delineate these two points, the investigator first determines the crest-to-crest period near the middle of the wave sequence. Then, working away from the middle, the investigator proceeds until he encounters a discontinuity in the wave period, representing a phase change on the order of 180°. These phase changes tentatively mark the boundaries of the wave group (Figure 2). This step is dependent upon the estimate of the initial crest-to-crest period, but is sufficiently accurate in view of the subjectivity involved. This procedure essentially limits the wave sequence to periods of approximately the same value.

The final step is application of a wave height limitation which may further reduce the number of waves in a group. It was arbitrarily decided to limit the waves in a group to those having heights equal to or greater than one-third the significant height of the 20-minute record. The waves of smaller height which are excluded contain ten percent or less of the energy inherent in waves of significant height. This height limitation was used infrequently, as it was found that the phase change limitation was a stricter criterion by which to limit the size of the wave group.

Many wave groups are not as uniform as the group illustrated in Figure 3a. Some irregular wave groups are due to the presence of more than one wave train. For example, Figure 3b depicts a wave group that is considerably more irregular in wave form than that in 3a. In this wave record a short period, low amplitude wave is superimposed upon the larger waves that are under consideration as a wave group. The basic wave form pattern exhibited by the longer waves still qualify it as a wave group. Wave groups from as many as 3 wave trains can sometimes be isolated. In this study, attention was restricted to only those wave groups associated with the wave train of maximum energy.

Long waves of period 30 seconds or greater are frequently encountered on wave records (Figure 3c). These waves were not measured in this study, but are considered when the centers of mass of the individual waves are being determined. It is of interest to note that wave group periods and other measures to be described later are independent of the presence of long waves; whereas, wave measurements obtained from conventional wave analysis which is dependent upon use of the zero line of the record, such as the zero-upcrossing period and the significant height, are altered by the presence of long waves.

## IV. WAVE GROUP MEASURES

A number of wave group measures were developed, tested, and modified. These include measures of the period, height, and regularity of form of the individual waves forming a wave group. Those which appeared to give useful information are introduced and defined in Section A below. Measures of the interrelationships between wave groups in a swell train were also considered and are presented in Section B.

The definition of a wave group described in the previous section automatically identifies the individual waves contained in the group and permits direct period measurement. Identification of the individual waves in turn, provides the basis for measurement of the individual wave heights.

### A. INDIVIDUAL GROUP CHARACTERISTICS

#### 1. Measures of Group Size

##### a. Wave Group Duration, D

Wave Group Duration is the time from the beginning to the end of a wave group. In Figure 4, the duration of a typical wave group is illustrated.

##### b. Number of Waves per Group, n

This characteristic is measured by summing the number of waves contained in a wave group of duration D (Figure 4).

2. Wave Period Measures

a. Individual Period, T

The period of an individual wave is defined as the time interval between centers of mass to the nearest second (Figure 4).

b. Wave Group Period, $T_g$

The average period of the wave group, termed the wave group period, is obtained by dividing the duration of the wave group by the number of waves in the group. The average wave group period of a 20-minute fast trace, $\overline{T}_g$, is obtained by averaging the values of $T_g$ in the trace.

c. Period Variability, $\frac{\Delta T}{T_g}$

The periods of the successive waves in a group are not constant, and it was felt that some measure of the period variability should be established. A measure such as the range of periods, $\Delta T$, encountered in a wave group was not considered indicative of a wave group's variability. A three second period variation in a group of 20-second waves has different significance than the same variation in a group of ten-second waves. Accordingly, a ratio of the range in periods, $\Delta T$, to the group period, $T_g$, was adopted as a representative measure.

3. Wave Height Measures

a. Individual Height, H

The wave height, H, is defined as the vertical distance from the highest crest elevation to the average elevation of the lowest point of the troughs on either side of the crest (Figure 4).

b. Height of the Largest Wave, $H_{max}$

The height of the largest wave in each group is taken from the wave height measurements for the group (Figure 4).

B. MEASURES OF RELATIONSHIPS BETWEEN WAVE GROUPS

The following measures were designed to show interrelationships between wave groups and how their frequency of occurrence changes over the life of a swell train.

1. Wave Group Periodicity, $T_G$

Wave group periodicity is the time interval between the occurrence of $H_{max}$ in two successive wave groups. The mean of $T_G$ over a twenty-minute trace is $\overline{T}_G$, and the mean of $\overline{T}_G$ over an entire swell train is $\overline{\overline{T}}_G$.

2. Percentage of Time that Wave Groups are Present, $t_{\%}$

This quantity is computed by summing the durations of all the wave groups occurring in one fast trace, and dividing this sum by the total amount of time in the fast trace. This figure is multiplied by 100 to give a percentage.

3. Time Interval Between Wave Groups, $t_G$

This quantity is the time interval between the end of one wave group and the beginning of the next.

4. Height of the Largest Wave in a Group per Fast Trace, $H_{max(max)}$

This measurement is obtained by locating the highest wave present in any wave group in a given 20-minute fast trace.

## V. PRESENTATION AND INTERPRETATION OF WAVE GROUP CHARACTERISTICS

In order to have a basis for comparing wave group characteristics with conventionally used properties of ocean waves, the spectral characteristics and significant heights of the five swell trains will be introduced first. Following this, the wave group data derived from the five trains are presented. Swell Train 2 has been chosen to illustrate the distribution of each wave group measure throughout this section.

### A. SPECTRAL AND STATISTICAL CHARACTERISTICS

#### 1. Period of Maximum Energy Density, $T_{max}$ (Figure 5)

The curves of $T_{max}$ versus time for the five selected swell trains, shown in Figure 5, were obtained from unpublished spectrum analyses (Austin, 1972). The periods are on the same time scale as the significant wave heights shown in Figure 6 so that the reader may follow the wave height-period history of each swell train from examination of the two graphs. That period, $T_{max}$, associated with the maximum significant height of the swell train is centered on the 36 hour mark and the remaining points are plotted at six-hour intervals.

The swell train labelled (1) is shown in two parts and is effectively two trains generated by the same storm; it is treated as one train in this study. The generating storm, after producing the earlier swell train, weakened and appeared ready to die out when the low shifted its position, intensified, and produced the later swell train. The period-time curve for Swell Train 4 is atypical because the usual period decrease with time does not occur. Its flatness presumably indicates a more distant source, and this is confirmed by Austin (1972).

2. Significant Height, $H_s$ (Figure 6)

The curves of significant height for the five swell trains are shown in Figure 6. The peak data point in each train is centered on the 36 hour mark. Wave recorder units are used, the conversion being ten units equal to one foot. The heights are not corrected for hydrodynamic damping. The wave periods involved, nearly all longer than 10 seconds, and the depth of water in which the recorder is located limit damping to less than 10%.

Additionally, shoaling and refraction processes (and always bottom recording) tend to make the waves more swell-like, i.e., their bandwidth is narrowed by these processes.

Swell Trains 4 and 5 are very low, and contain energy not much greater than the wave background out of which the trains grow and disappear again. This may have affected some wave group measures as is discussed later. The background noise level varied between 5 and 10 wave recorder units (0.5 to 1.0 feet) during all five swell trains.

## B. WAVE GROUP CHARACTERISTICS

### 1. Time Series Presentation

a. Wave Group Period, $T_g$ (Figures 7 and 8)

The decrease of wave group period with time is shown for Swell Train 2 in Figure 7. The dots represent individual wave group periods, while the circled values represent the average group period, $\overline{T}_g$, derived from each fast trace. The number of period measurements in a 20-minute record, and the range of their values may be noted in the figure.

$\overline{T}_g$ was found to agree closely with the spectral peak period, $T_{max}$, which is also illustrated on Figure 7; accordingly, plots of $\overline{T}_g$ for all five wave trains are not shown. (Figure 5, in effect, illustrates the distribution of $\overline{T}_g$ that was found.)

The relationship between $\overline{T}_g$ and $T_{max}$ is illustrated in Figure 8. The swell trains are not differentiated because of the closeness of the fit. It is evident from the figure that, in general, $T_{max}$ is slightly greater than $\overline{T}_g$. A straight line chosen by eye to fit the data points shows that $T_{max}$ is larger than $\overline{T}_g$ by about 4%. For practical purposes the two can be considered equal.

b. Wave Period Variability, $\frac{\Delta T}{T_g}$ (Figures 9 and 10)

Variability of the period measurements over the life of a swell train is illustrated for Swell Train 2 in Figure 9. The dots show wave period variability for each wave group, and the circles represent the average for each fast trace. The scatter of the values is seen to be large.

The average variability of wave group period for all five swell trains is shown in Figure 10. There appears to be no general trend in period variability from the beginning to the end of a wave train. The average values for a 20-minute record range from 0.10 to 0.26. The average wave period variability of the individual swell trains ranges from 0.14 to 0.19, and has a value of 0.16 for all trains. The latter value indicates that a wave group with a 20-second group period, contains, on the average, individual wave periods in the range of 18.4 to 21.6 seconds.

The reason for the absence of a general trend is that although larger $\Delta T$ values occur at the initial arrival of swell, the denominator, $T_g$, is also larger. As shorter period swell arrive, $\Delta T$ decreases, thus giving a fairly constant numerical value throughout the duration of swell arrival.

c. Maximum Wave Group Height, $H_{max}$ (Figures 11, 12 and 13)

In Figure 11 a plot of $H_{max}$ versus time for Swell Train 2 is illustrated. The circled values represent $\overline{H}_{max}$, the average $H_{max}$ for a given 20-minute record. A plot of the significant height, $H_s$, for each fast trace is also shown. From the figure it is observed that throughout the course of the swell train, $\overline{H}_{max}$ closely parallels $H_s$ but is smaller.

The observation that $\overline{H}_{max}$ is smaller than $H_s$ might appear contradictory. However, wave groups, which by definition can contain waves as small as one-third the significant height, may have an $H_{max}$ value not much larger. Further, an observer on the beach would probably consider as wave groups only those higher series of waves which arrive and are easily discernible to the naked eye; however, when isolating wave groups on a wave record, smaller, orderly waves can meet the requirements for wave groups as defined here as easily as larger waves.

In Figure 11, data points are shown which illustrate that quite small amplitude sequences may meet the wave group criteria. Some of these wave groups contain $H_{max}$ values that are too small to be included in the computation of $H_s$. Further, the computation of $H_s$ involves the averaging of the 1/3 highest waves in a given record, regardless of their position with respect to wave groups. All isolated waves included in the 1/3 highest waves in a given record are thus excluded from consideration in computation of $\overline{H}_{max}$. This increases the magnitude of $H_s$ with respect to $\overline{H}_{max}$.

Figure 12 illustrates the relationship between $\overline{H}_{max}$ and $H_s$ for all five swell trains. The wave trains are not differentiated because of the closeness of the fit. The figure shows that a very close relationship exists between the two measures and that $H_s$ is slightly larger than $\overline{H}_{max}$ by about 8%. For practical purposes the two can be considered equal. It may be concluded from this that the significant height of a swell train from a distant source can be computed to a generally acceptable degree of accuracy by averaging the $H_{max}$ values for all wave groups in a given fast trace.

Figure 13 illustrates the single highest wave encountered in a wave group in a 20-minute fast trace, $H_{max(max)}$, plotted against the significant height of the trace. A straight-line fit for all five swell trains was made. The figure shows that on the average $H_{max(max)}$ is 40% greater than the significant height, $H_s$.

Statistical analysis by Longuet-Higgins (1952) permits prediction of the most probable maximum wave height in a given number of waves. The average number of waves in a 20-minute trace was 82 in the present study. Application of the Longuet-Higgins relationship yields a probable maximum wave 48% higher than the significant height. In this investigation, the highest wave in a fast trace appearing in the wave groups was found to be 40% greater than the significant height. The difference between the two percentages may be attributed to the fact that in the identification of wave groups, isolated high waves are excluded from consideration.

d. Number of Waves Per Group, n (Figures 14 and 15)

The number of waves in a group ranged from the defined minimum of two to a maximum of eighteen. Although this number generally varied among the wave groups of any given 20-minute trace, it was found that the largest groups occur about the time of peak swell arrival, i.e. the middle period range of the swell train. This is illustrated for Train 2 in Figure 14. The dots represent the number of waves in each individual wave group while the circles represent the average value for each fast trace. The average number of waves per group for all five trains is shown in Figure 15.

The general absence of large wave groups at the beginning and end of a swell train probably can be explained by the fact that during these periods the energy level of the swell train is either rising above or sinking into the energy level of the background wave noise. Thus, when the energy level of the swell approaches that of the background, only the larger waves in a group are evident, the smaller ones being lost in the wave noise. At the time of peak swell arrival, nearly all waves in a group are well above the background noise level.

e. Duration of Wave Group, D (Figures 16 and 17)

Figure 16 shows the duration distribution with time for Swell Train 2. The dots show durations of individual wave groups while the circles represent the average duration for each fast trace. It is observed that the longest duration occurs when the largest number of waves per group occur, or in general during the time of peak swell arrival. At the end of swell arrival, shorter periods coupled with few waves per group give durations of 0.3 to

1.3 minutes. Figure 17 illustrates the time change in average duration for all five swell trains.

The duration of individual wave groups is directly related to the number of waves per group through $T_g = D/n$. Since the time rate of change of $\overline{T}_g$ is small, then the variation of $\overline{D}$ with time (Figure 17) reflects largely the variation of $\overline{n}$ with time (Figure 15).

f. Wave Group Periodicity, $T_G$ (Figures 18 and 19)

The wave group periodicity, $T_G$, is shown for Swell Train 2 in Figure 18. The dots represent individual values of periodicity, while the circles represent average values for each fast trace. Individual values of periodicity ranged from 0.2 to 6.5 minutes per 20-minute fast trace.

$\overline{T}_G$ for all five trains is illustrated in Figure 19. As may be seen in the figure, $\overline{T}_G$ is highly variable but does exhibit a slight decrease with time.

The range of $\overline{T}_G$ per fast trace and the average $\overline{T}_G$ for each swell train are shown in the following table.

| Swell Train | Range of $\overline{T}_G$ Per Fast Trace | Average $\overline{T}_G$ Per Swell Train |
|---|---|---|
| 1 | 1.3 - 2.9 minutes | 1.9 minutes |
| 2 | 1.6 - 3.3 | 2.4 |
| 3 | 1.4 - 1.9 | 1.7 |
| 4 | 1.0 - 1.8 | 1.3 |
| 5 | 1.6 - 2.5 | 1.85 |

An interesting observation that is worthy of mention concerns the saying "Every seventh wave is the highest" that is common on the beaches of the Pacific Coast. The average group periodicity for the five swell trains combined is 1.83 minutes. The average group period that is encountered in the five swell trains is 14.5 seconds. The corresponding average number of waves is 7.6 between the $H_{max}$ of successive wave groups.

g. Time Interval Between Wave Groups, $t_G$ (Figures 20 and 21)

The average time interval between the end of one wave group and the beginning of the next for the five swell trains is shown below:

| Swell Train | Average Time Interval |
|---|---|
| 1 | 52 seconds |
| 2 | 70 |
| 3 | 54 |
| 4 | 49 |
| 5 | 51 |

It is seen that Swell Train 2 had a considerably higher average time interval than the others. For this swell train, shown in Figure 20, the time intervals were greater at the beginning of swell arrival than for any others observed in this study. Reference to the wave record showed that the waves were highly irregular and made wave group identification difficult, thus creating large time intervals between groups. The other four swell trains, illustrated in Figure 21, showed generally the same values of time interval. In Swell Train 1, a very low time interval was observed at the time of peak swell arrival. This is due to the extremely large number of groups present at this time. There appeared to be no trend common to all five swell trains with time.

h. Percent of Time Groups are Present, $t_{\%}$ (Figure 22)

The percent of time that groups were present ranged from 35 to 95% for a 20-minute record, as may be seen in Figure 22. Although quite variable from one record to the next, the percentage appears to be related to the wave height, being somewhat greater near times of peak swell arrival.

2. Interrelationships Between Wave Group Measures

In addition to investigating the variation of wave group properties with time, group period and height measures as a function of duration and number of waves per group were examined. The variability of the data for all of the wave group relationships is large; accordingly, straight-line fits are used. These are visually made fits since the data spread does not allow for strict quantitative interpretation, but only general trends.

a. Wave Group Period, $T_g$ (Figures 23-26)

General conclusions drawn from the comparison of wave group period with duration and number of waves per group are illustrated in Figures 23-26. These conclusions are as follows:

1. Wave group duration increases with increasing wave group period.

2. The number of waves per group increases with increasing period.
3. An upper limit to the duration and number of waves in a wave group, the limit being a function of the wave group period, was found for all five swell trains.

In Figure 23 a plot of the average group duration, $\overline{D}$, for all five swell trains is illustrated. The values shown were obtained as described below in the discussion of Figure 25. Straight-line fits to the average values of each swell train have been made. It is observed that all five swell trains exhibit roughly equal slopes, such that for a one-second change in the average group period a duration change of about 40 seconds occurred. Swell Train 4 lies in a different position on the graph from the other trains because of its shorter periods. In Figure 24, a plot of average group period, $\overline{T}_g$, and the average number of waves per group, $\overline{n}$, is illustrated. As in Figure 23, it is observed that although Swell Train 4 is of shorter period, the slopes of the straight line fits are essentially equal. It may be seen that an increase in the average wave group period of one second is accompanied by the addition of three waves to the wave groups, on the average.

Figure 25 shows a plot of wave group period, $T_g$, versus wave group duration, D , for Swell Train 2. The dots represent the period-duration relationship for each wave group in the swell train. The squares represent the mean period, $\overline{T}_g$, for all $T_g$ within a duration interval of 0.3 minutes. Although the spread of data points is wide, averaging in this manner yields a trend as indicated by the straight-line fit to the mean values. Although wave groups of short duration do occur at the beginning and end of the swell train, as may be seen in Figure 16, Figure 25 shows that most short duration wave groups occur at the low period end of the train. Likewise, small wave groups of two and three waves occur at both the beginning and end of a train, with most occurring at the end (not illustrated for Swell Train 2). The average values and the straight-line fit shown in Figure 25 for Swell Train 2 are replotted in Figure 23 showing all five swell trains.

In examining the wave group period-duration relationship for all five swell trains, it was observed that for a given wave group period, the wave group duration has an upper limit such that no durations longer than the limiting duration were found to occur for that period. This limit for Swell Train 2 is illustrated in Figure 25 by the lower line. The duration limit for all five swell trains is shown in Figure 26. The slopes of the limits are seen to be approximately equal.

b. Wave Group Period Variability, $\frac{\Delta T}{T_g}$ (Figures 27-30)

General conclusions drawn from the comparison of period variability with duration and number of waves per group are illustrated in Figures 27-30. These conclusions are as follows:

1. Wave group period variability increases with increasing wave group duration.
2. Wave group period variability increases with an increasing number of waves per group.

In Figure 27 a plot of the average period variability versus the average duration for all five swell trains is presented. As would logically be expected, as the duration of a wave group increases, the period variability likewise increases. It may be noted that all trains possess approximately the same slopes. It may also be recalled that Train 4 has significantly shorter periods than the other trains. The fact that the period variability-duration relationship for this train is only slightly larger than that for the other trains indicates that this relationship is largely independent of the swell period. Figure 28 shows a plot for Swell Train 2 of the period variability-duration relationship for each wave group. The squares represent average values of $\Delta T/T_g$ computed over duration intervals of 0.3 minutes. Scatter of the data points is seen to be large.

In Figure 29, a plot of the average period variability versus the average number of waves per group for the five swell trains is presented. This plot points out the fact that the variability-number of waves relationship is nearly the same among the five wave trains and that groups possessing more waves are also more variable in period. In Figure 30, a plot of period variability versus the number of waves per group for Swell Train 2 is shown. The number of wave groups having zero variability drop off radically when larger wave groups are examined. Interestingly, although wave groups of up to eighteen waves were encountered in this study, no group of more than six waves exhibited zero period variability.

c. Maximum Wave Height per Group, $H_{max}$ (Figures 31-34)

General conclusions drawn from the comparison of $H_{max}$ with wave group duration and the number of waves per group are:

1. Wave group duration and the number of waves per group increase with increasing $H_{max}$.
2. The rate of increase of duration and number of waves per group with respect to $H_{max}$ increases as the energy of the swell train decreases.

In Figure 31 it is apparent that the wave groups exhibiting greater $H_{max}$ values in a given swell train are also the longer duration wave groups. In this graph, however, each straight-line fit exhibits a different slope, the value of which is related to the energy of the swell train (Figure 6). Swell Train 1 which exhibits a marked energy change over its history, possesses a high slope. Conversely, low energy swell such as Trains 4 and 5 have a low slope. Figure 32 shows a plot of $H_{max}$ versus wave group duration for Swell Train 2. The points represent the $H_{max} - D$ relationship for each wave group. The squares represent average values computed at duration intervals of 0.3 minutes. A straight-line fit is made to these average values. Although it is possible to delineate an upper limit of the duration for a given $H_{max}$ in this graph, the other four swell trains did not adequately reflect this condition; consequently, this was not attempted.

Figure 33 illustrates the relationship between the average number of waves in a group and $\overline{H}_{max}$ for all five swell trains. It is observed that in general the larger groups in a swell train are associated with greater $\overline{H}_{max}$ values. The slopes of the lines, as in Figure 31, are related to the energy of the swell train. Figure 34 shows a plot of $H_{max}$ versus number of waves per group for Swell Train 2. The points represent the $H_{max} - n$ relationship for each wave group and the circles represent average values.

## VI. SUMMARY

In order to measure the properties of wave groups appearing in ocean swell in a systematic way, it was first necessary to define what is meant by a wave group. The definition arrived at in this study is as follows: A wave group is a sequence of three or more successive crests having approximately the same period, the group terminating at either end whenever a 180° phase change occurs, or whenever waves less than one-third the significant height are encountered.

Various measures of an individual group and of the relationship between groups are defined in Section IV. All of these quantities were obtained from manual analysis of 20-minute wave records in analog form using simple procedures. Wave records from five swell trains were analyzed in this study in order to obtain an insight into the variation of wave group properties with time.

All five swell trains analyzed were generated 2000-3000 miles from the wave recorder site. Since the frequency bandwidth of swell decreases with increasing source distance, swell trains from longer distances might be expected to contain longer duration wave groups for the same energy. This might be attributed to the fact that the beat period of the interfering periodic wave trains considered to compose the swell presumably increases as the bandwidth decreases.

In reviewing the findings of this study, no importance is placed on the order in which the various wave group properties are presented; rather, they appear below in the order in which they are discussed in the thesis.

1. The average wave group period, $\overline{T}_g$, was found to be equal, for all practical purposes, to the period of maximum energy density, $T_{max}$, derived from spectrum analysis.

2. The average maximum wave height per group, $\overline{H}_{max}$, was found to closely approximate the significant height of the swell, being about 8% less on the average.

3. The single highest wave in a group in a given fast trace, $H_{max(max)}$, was found to be approximately 40% greater than the significant wave height.

4. No trend with time was apparent in wave group period variability, $\frac{\Delta T}{T_g}$. Average values for a fast trace ranged between 0.10 and 0.26. The average variability for all five swell trains was 0.16, which indicates that a 20-second group period contains, on the average, periods ranging from 18.4 to 21.6 seconds.

5. The number of waves in a group, n, is dependent on the energy difference between the swell train and the background noise. In this study, the number of waves in an individual group ranged from two to eighteen. The largest number generally occurs

about the time of peak swell arrival. At the beginning and end of a train, groups of two to four waves are predominant.

6. The duration of wave groups, D, is dependent on the energy difference between the swell train and the background wave noise. The longest wave groups of about five minutes duration occur, as a result, about the time of peak swell arrival.

7. Wave group periodicity, $T_G$, decreases slightly with time. The average periodicity for the five swell trains was 1.83 minutes with a range of 1.0 to 3.3 minutes.

8. An average of 7.6 waves between the $H_{max}$ of successive wave groups was arrived at by dividing the average periodicity of the five swell trains (1.83 minutes) by the average period (14.5 seconds). This average is consistent with the saying common to the Pacific Coast that every seventh wave is the highest.

9. The average time interval between wave groups, $\bar{t}_G$, showed no consistent trend with time. For the five swell trains the average time interval between wave groups was 55 seconds with a range from 0.10 to 1.85 minutes.

10. Wave groups occur most often during the time of peak swell arrival for a given swell train. Up to 95% of the waves in a given fast trace were found to be

included in wave groups during this time, with the average percentage for all five swell trains being 67%.

11. For a change in group period of one second, the wave group duration changed 40 seconds on the average for the five swell trains.
12. For a change in group period of one second, the number of waves in a group increased by four on the average.
13. An upper limit to the duration of a group can be expected for a given wave group period.
14. The average wave group period variability increases 0.1 with a one minute increase in duration, or with an increase in the number of waves per group of four or five, on the average.
15. An increase in $\overline{H}_{max}$ results in an increase in average duration and number of waves per group, the rates of increase being proportional to the energy in the swell train.

## VII. APPLICATIONS TO AMPHIBIOUS WARFARE

It is felt that the results obtained in this study have a direct practical application to certain naval operations. Conventional amphibious warfare is highly dependent on the nature of surf for its success. At present, wave forecasting for amphibious landings yields estimates of standard statistical wave height parameters such as the significant height, but none of these incorporate a consideration of wave groups. A forecaster who could give an assault boat coxswain an estimate of the number of high waves that should be expected in a group and the time interval that might be expected between wave groups would aid an operation significantly. Unconventional warfare groups such as U.S. Navy SEALS and U.S. Army Special Forces are often tasked with missions which require night surf passage on rocky coastlands. It has been the author's experience that when transitting the surf in rubber rafts, an estimate of wave group characteristics as well as wave height and period would have been very useful. In the especially difficult operation of extracting through the surf, knowledge of the time interval between the wave groups is of particular importance.

This study, using basically simple manual methods, gives an insight into a previously unresearched area of ocean wave properties. Ultimately, an objective method of identifying wave groups and measuring their properties using computers would be hoped for.  With the knowledge that could be gained from analysis of a great number of swell trains, it is possible that far more definitive results might ensue.

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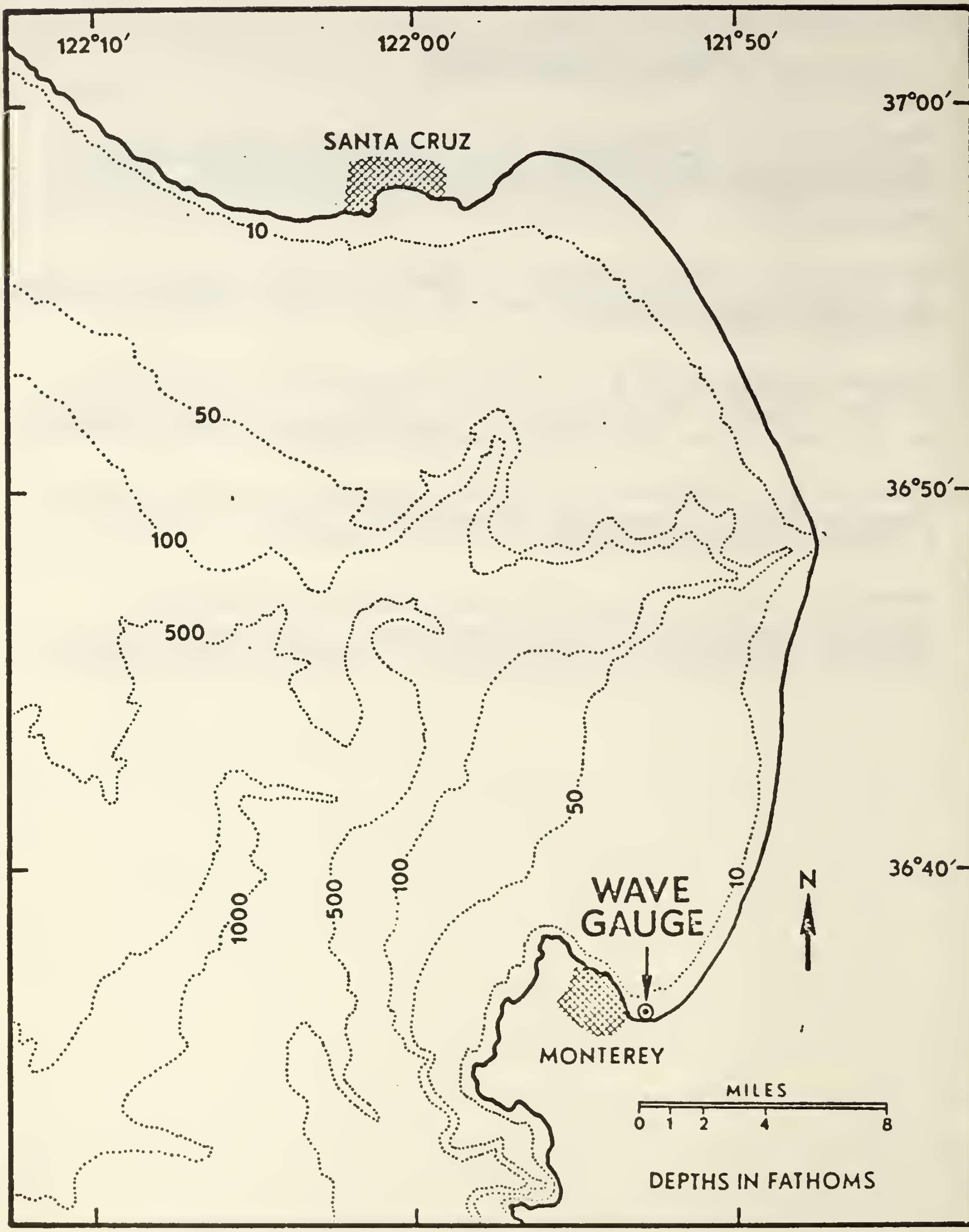


Figure 1: WAVE-GAUGE LOCATION IN MONTEREY BAY

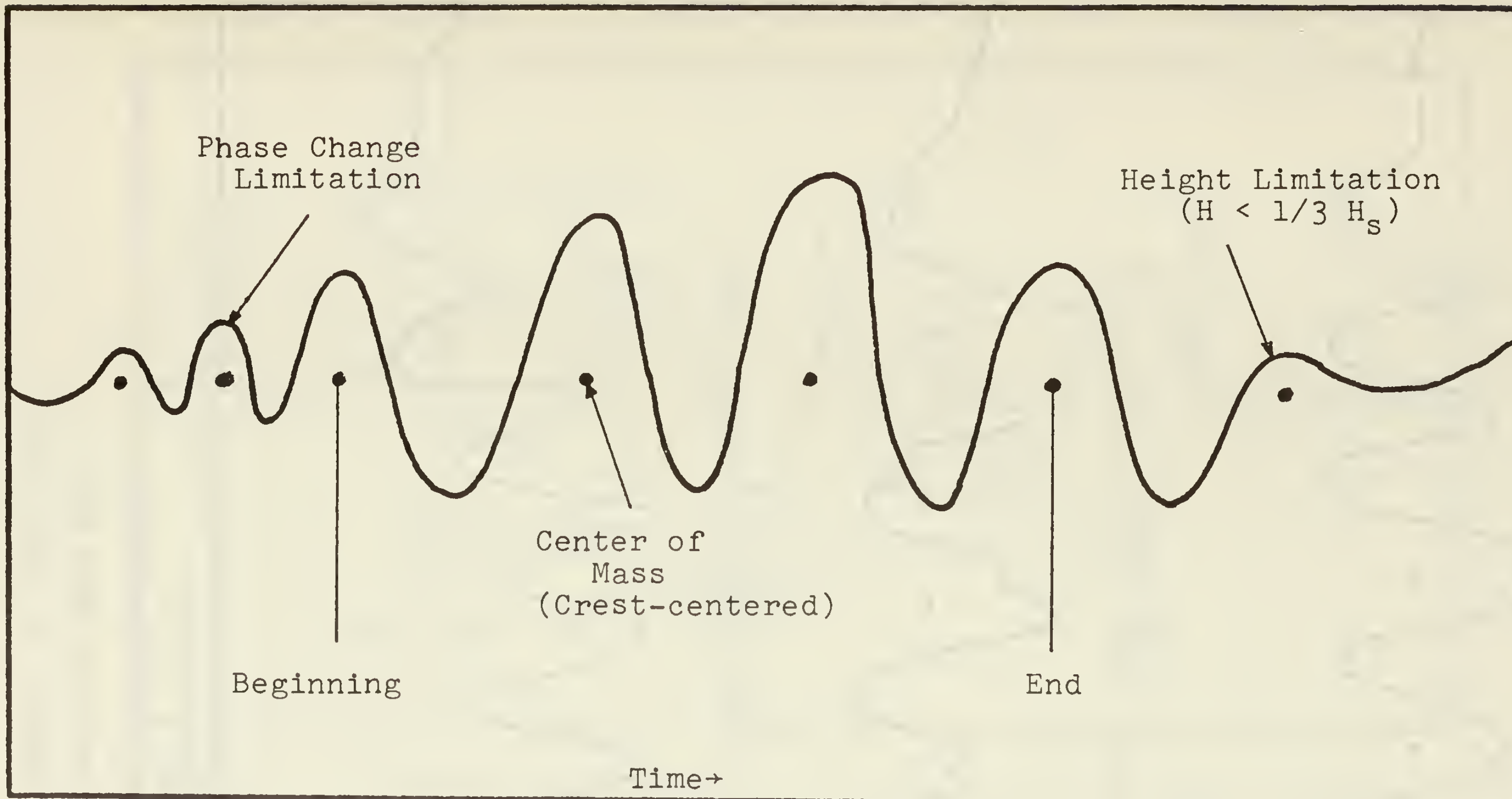


Figure 2: DEFINITION OF A WAVE GROUP

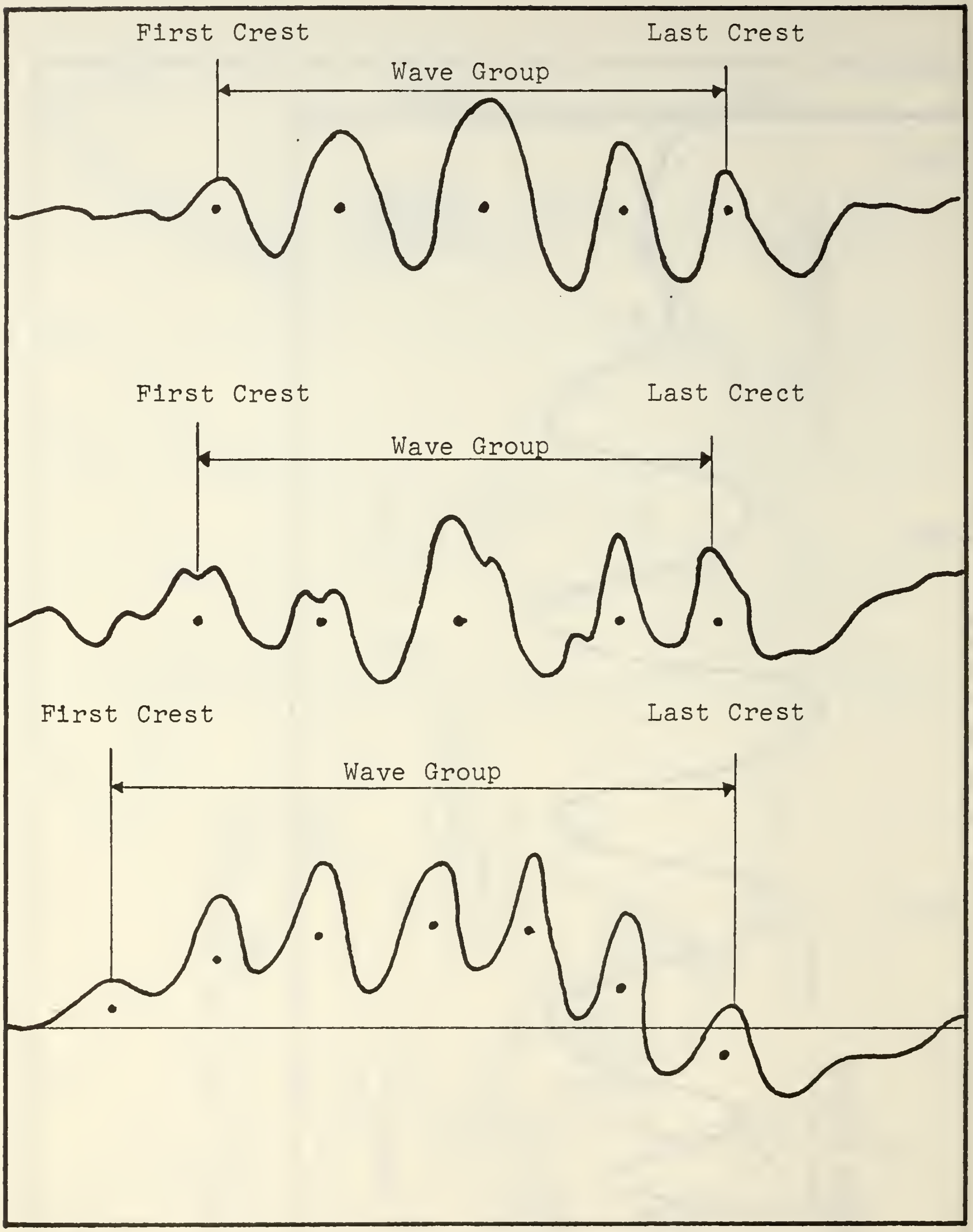


Figure 3: WAVE GROUP TYPES

a. Regular Wave Form

b. Irregular Wave Form

c. Presence of Long Wave

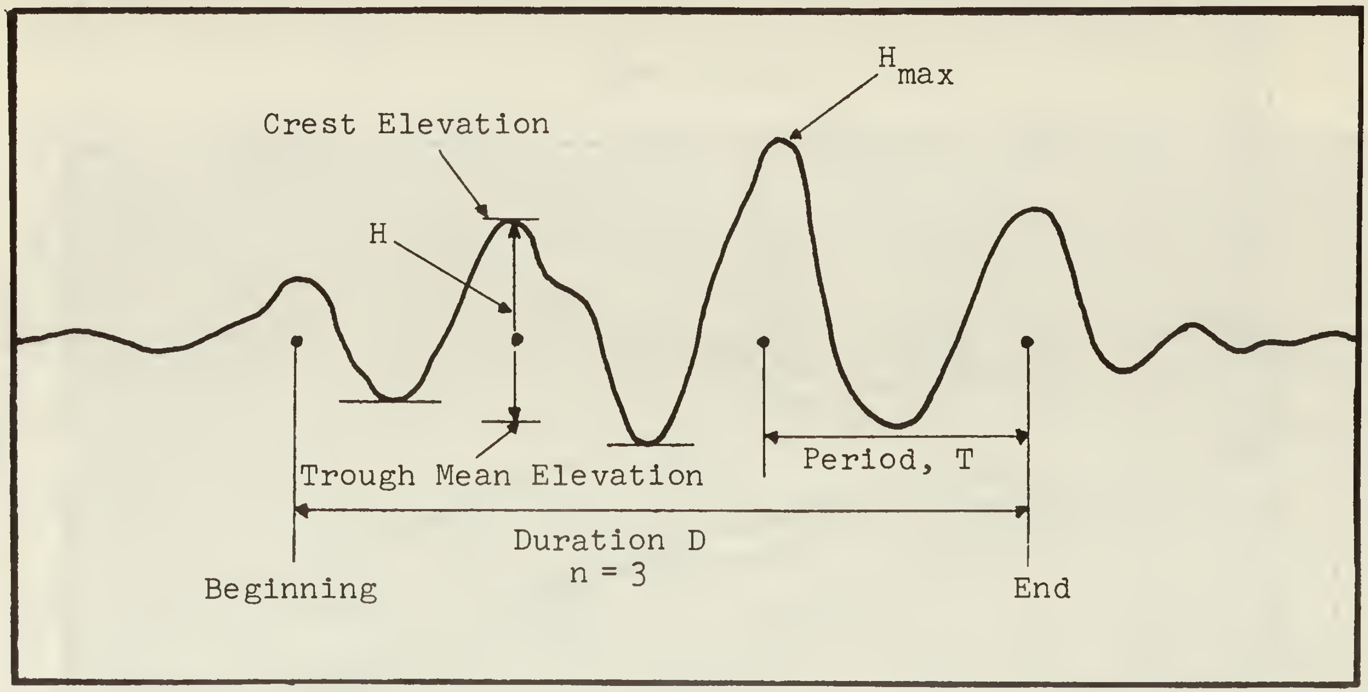


Figure 4: WAVE GROUP MEASURES

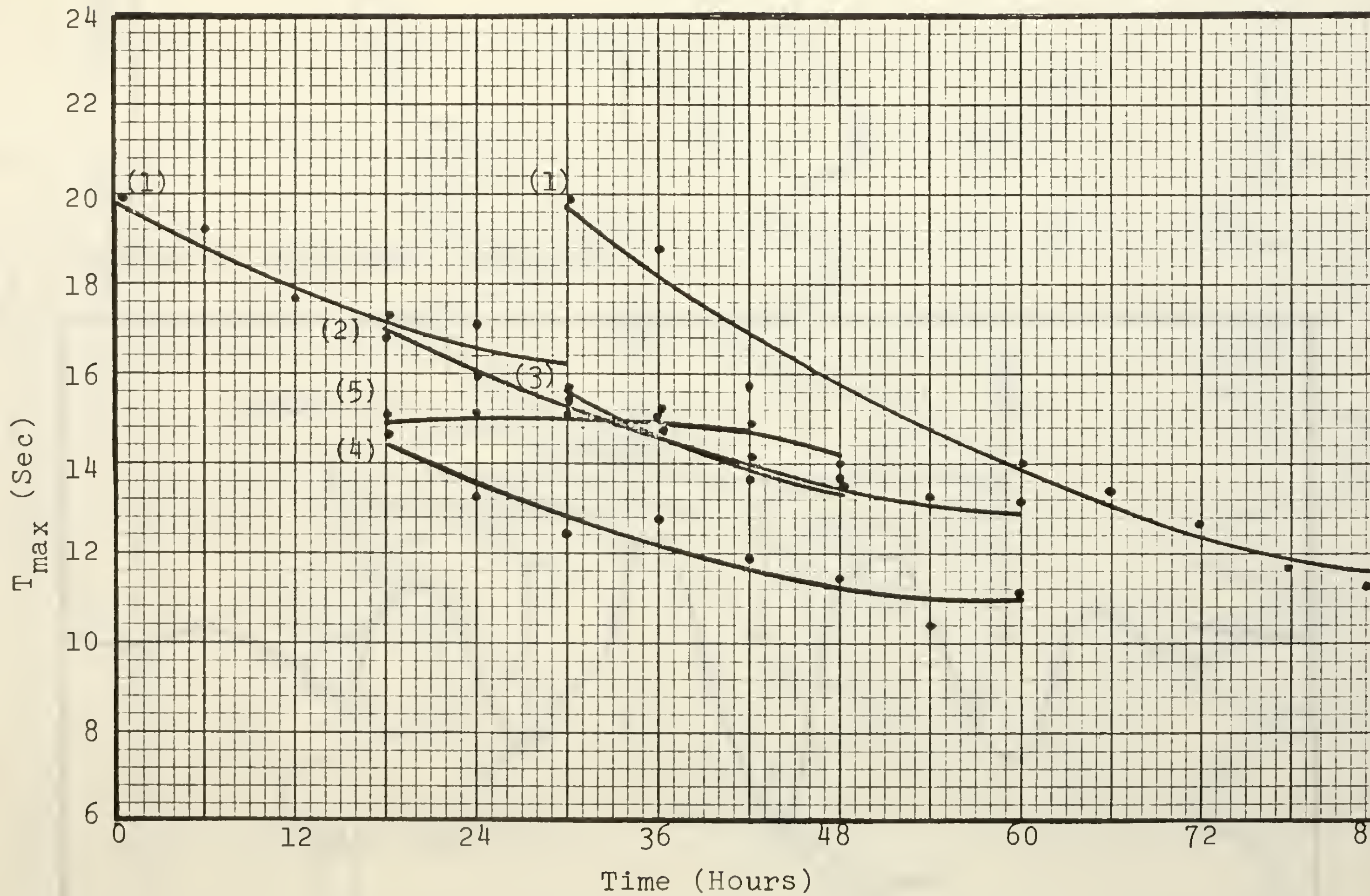


Figure 5: PERIOD OF MAXIMUM ENERGY DENSITY FOR SWELL TRAINS 1 THROUGH 5

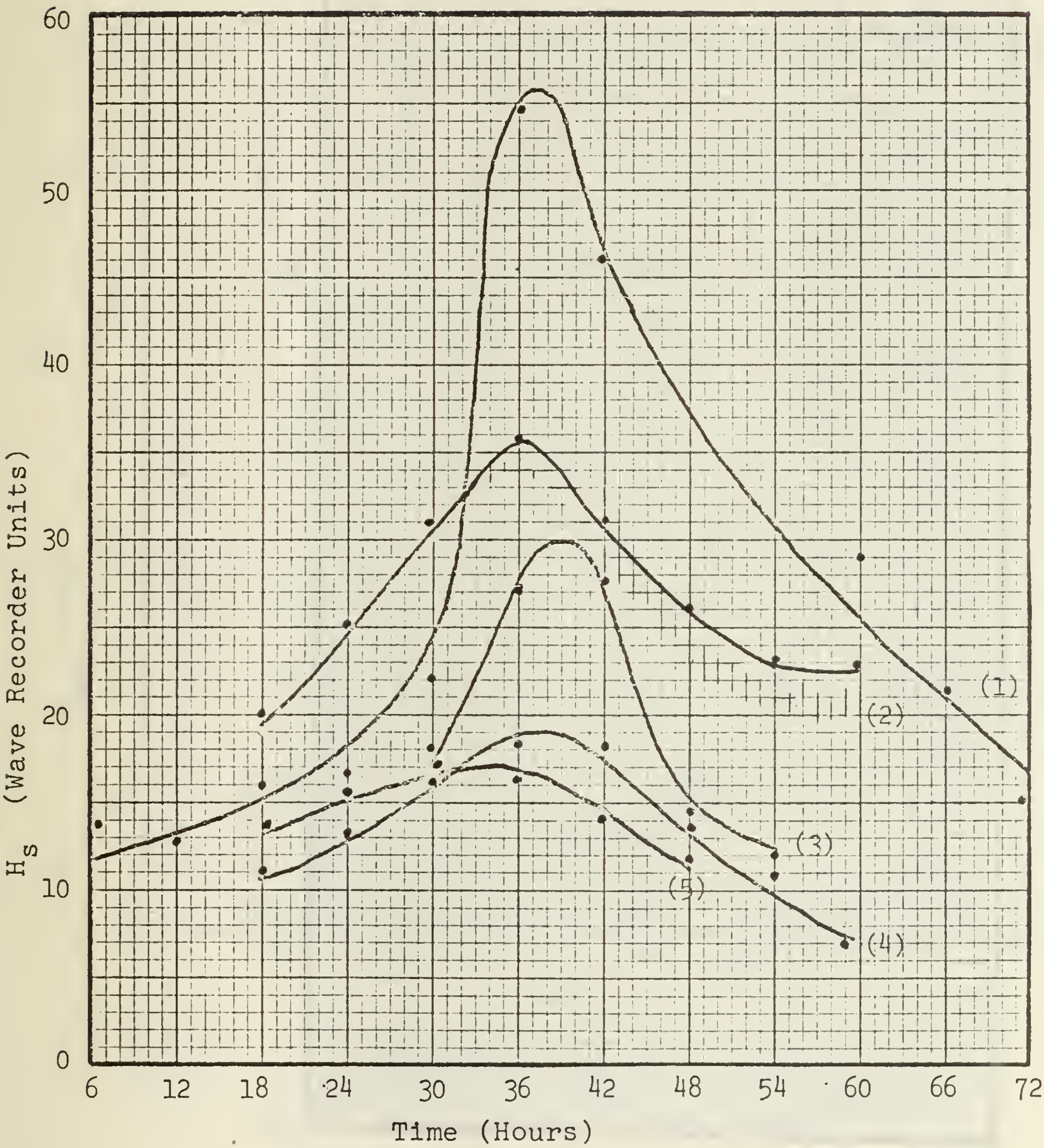


Figure 6: SIGNIFICANT HEIGHT FOR SWELL TRAINS 1-5
(10 wave recorder units = 1 foot)

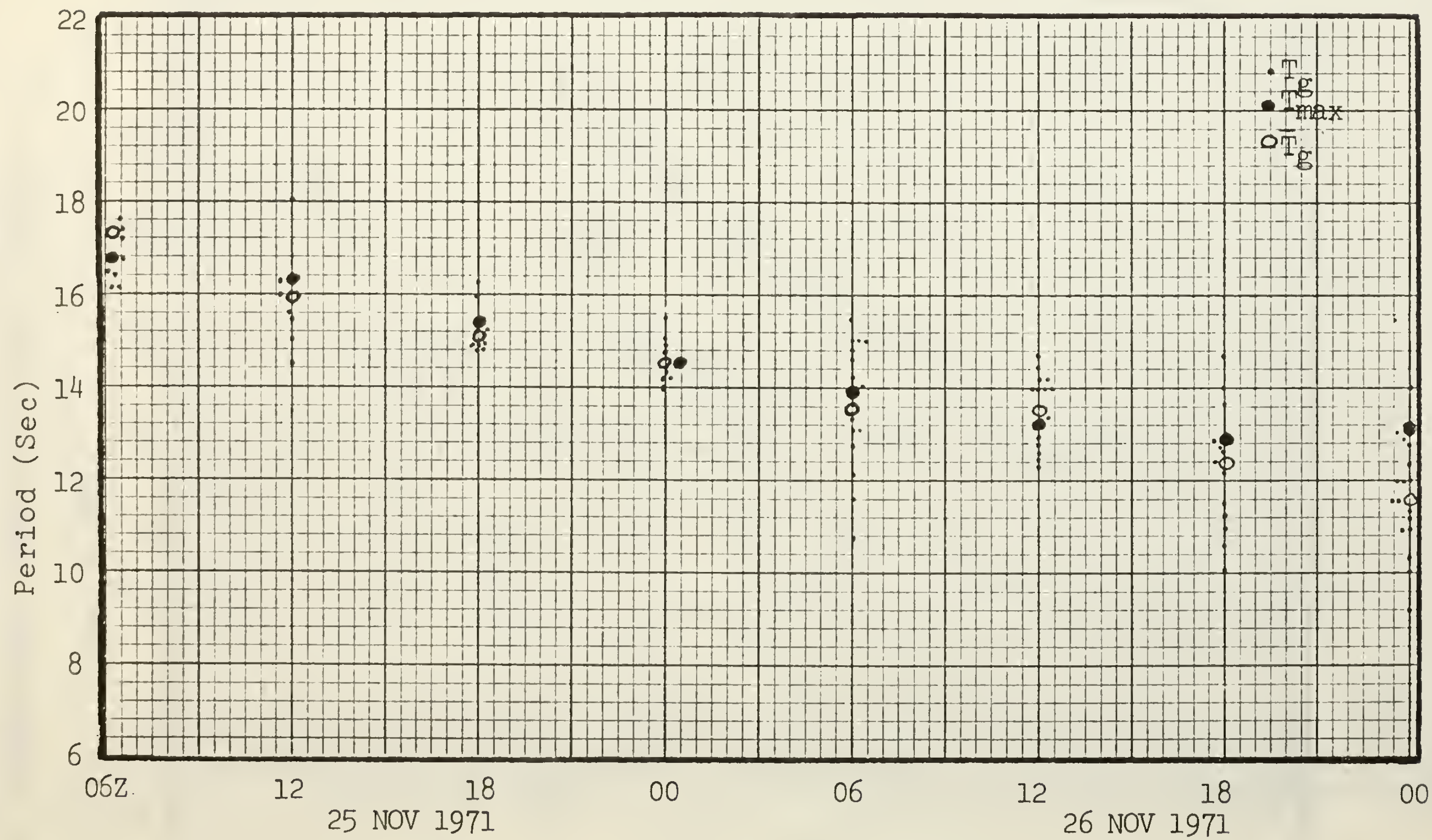


Figure 7: WAVE PERIOD FOR SWELL TRAIN 2

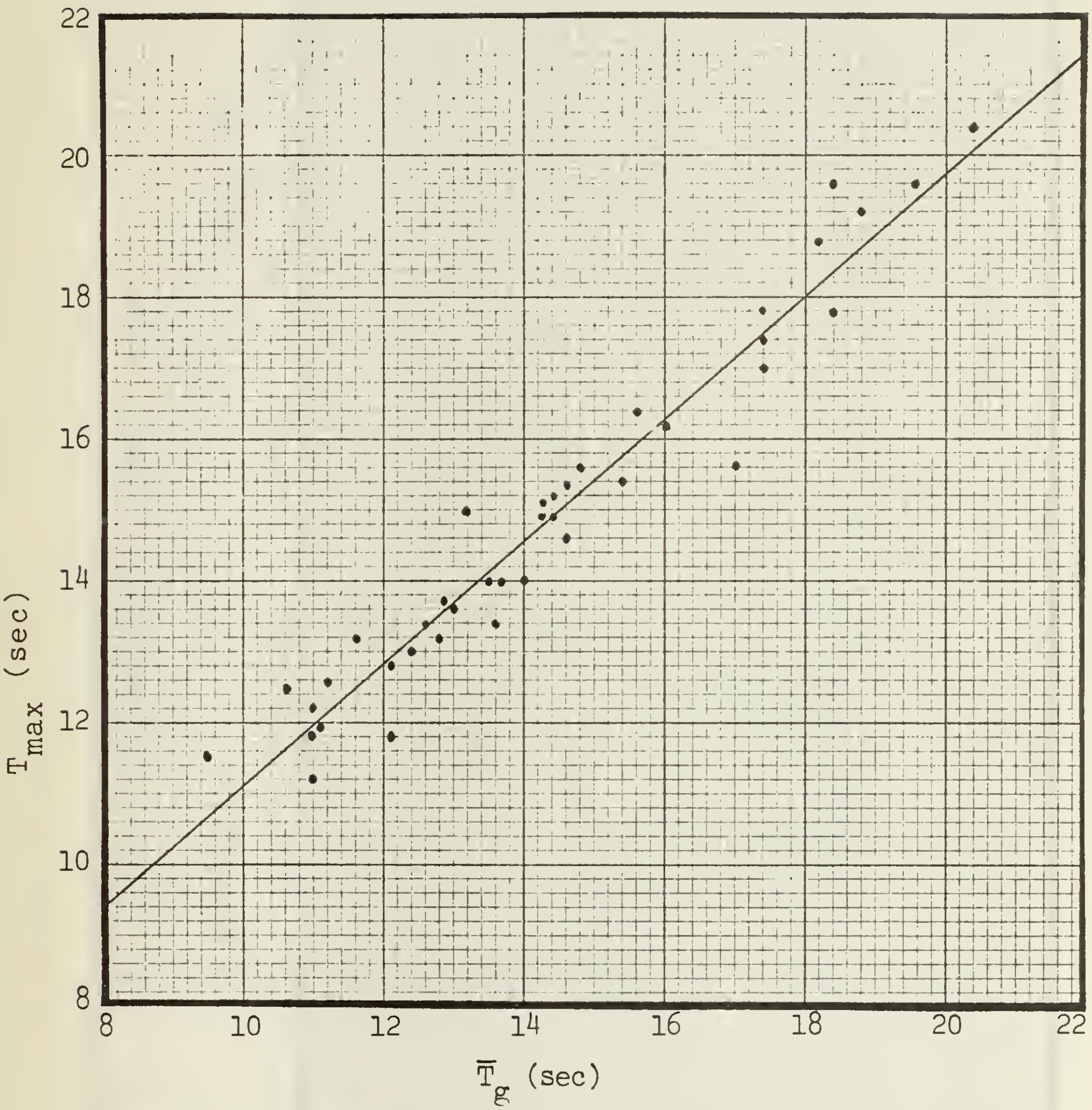


Figure 8: COMPARISON OF AVERAGE WAVE GROUP PERIOD AND PERIOD OF MAXIMUM ENERGY DENSITY FOR SWELL TRAINS 1 THROUGH 5

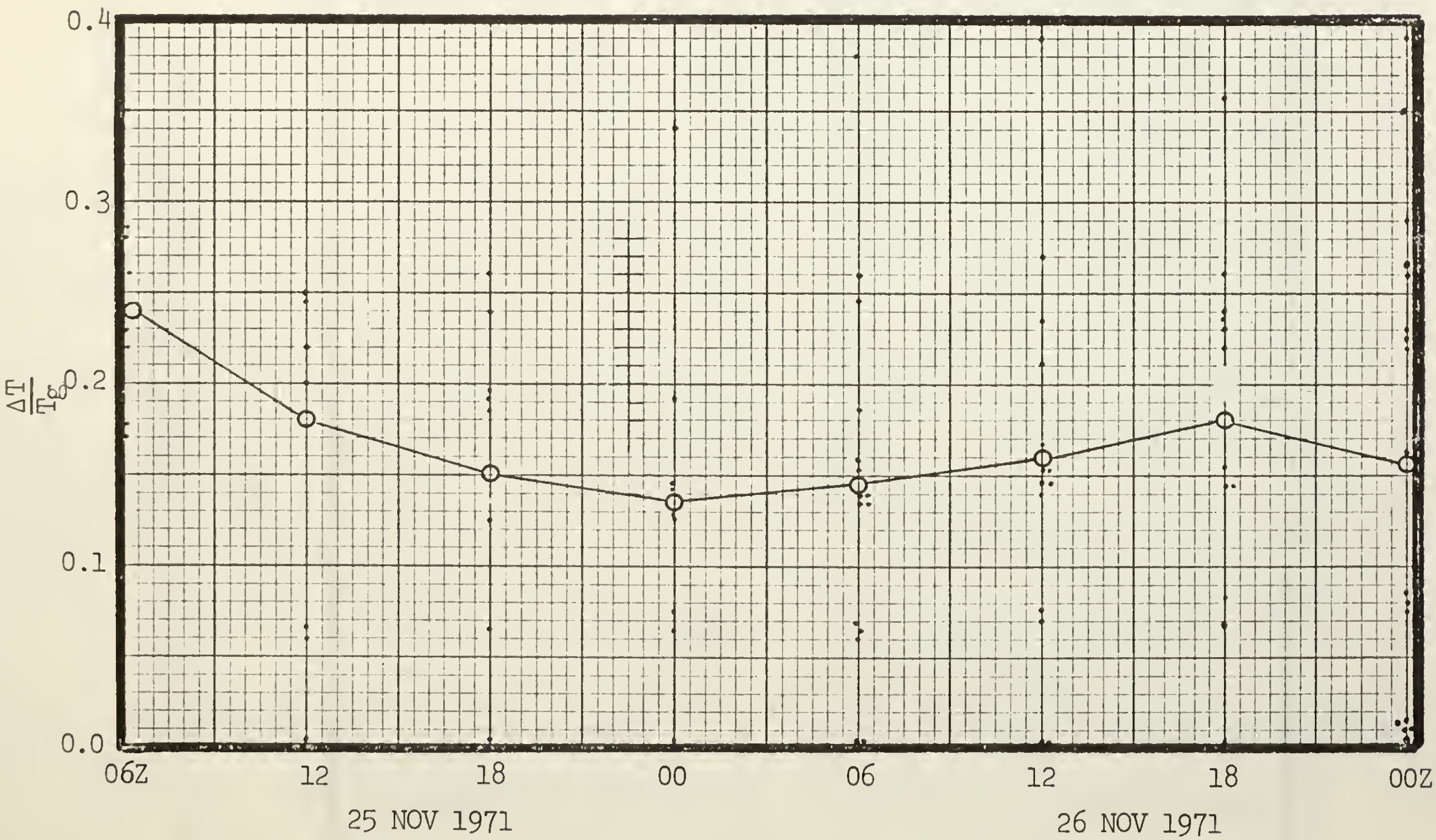


Figure 9: WAVE PERIOD VARIABILITY FOR SWELL TRAIN 2

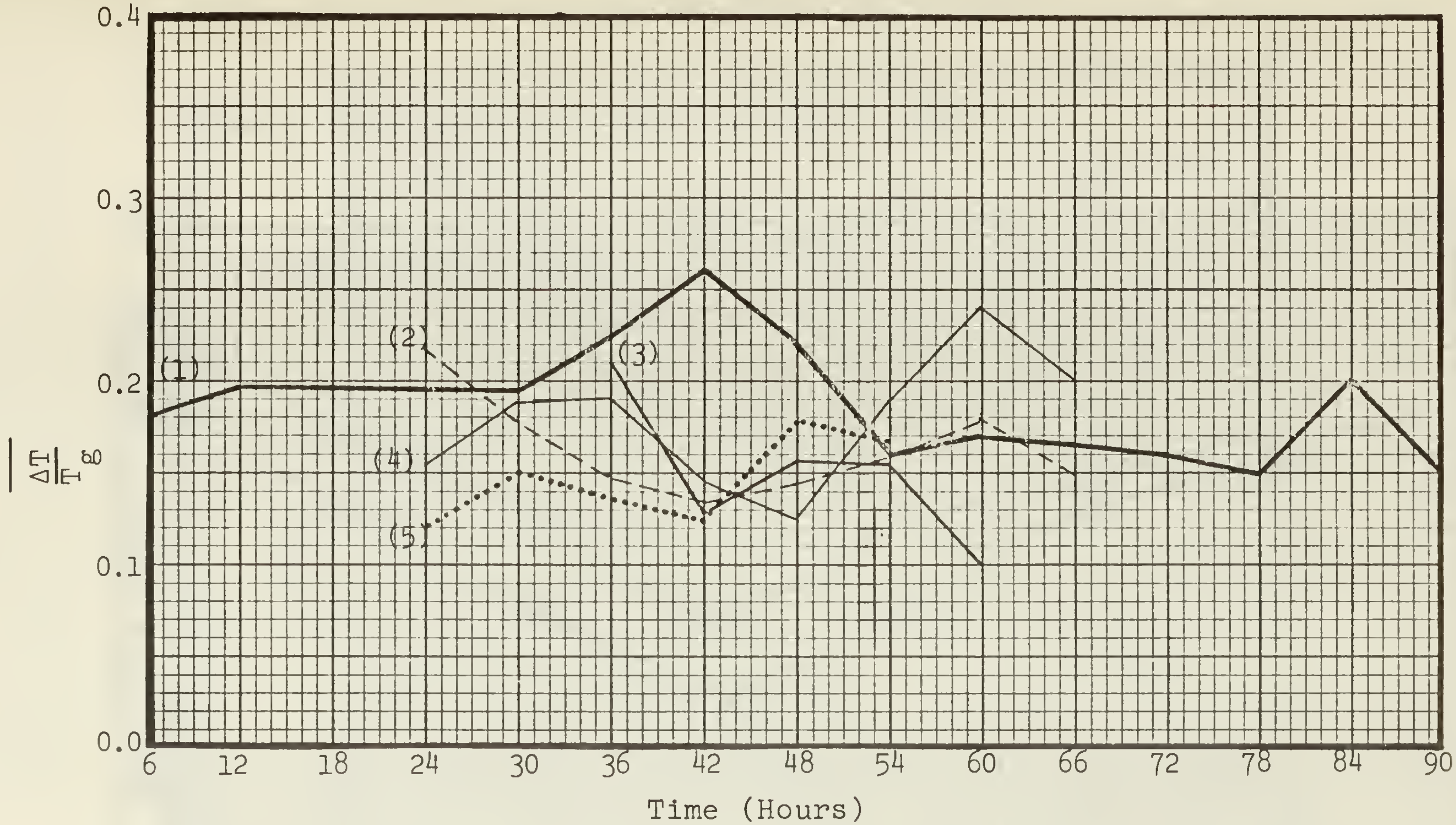


Figure 10: AVERAGE WAVE PERIOD VARIABILITY FOR SWELL TRAINS 1 THROUGH 5


Figure 11: WAVE HEIGHT DATA FOR SWELL TRAIN 2

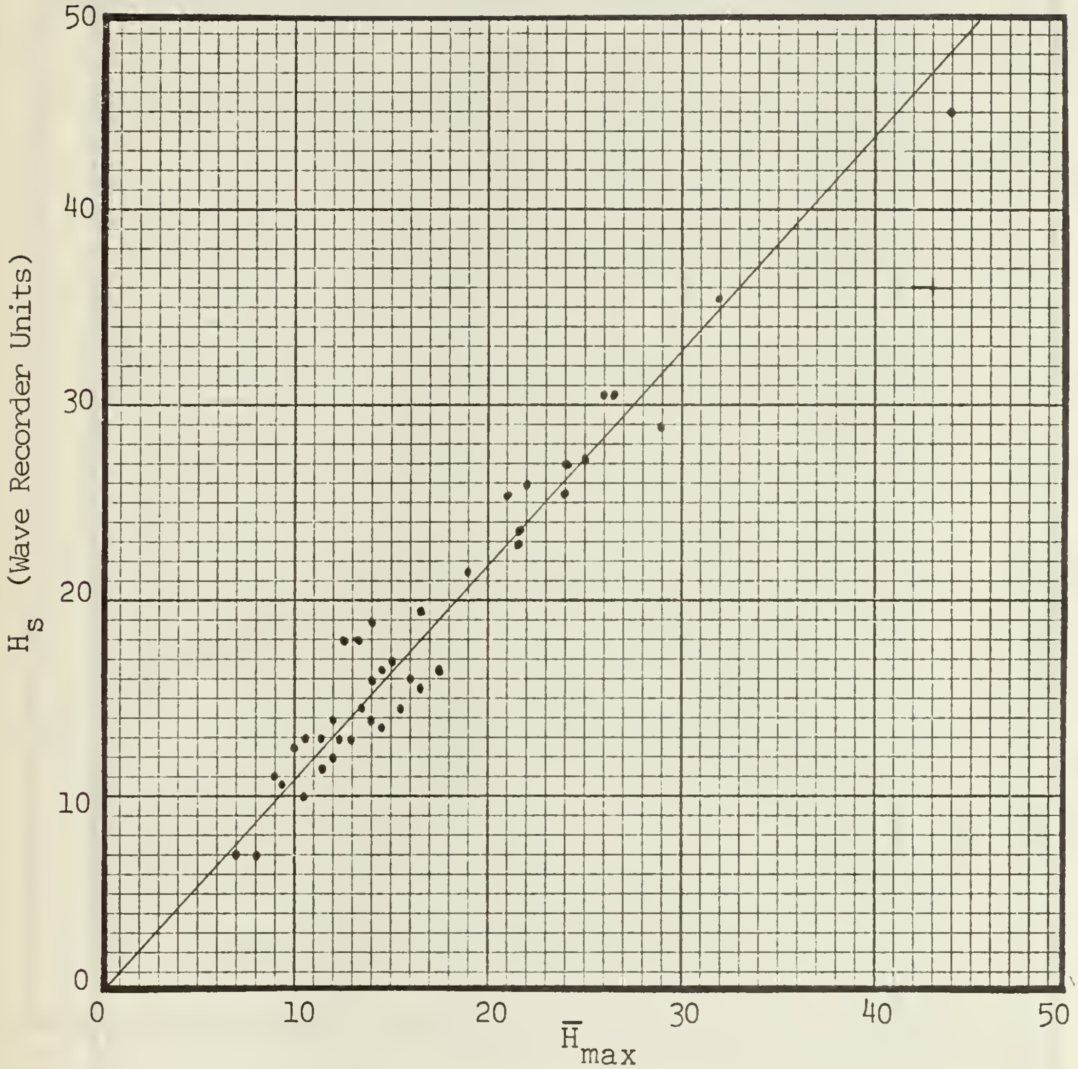


Figure 12: COMPARISON OF SIGNIFICANT HEIGHT AND AVERAGE MAXIMUM WAVE HEIGHT PER GROUP FOR SWELL TRAINS 1 THROUGH 5 (Heights in Wave Recorder Units)

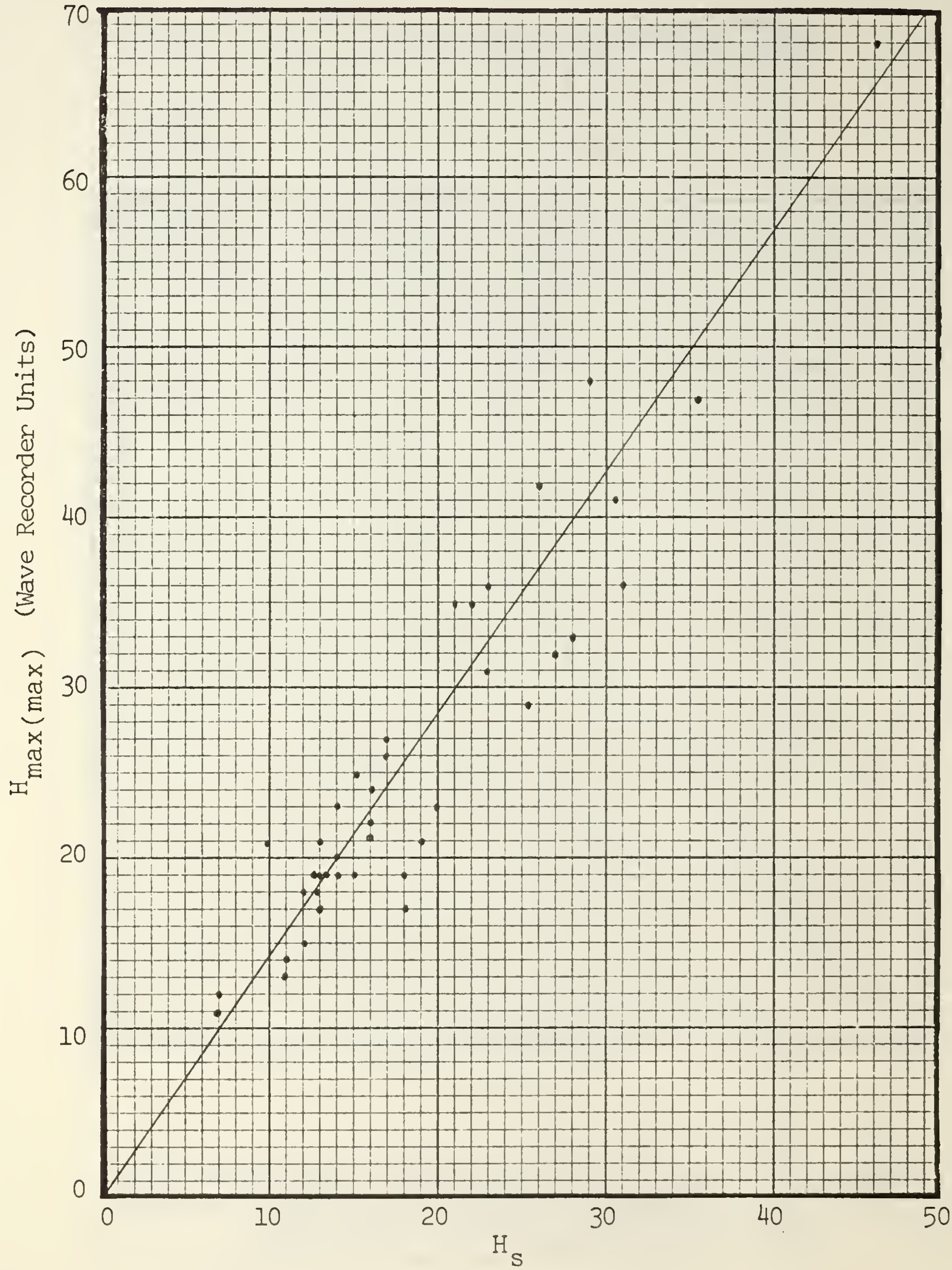


Figure 13: COMPARISON OF SIGNIFICANT HEIGHT AND HIGHEST WAVE IN A GROUP PER FAST TRACE FOR SWELL TRAINS 1 THROUGH 5 (Heights in wave recorder units)

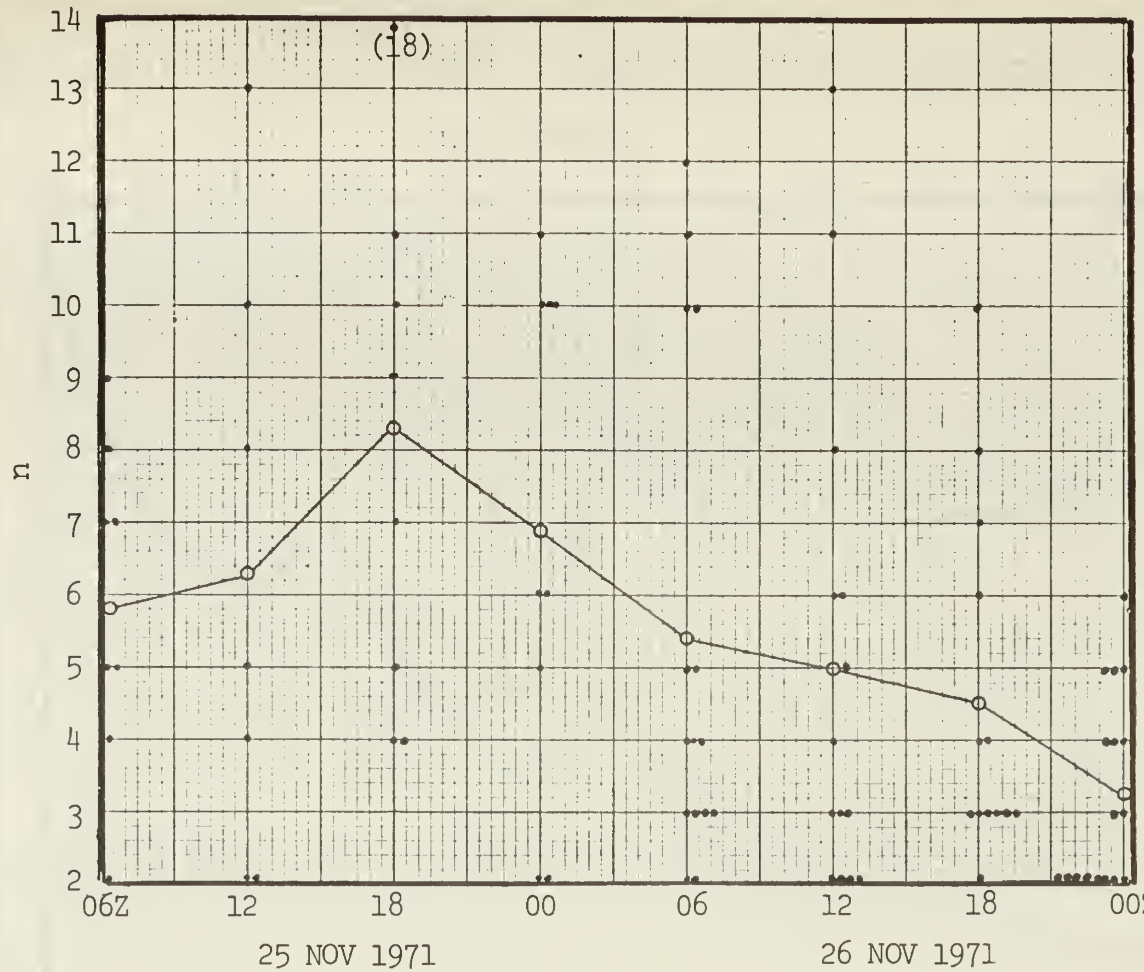


Figure 14: NUMBER OF WAVES PER GROUP FOR SWELL TRAIN 2

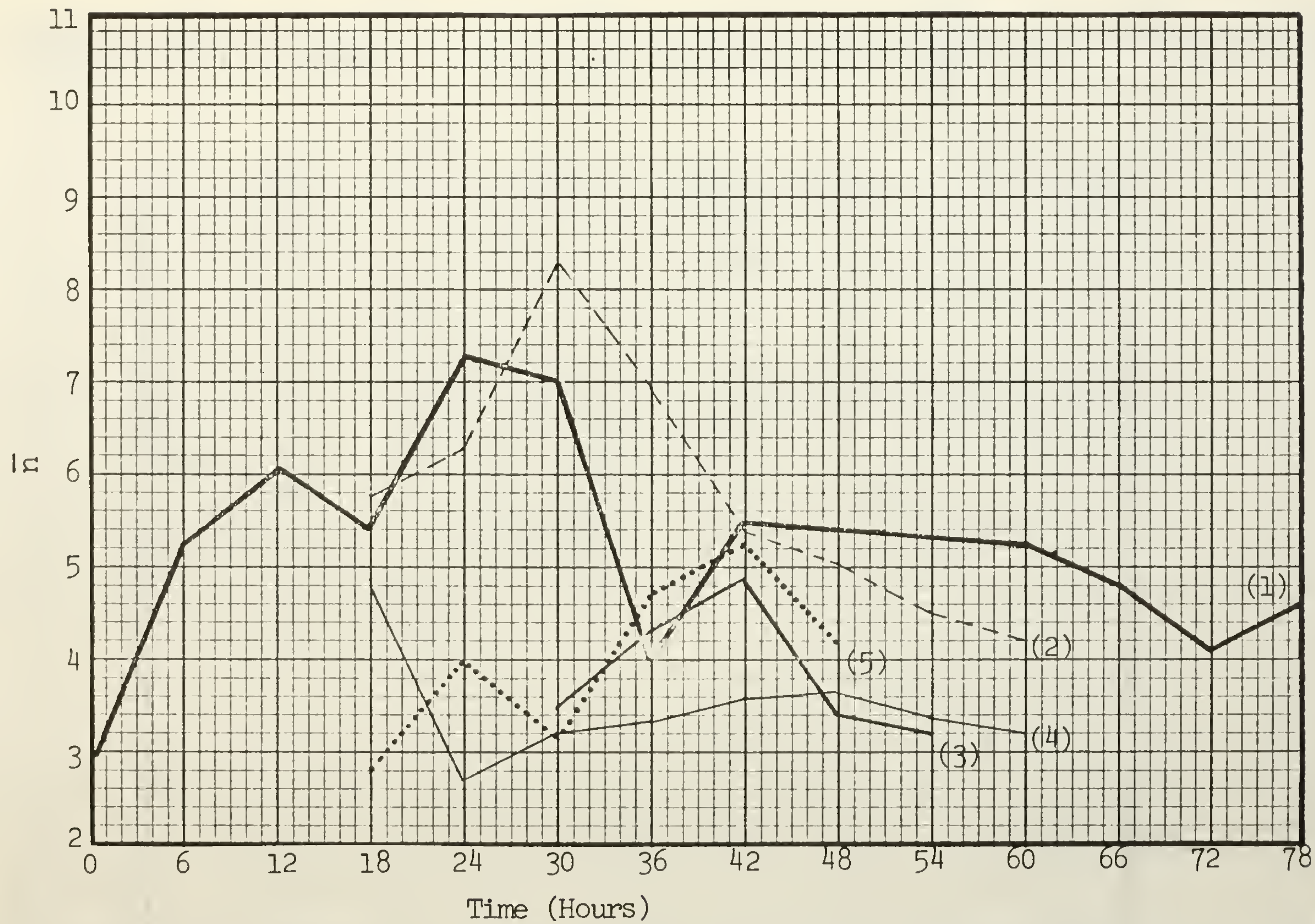


Figure 15: AVERAGE NUMBER OF WAVES PER GROUP FOR SWELL TRAINS 1 THROUGH 5

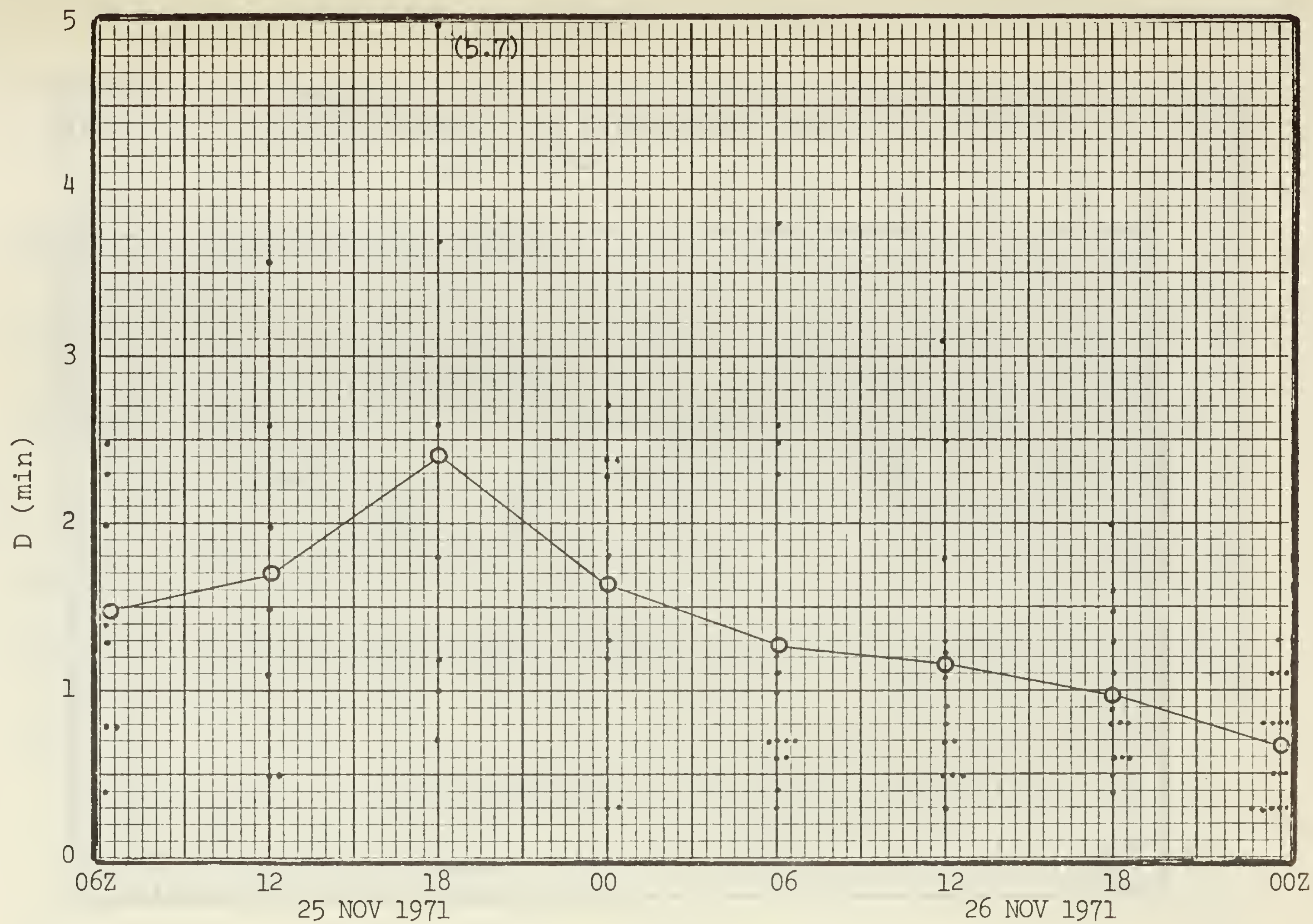

Figure 16: DURATION OF WAVE GROUPS FOR SWELL TRAIN 2

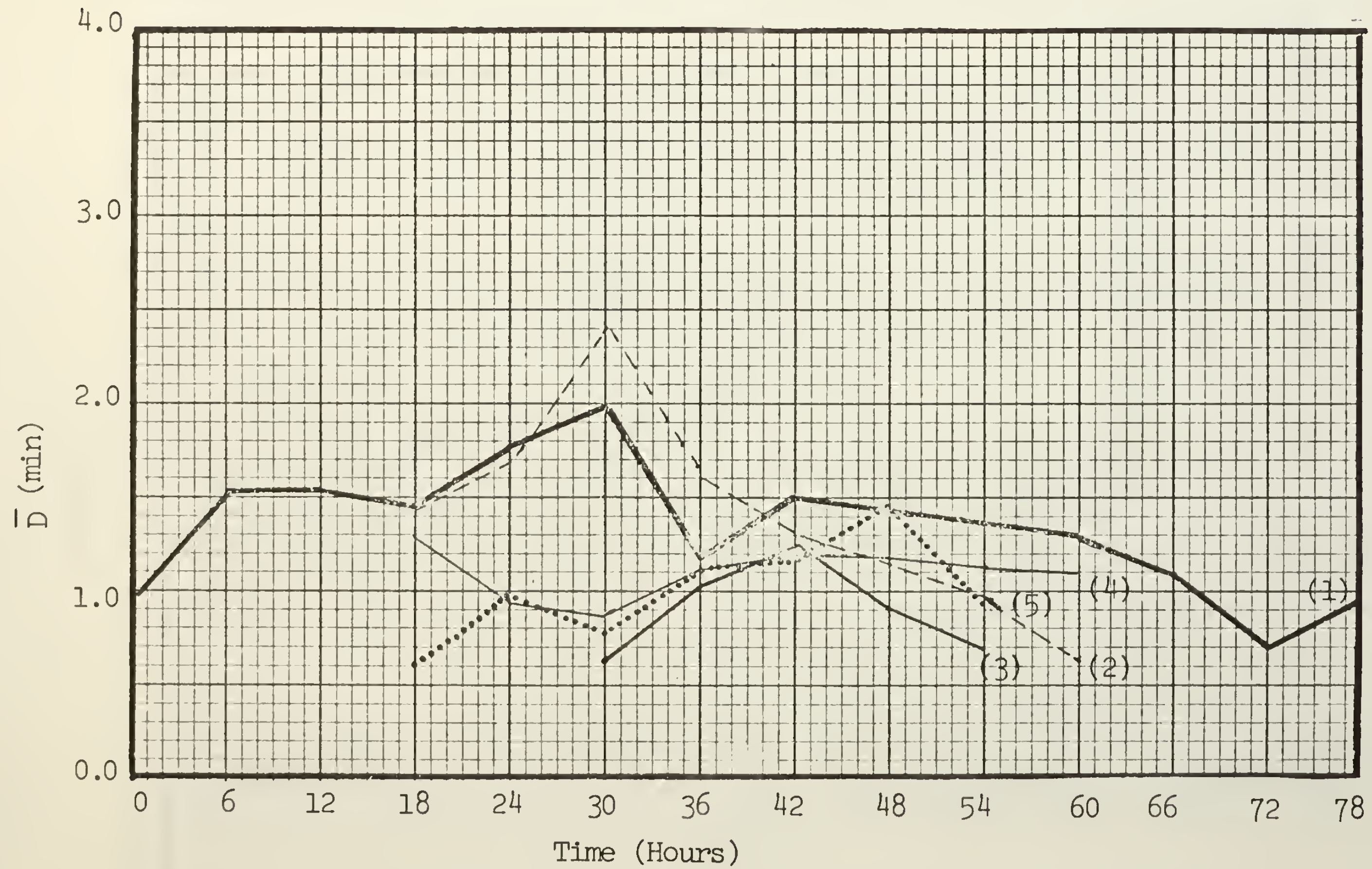


Figure 17: AVERAGE DURATION OF WAVE GROUPS FOR SWELL TRAINS 1 THROUGH 5

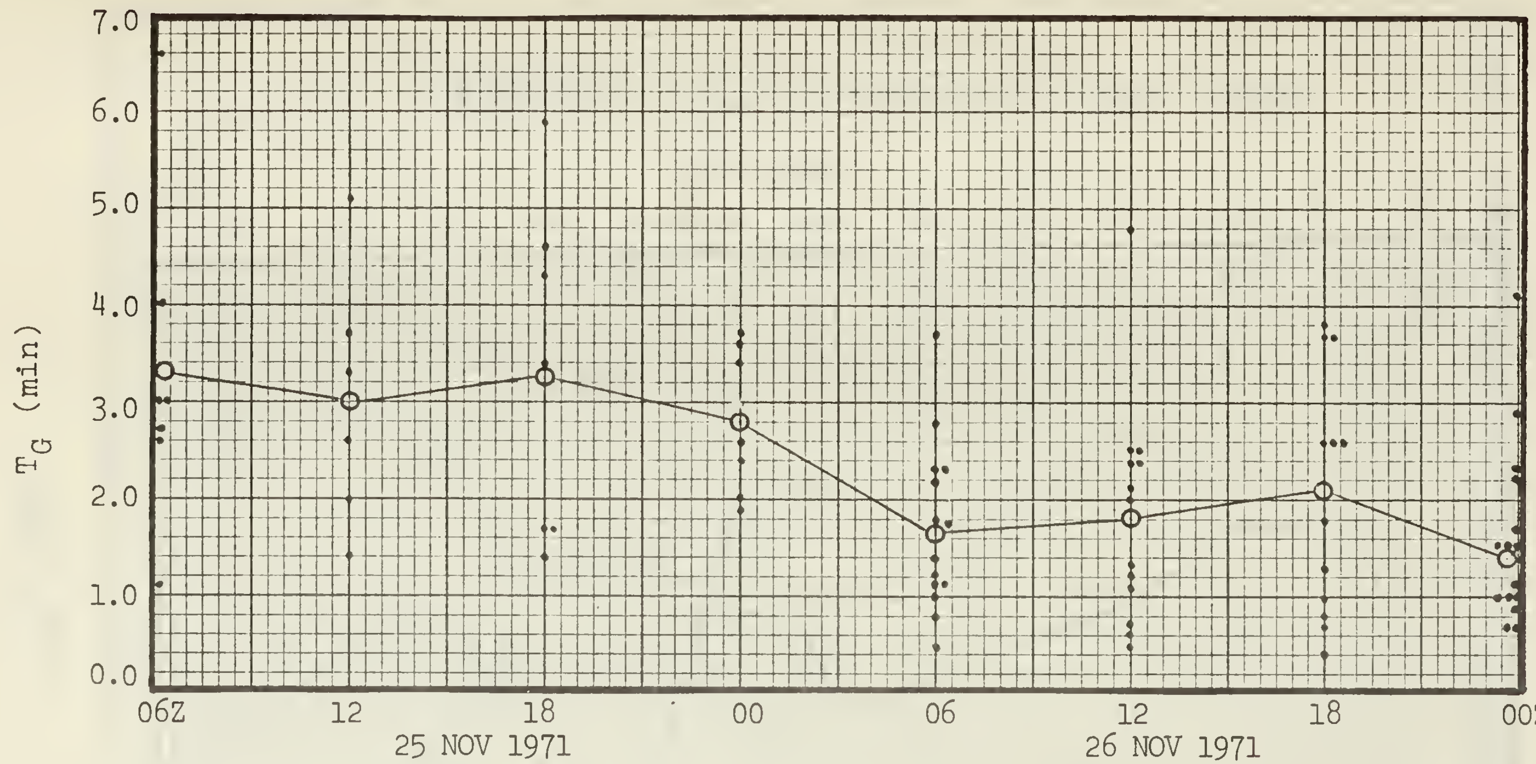


Figure 18: WAVE GROUP PERIODICITY FOR SWELL TRAIN 2

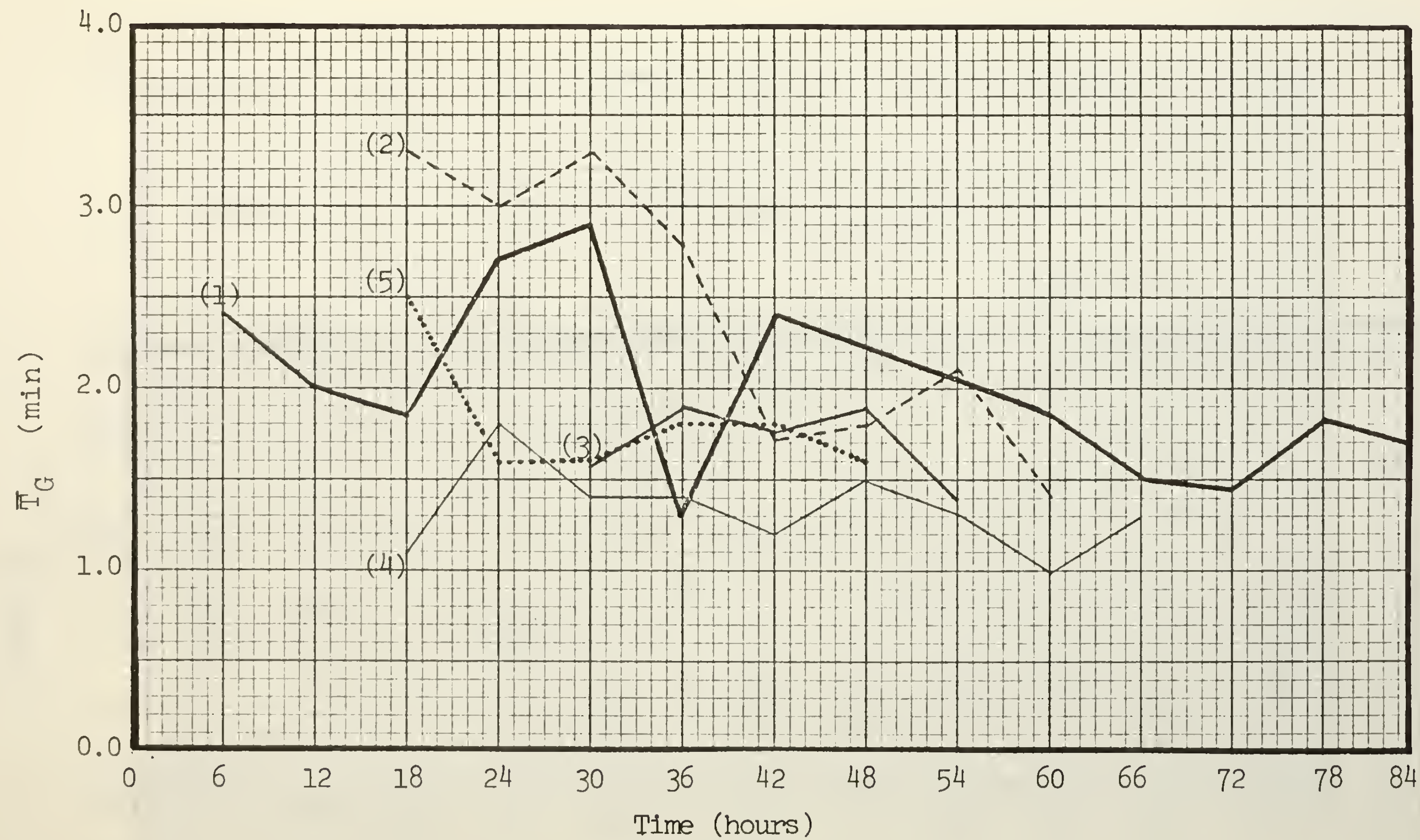


Figure 19: AVERAGE WAVE GROUP PERIODICITY FOR SWELL TRAINS 1 THROUGH 5

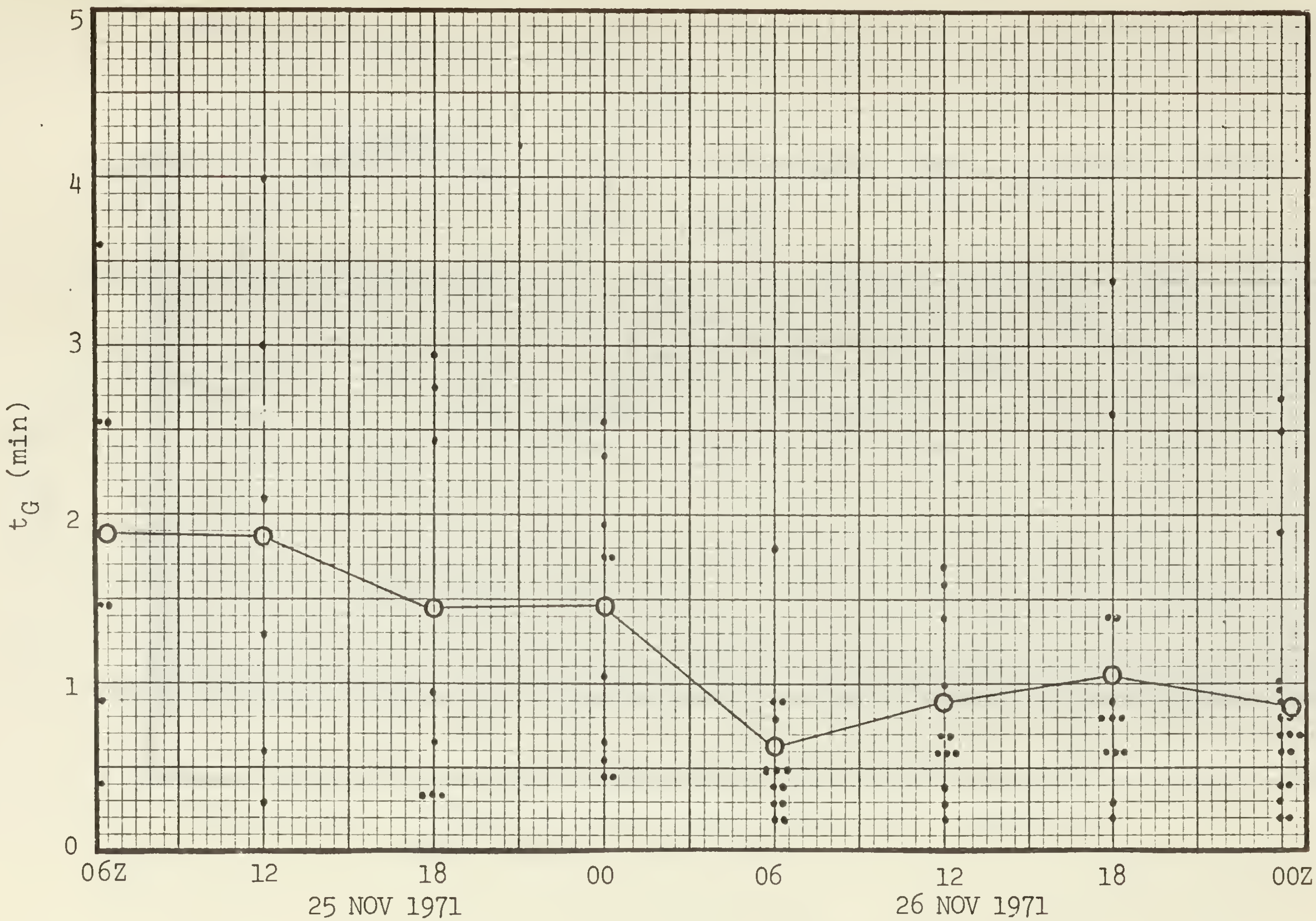

Figure 20: TIME INTERVAL BETWEEN WAVE GROUPS, $t_G$, FOR SWELL TRAIN 2

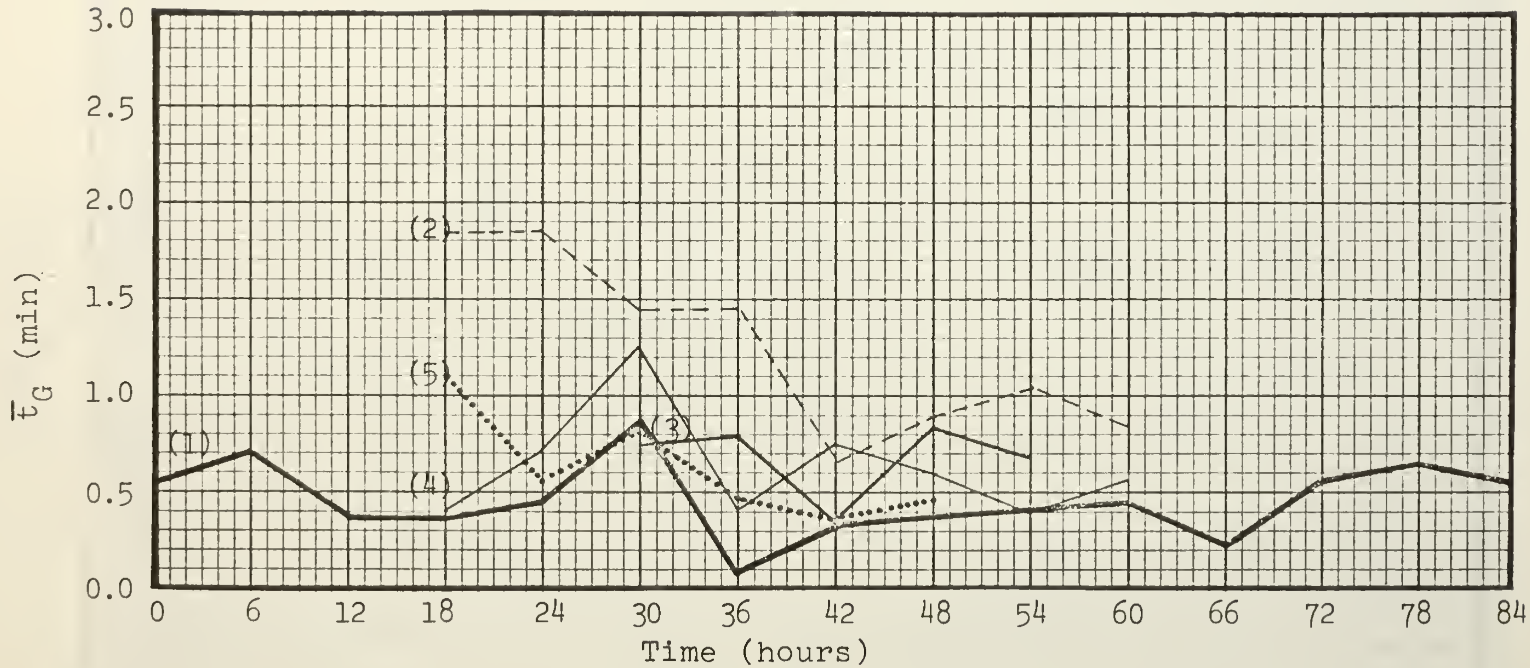


Figure 21: AVERAGE TIME INTERVAL BETWEEN WAVE GROUPS FOR SWELL TRAINS 1 THROUGH 5

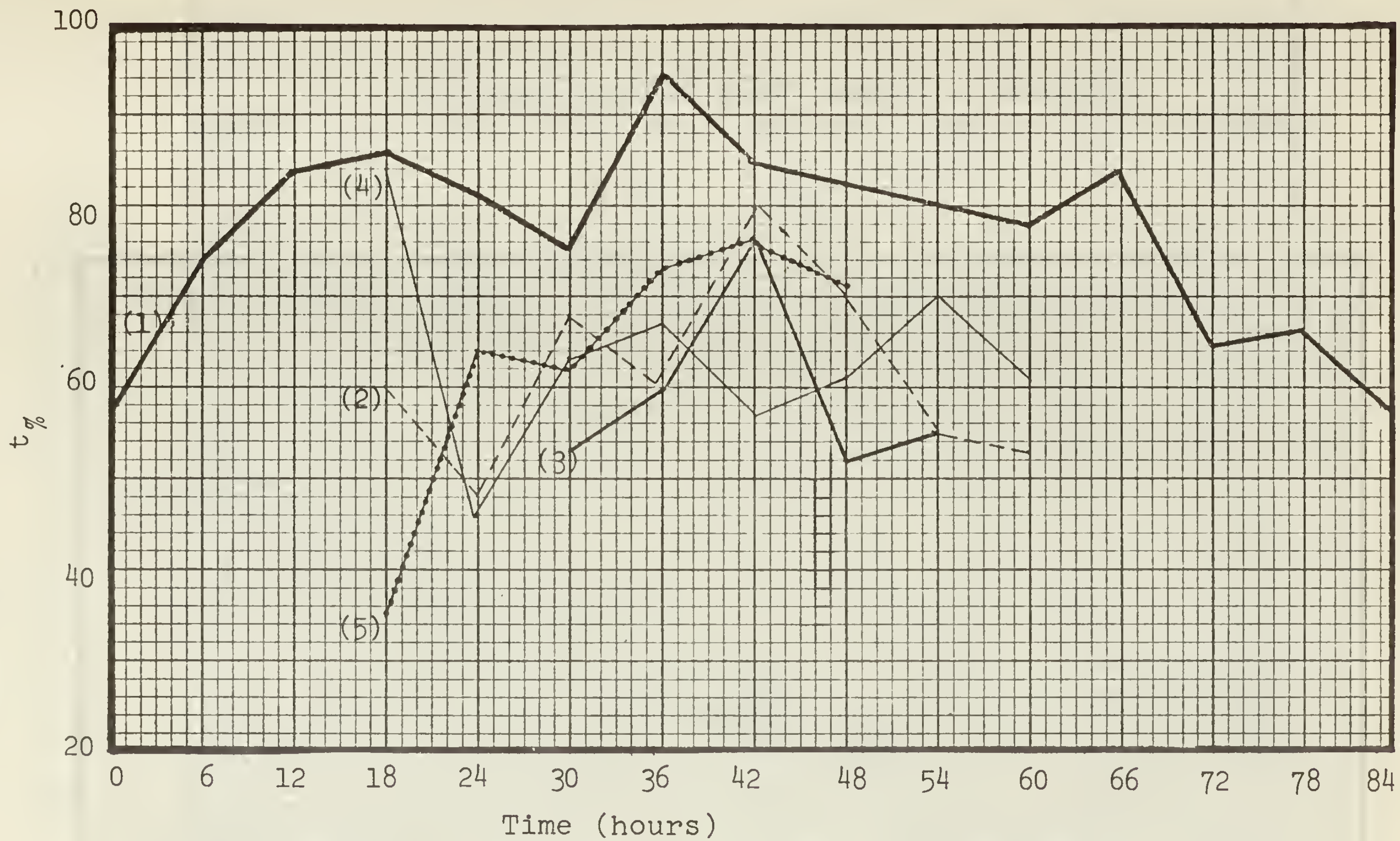


Figure 22: PERCENT OF TIME WAVE GROUPS ARE PRESENT FOR SWELL TRAINS 1 THROUGH 5

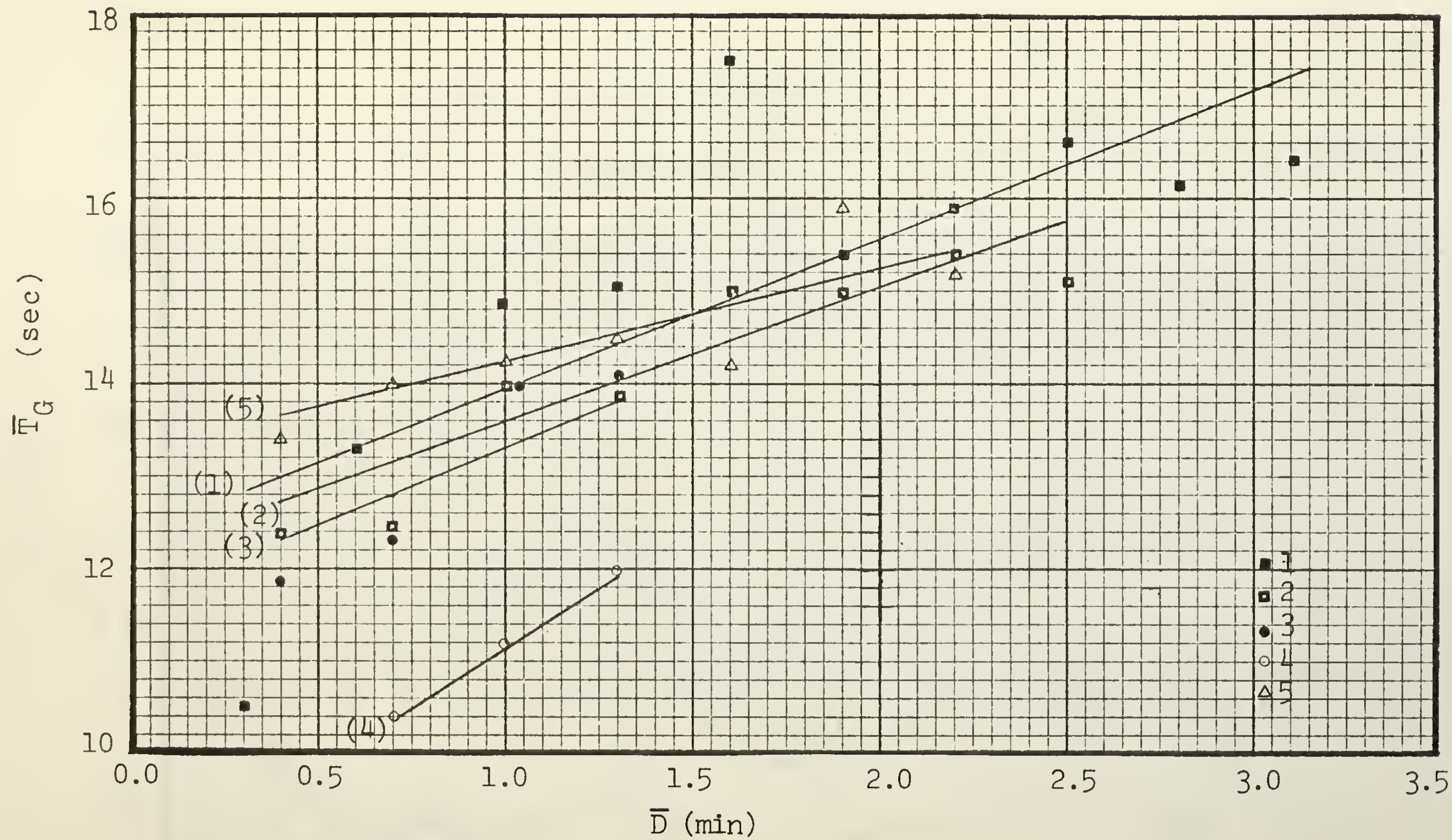


Figure 23: AVERAGE WAVE GROUP PERIOD - AVERAGE GROUP DURATION DISTRIBUTION FOR SWELL TRAINS 1 THROUGH 5

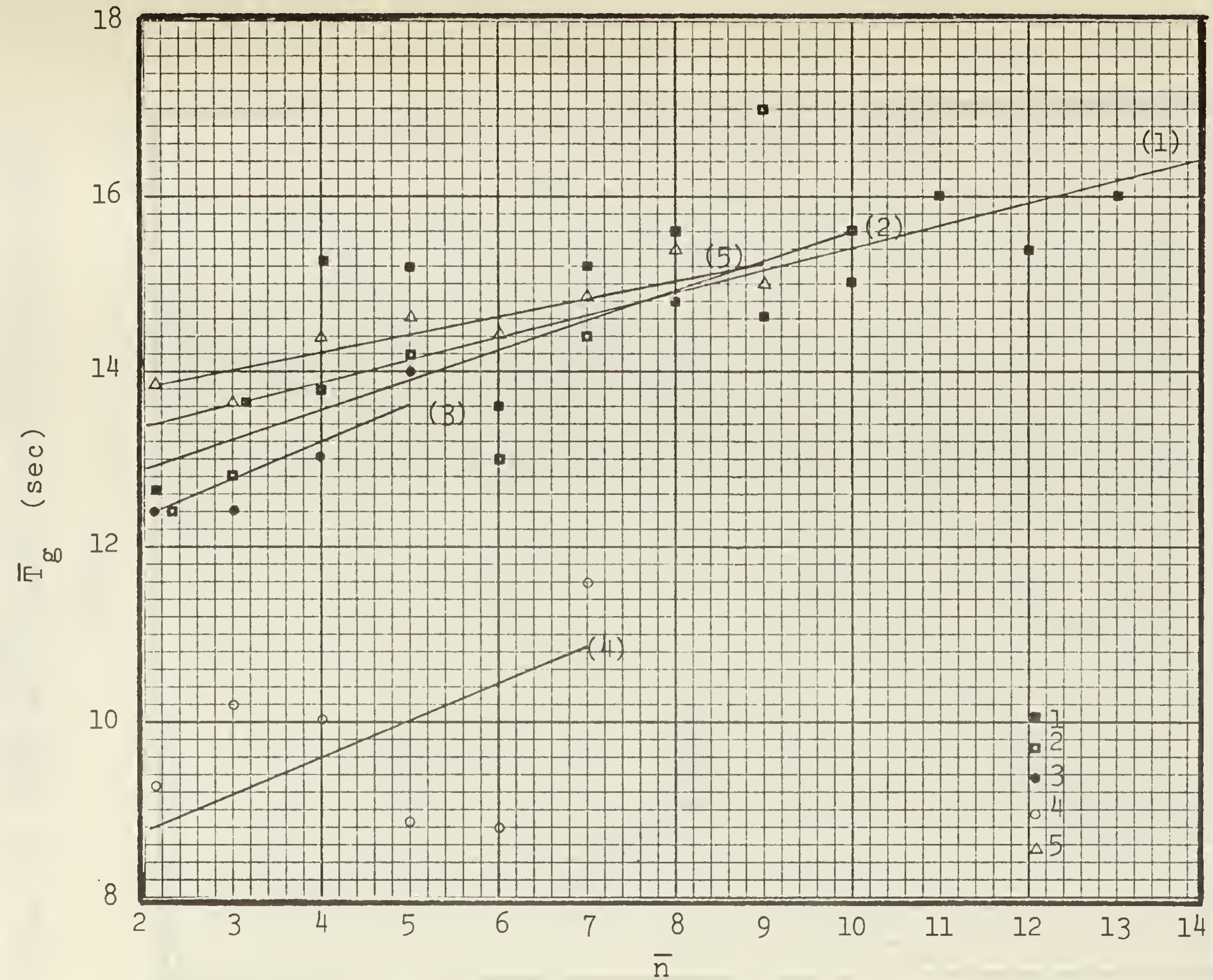


Figure 24: AVERAGE WAVE GROUP PERIOD - AVERAGE NUMBER OF WAVES DISTRIBUTION FOR SWELL TRAINS 1 THROUGH 5

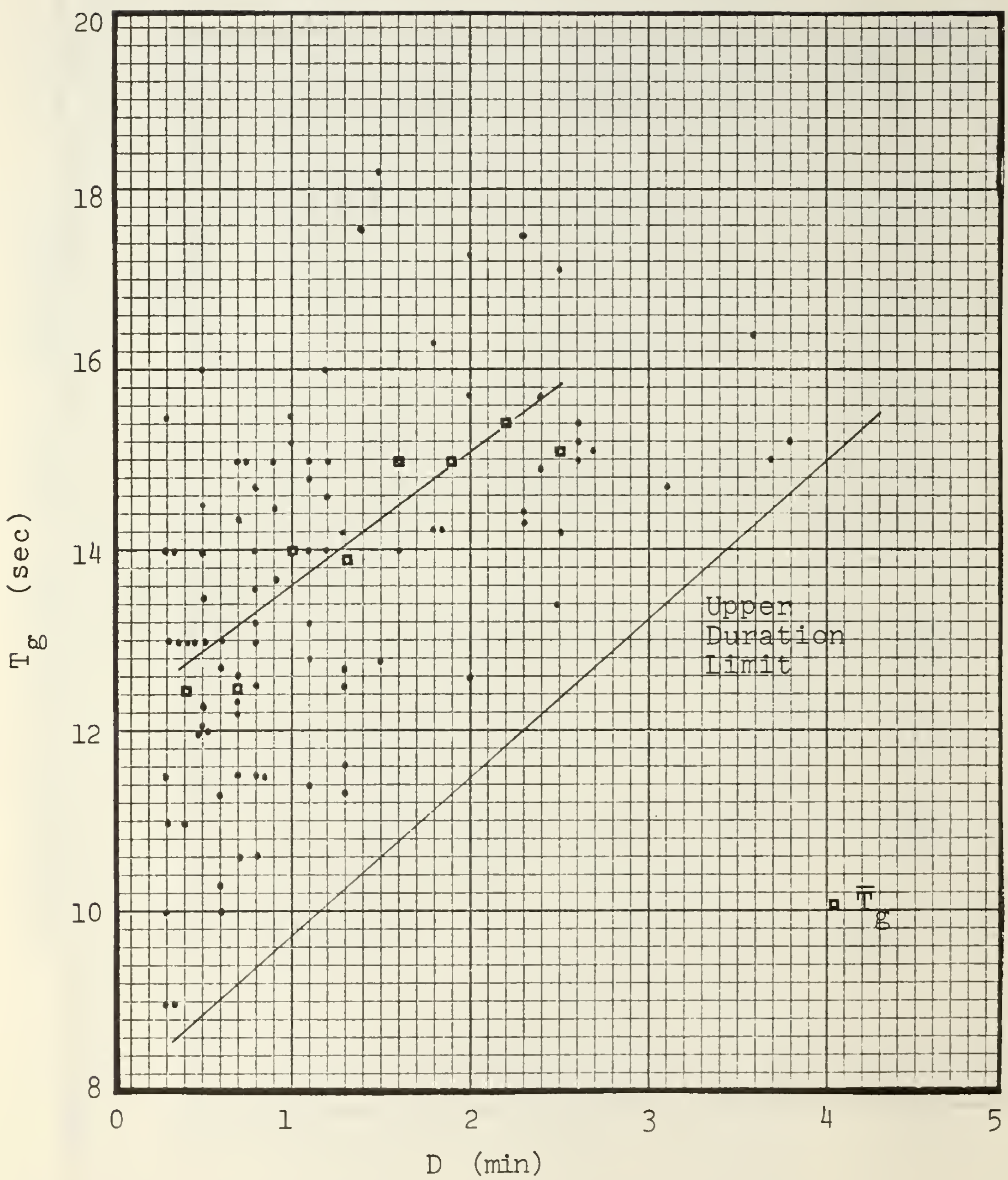


Figure 25: WAVE GROUP PERIOD VERSUS DURATION FOR SWELL TRAIN 2

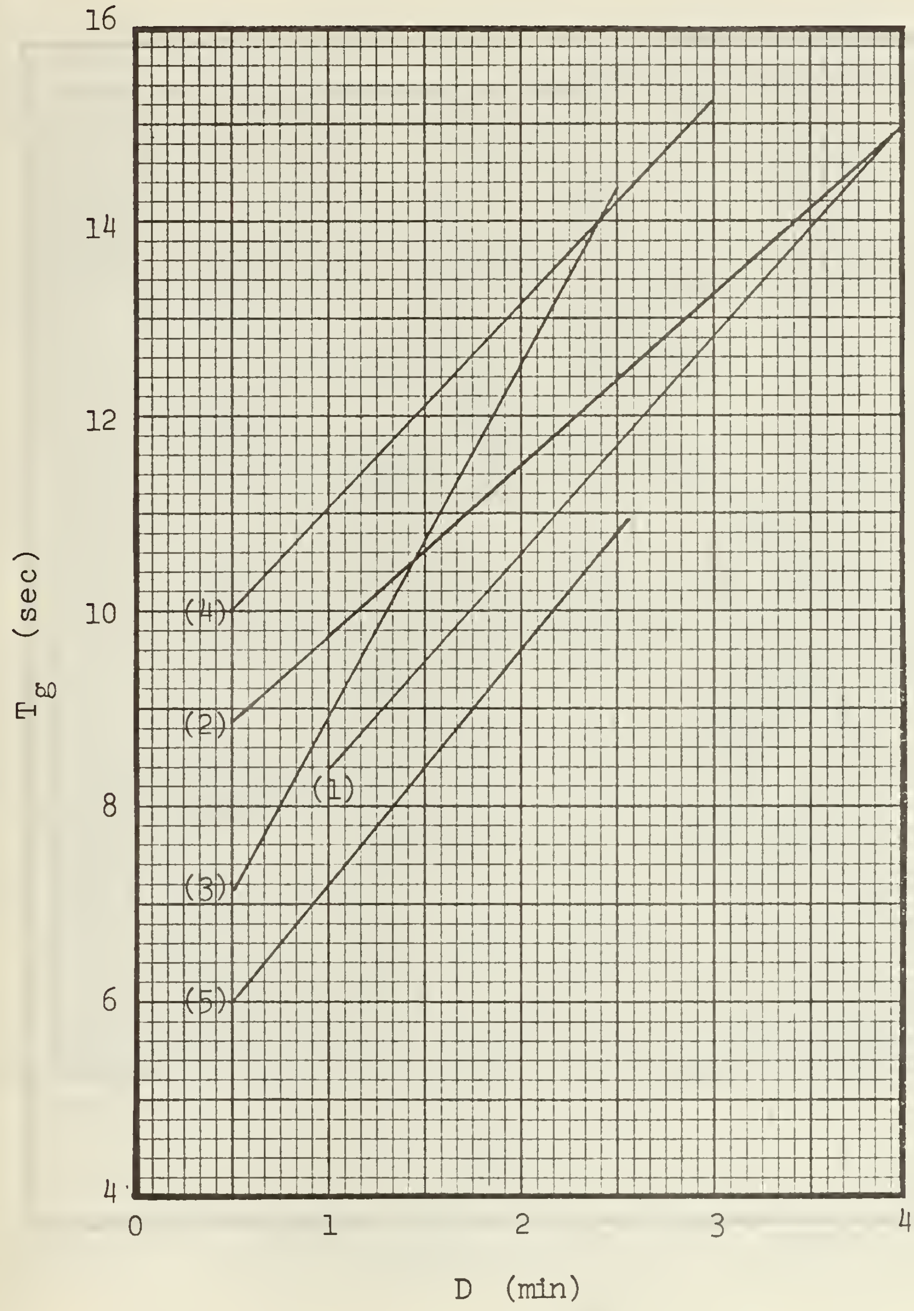


Figure 26: DURATION LIMIT FOR SWELL TRAINS 1 THROUGH 5

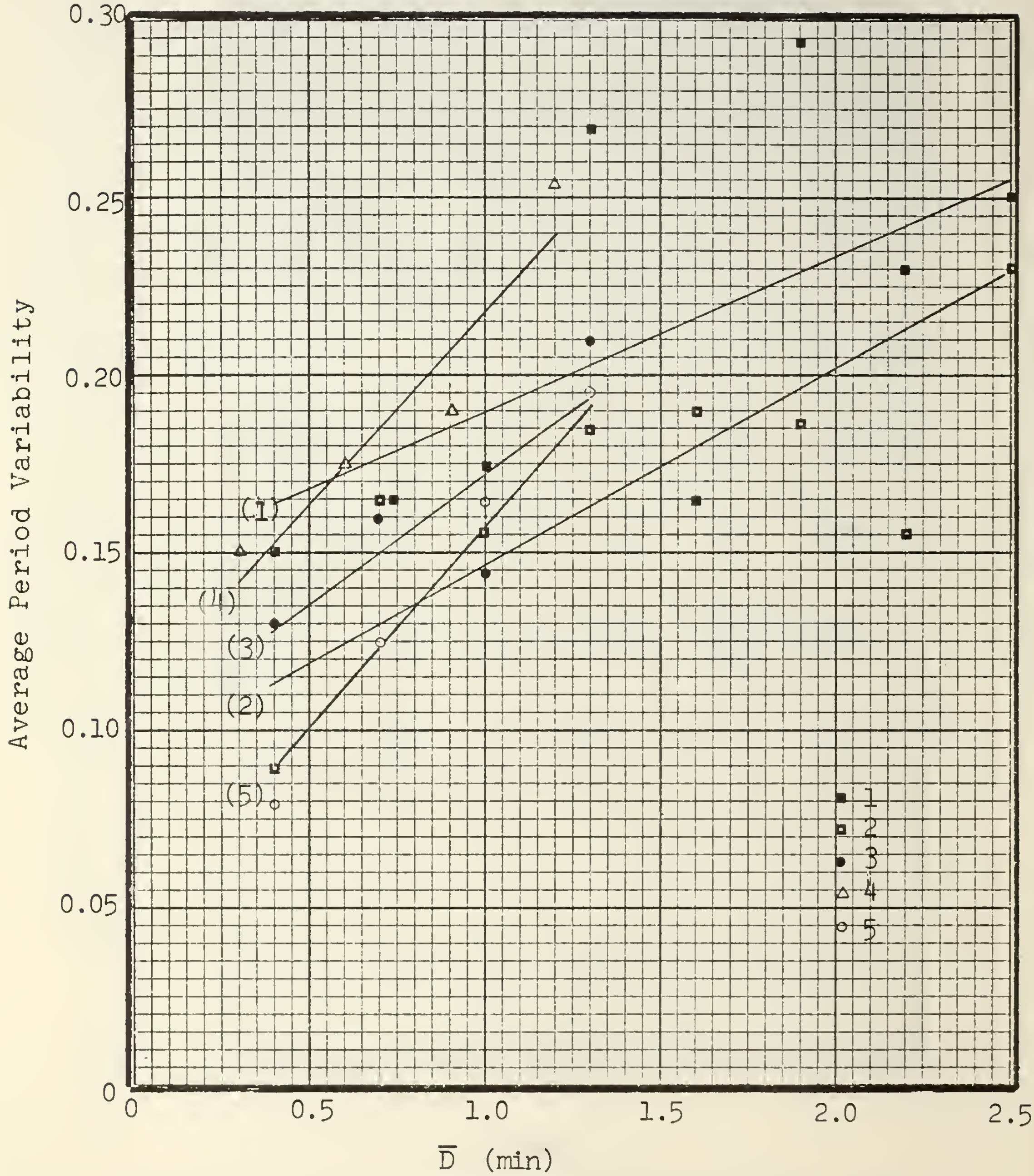


Figure 27: AVERAGE PERIOD VARIABILITY - AVERAGE DURATION DISTRIBUTION FOR SWELL TRAINS 1 THROUGH 5

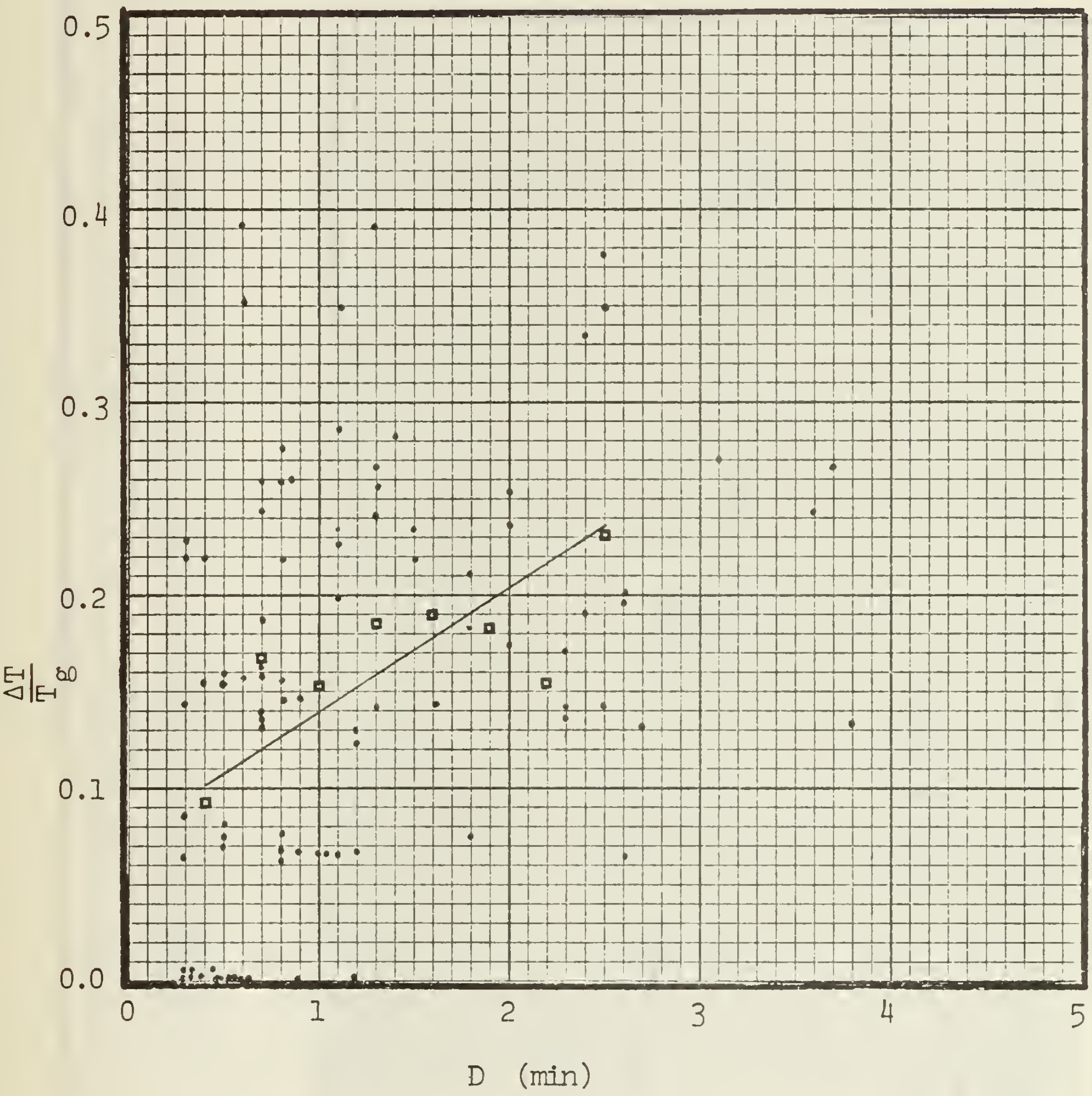


Figure 28: PERIOD VARIABILITY VERSUS DURATION FOR SWELL TRAIN 2

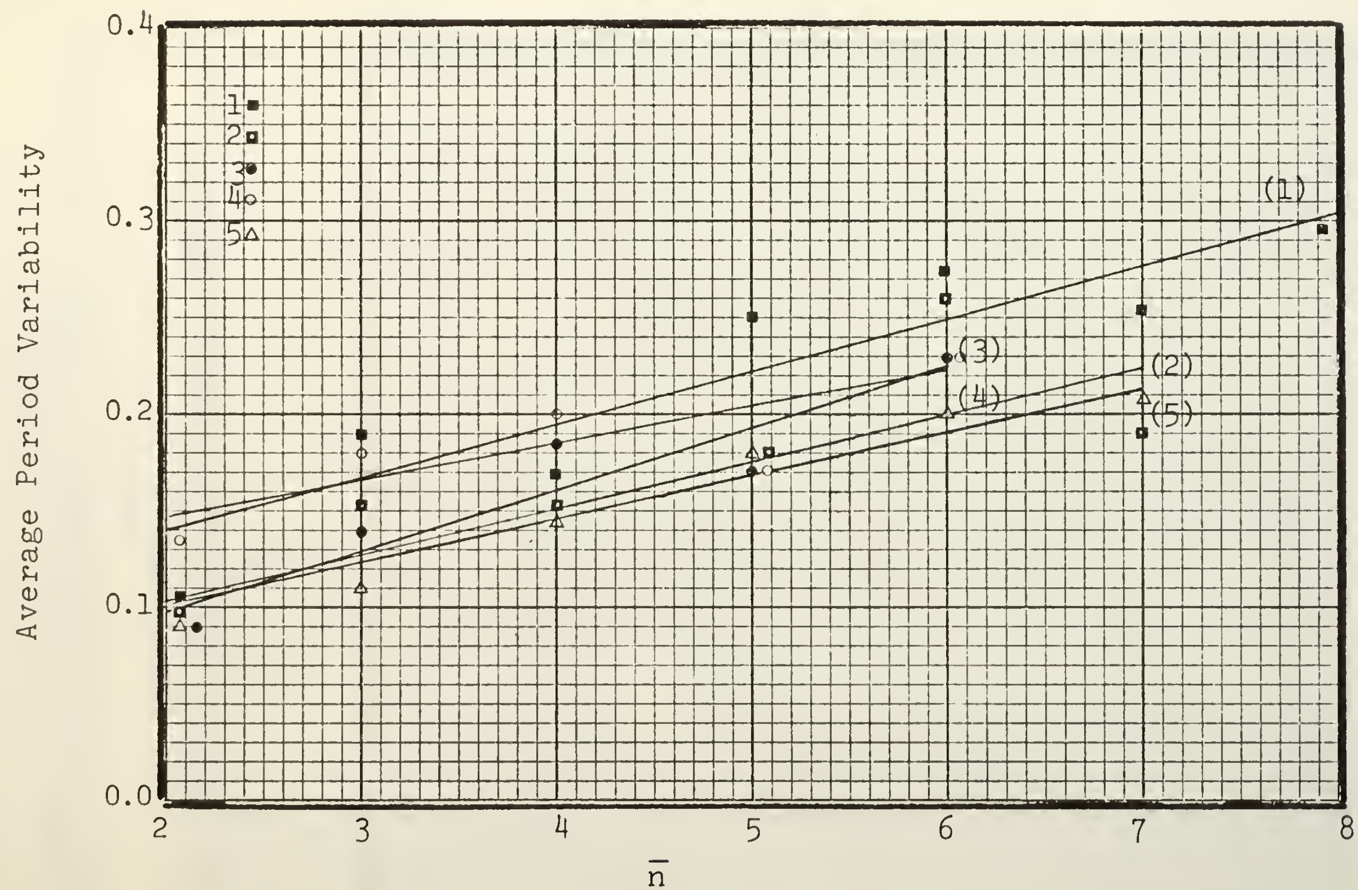


Figure 29: AVERAGE PERIOD VARIABILITY - AVERAGE NUMBER OF WAVES DISTRIBUTION FOR SWELL TRAINS 1 THROUGH 5

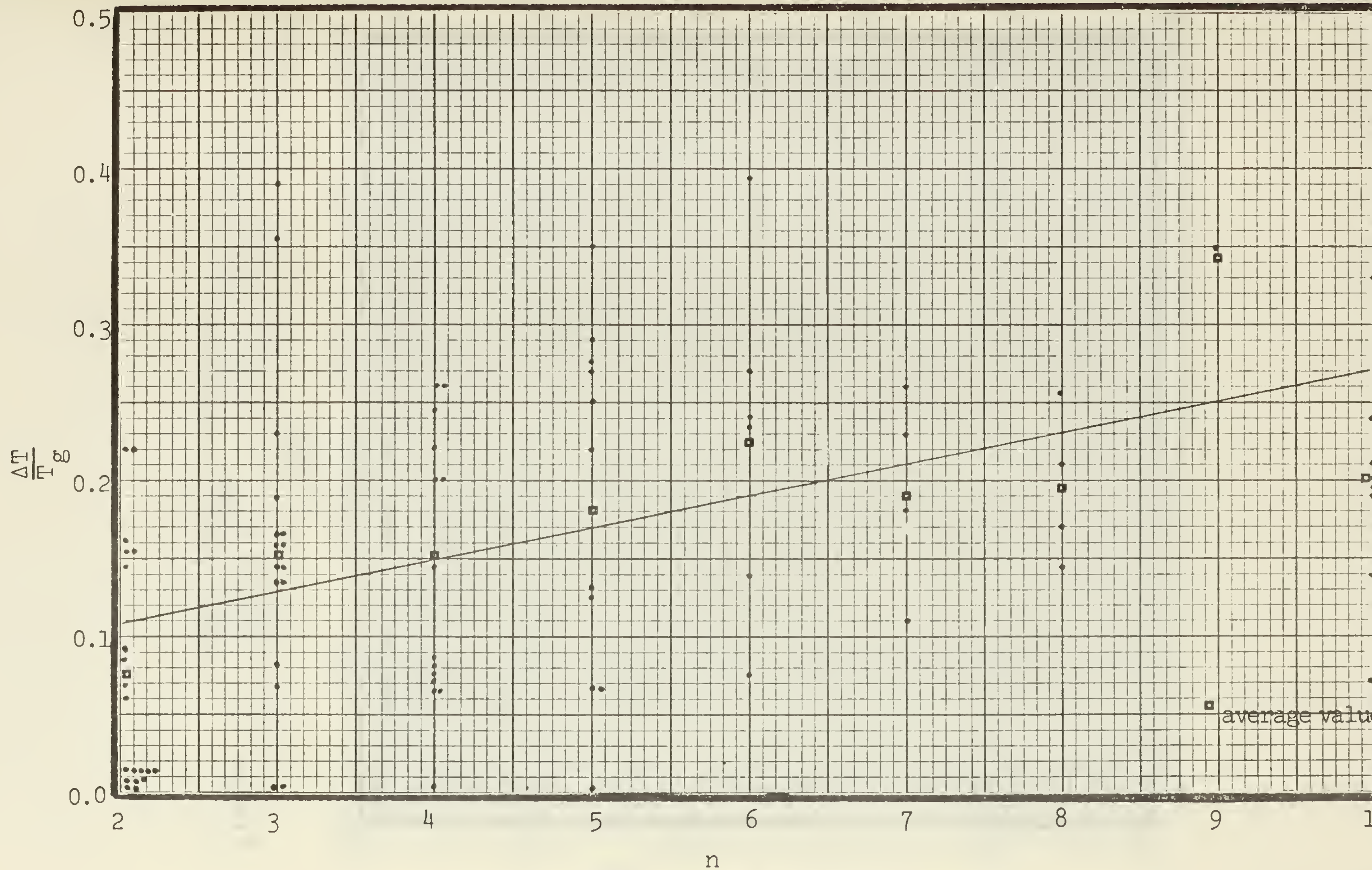


Figure 30: PERIOD VARIABILITY VERSUS NUMBER OF WAVES PER GROUP FOR SWELL TRAIN 2

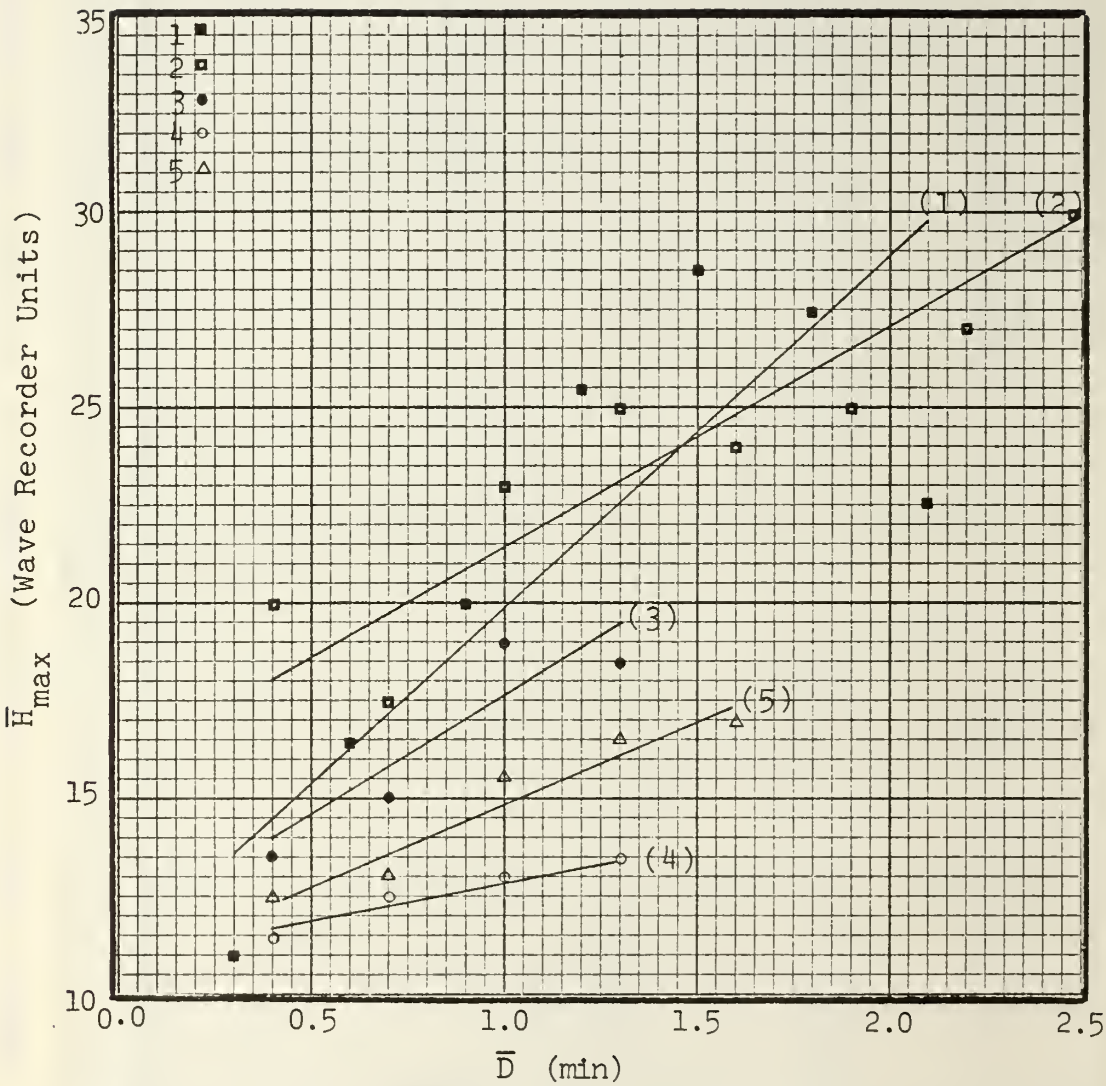


Figure 31: AVERAGE $H_{max}$ - AVERAGE DURATION FOR SWELL TRAINS 1 THROUGH 5

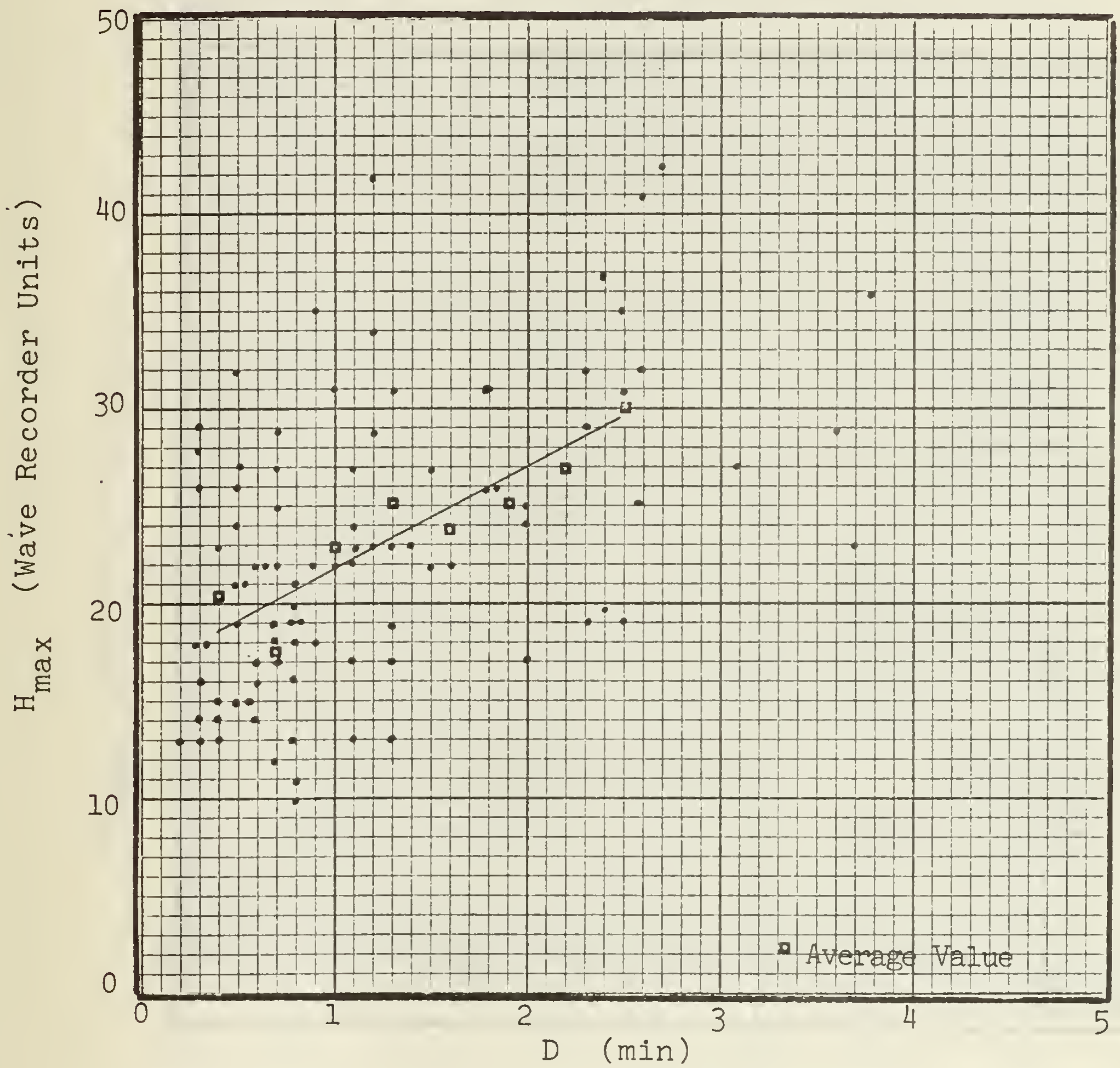


Figure 32: $H_{max}$ VERSUS DURATION FOR SWELL TRAIN 2

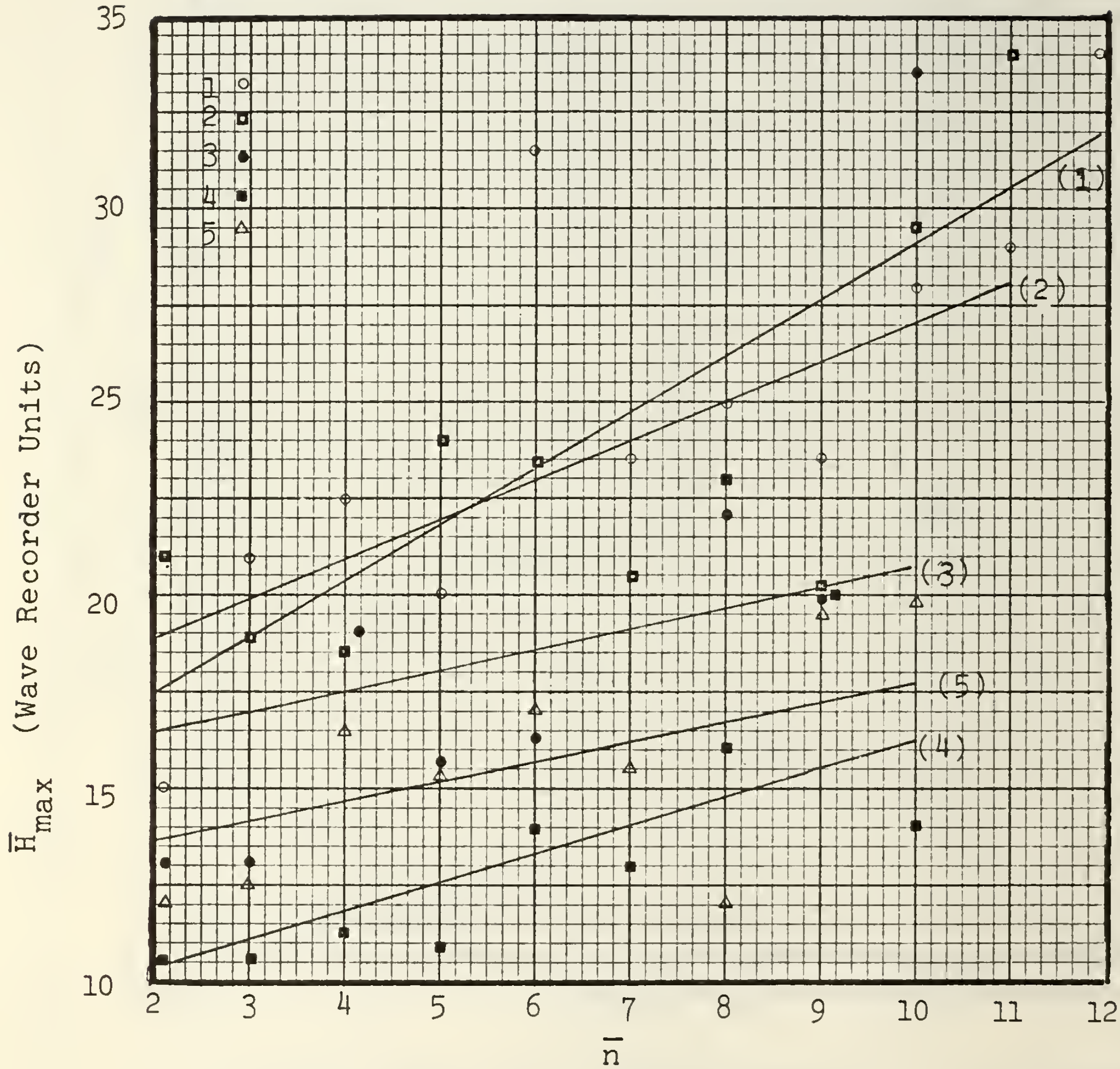


Figure 33: AVERAGE MAXIMUM WAVE HEIGHT PER GROUP - AVERAGE NUMBER OF WAVES PER GROUP DISTRIBUTION FOR SWELL TRAINS 1 THROUGH 5

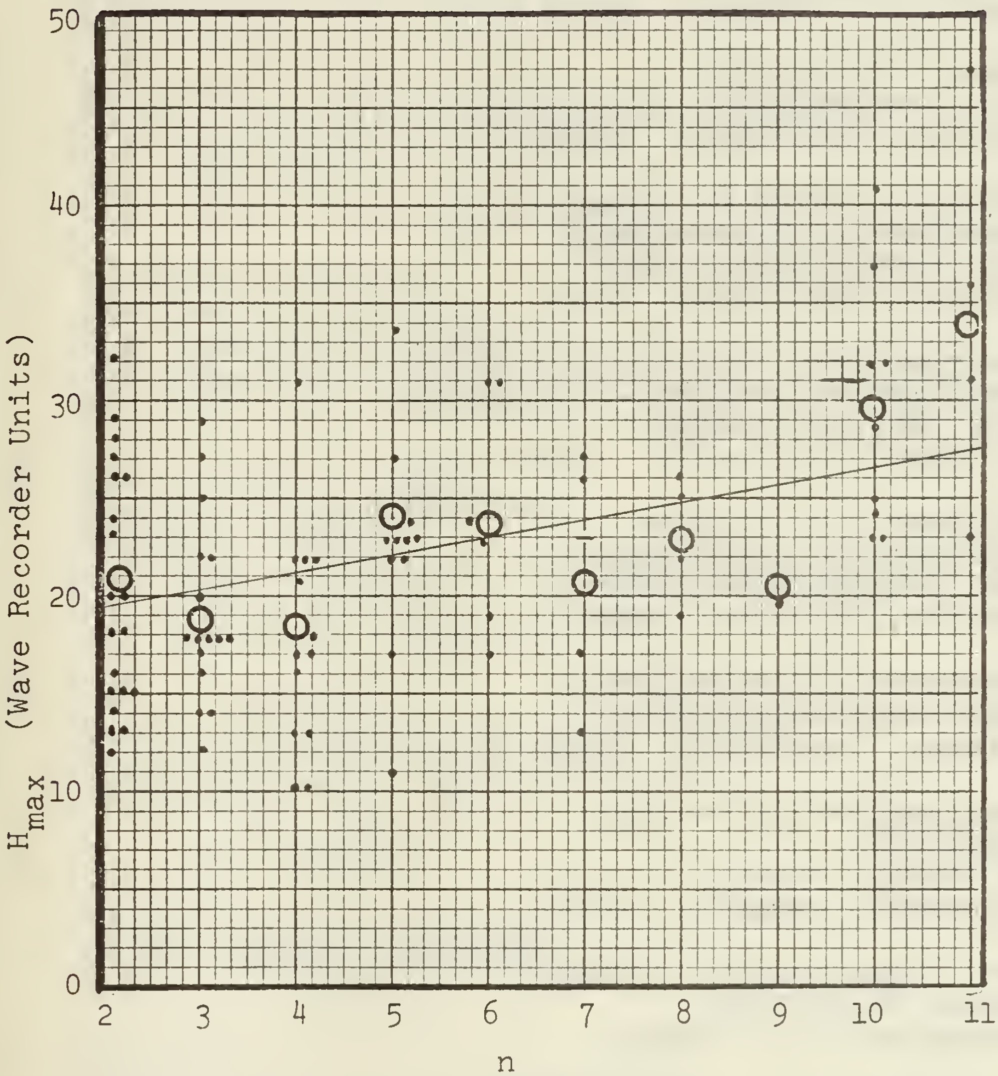


Figure 34: MAXIMUM WAVE HEIGHT PER GROUP VERSUS THE NUMBER OF WAVES PER GROUP FOR SWELL TRAIN 2

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