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Series 3, Issue 362

LABORATORY STUDIES OF GRAVITY WAVES GENERATED BY THE MOVEMENT OF A SUBMERGED BODY

by
R. L. Wiegel

Berkeley, Calif.
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UNIVERSITY OF CALIFORNIA
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Abstract

In order to gain some insight into the phenomenon of gravity waves generated by underwater seismic disturbances, the Tsunami, a laboratory study was made of the waves resulting from an idealized two dimensional model of the movement of a submerged body. Bodies of several shapes, sizes and weights were allowed to drop vertically or to slide down inclines of several angles, in water of various depths, from several heights above the bottom, but always below the water surface. The surface time histories were recorded at a point close to the origin of the disturbance, and at a point or po[illegible] distance from the origin. In addition, motion pictures were taken of several of the tests. It was found that a crest always formed first, followed by a trough from one to three times the amplitude of the first crest (depending primarily upon the slope of the incline), followed by a crest with about the same amplitude as the trough. Due to the dispersive qualities of the waves, additional crests and troughs continued to form with increasing distance from the origin. The magnitude of the amplitudes depended primarily upon the submerged weight of the body, but also upon the depth of submergence, the water depth and other characteristics of the generation. Within the limits of experimental conditions, it was found that the time intervals between the first and second crests remained constant regardless of the water depth, the distance of fall, the weight of the body or the time of the fall. It was, however, found to be related to the length of the body, with the period increasing with increasing length, and to the slope of the incline, with the smaller the incline the greater the period.

Introduction

The Tsunami which caused so much damage to the Hawaiian Islands and to many locations along the Pacific Coast of North America on 1 April 1946 was caused by a movement of the sea bottom on the northern slope of the Aleutian Trough, south of Unimak Island, Alaska (SHEPARD, F.P., MacDONALD, G.A. and COX, D.C. - 1950). The severity of the damage created considerable interest in the general phenomenon. A review of the literature indicated that many studies had been made of certain of the characteristics of actual Tsunamis, and that theoretical studies had been made of the Cauchy-Poisson wave phenomenon (see UNOKI, S., and NAKANO, M., 1953, for example), but that no laboratory studies had been made of the relationship between, say, an underwater landslide and the resulting gravity water waves.

A series of experiments was undertaken in 1946 by SAUER, F.M. and WIEGEL, R.L. (1946) to study the characteristics of the waves generated by a submerged body sliding down a 1:1 slope in a channel three feet deep by one foot wide by sixty feet long. Exploratory work, just prior to the first series of tests, consisted of piling coarse gravel as steeply as possible on top of a piece of sheet metal at one end of the channel, then pulling the sheet from under the pile to destroy its equilibrium and cause a slide. However, a true slide did not result, but rather a slump occurred in the center of the pile. The next attempt consisted of placing a vertical gate in the channel, piling sand behind it, then pulling the gate vertically out of the water; however, the removal of the gate generated waves of the same order of magnitude as those produced by the slumping sand. As a result of these tests it was decided to use a box sliding down an incline as a model underwater landslide.

Recently these tests have been extended to include a study of a submerged body falling vertically through water of several depths and from several initial elevations for each depth, with the effect of weight and body movement included. In addition, a series of experiments was performed to study the effect of different slopes down which the body slid.

Experimental Procedure.

Most of the experimental work was performed in a glass-walled wave channel three feet deep by one foot wide by sixty feet long in the Fluid Mechanics Laboratory of the University of California, Berkeley (see Figure 1a).

The first set of experiments (Series I) consisted of generating waves by allowing a submerged wooden box to slide freely down an incline with a 1:1 slope (Figure 1b). The box was triangular in cross section (12" x 12") and extended across the width of the channel. Six different weights at each of three initial elevations were investigated (Table III). Two Stevens Wave Recorders were used to record the waves. Previous tests with these recorders indicated that under laboratory conditions these recorders would determine wave height with a probable error of plus or minus 12 percent (PUTNAM, J.A., and ARTHUR, R.S. 1948). One was located 8 feet (Station A), and the second $25\frac{1}{2}$ feet (Station B) from the intersection of the water surface and the inclined board down which the box slid. The far end of the channel was equipped with an inclined beach to minimize reflection; even so, some reflection occurred and was apparent after the second wave crest. The water depth was maintained at 2.5 feet.

A second set of experiments (Series II) consisted of four parts:

1. A submerged rectangular box 0.6 foot deep by 0.6 foot long, extending the width of the channel, was allowed to fall freely in a vertical direction in water of several depths (1.50 feet, 1.92 feet, and 2.86 feet) and ~~from two or more~~ submergences for each water depth. Seven different box weights (from 1-3/8 to 26 pounds, net, submerged) at each depth and submergence were used. Two parallel wire resistance elements were used to measure the waves. The first

(Station 1) was located at a distance of 1.09 feet and the second (Station 2), 4.82 feet from the leading edge of the submerged body. A sloping beach was located at one end of the channel to absorb the waves, but the waves were reflected from the opposite end. However, the reflected waves arrived after the initial disturbance had completely passed the recording elements, and thus were of no consequence. The conditions are shown in Figure 1c and are presented in Table I.

2. A series of submerged rectangular boxes 0.6 foot deep by 1.0 foot, 2.0 feet, and 3.0 feet in length, extending the width of the channel, were allowed to fall freely in a vertical direction in water about one and a half feet deep (see Figure 6). The initial position of the box in all cases was such that the top was barely under the water surface, that is, at zero submergence. The net weight of the submerged box varied from 30-1/4 pounds for the 3.0 foot box to 32-1/4 pounds for the 1.0 foot box. Two parallel wire resistance elements were used, and located as in Case 1.

3. The box used in Case 1, fitted with two small, lightweight, metal runners on the bottom, was allowed to slide down an inclined metal plate with slopes ranging from vertical to 1:2.4 (22.7°), see Table II. It was found that a slope of 24.2 degrees was the flattest that the box would slide down in a uniform manner. The net submerged weight of the box was 20½ pounds and the water depth was between 1.43 feet and 1.48 feet. The highest point of the box at its initial position was at zero submergence. Two parallel wire resistance elements were used, and located as in Case 1 and Case 2 (Figure 1c).

4. A lead plate 3/16 inch thick by 6 inches long, extending the width of the channel was allowed to drop in water 0.14 foot, 0.24 foot and 0.38 foot deep and from two or more depths of submergence for each condition (Table IV). The net submerged weight of the lead plate was 3½ pounds. Wave measurements were made by a series of four parallel wire resistance elements located at 1.09 foot (Station 1), 10.96 feet (Station 2), 23.82 feet (Station 3) and 38.49 feet (Station 4) from the center of the submerged body (Figure 1c). These tests were

performed in a wave channel similar to the one used in the other tests.

Previous tests with the parallel wire resistance elements indicated that under laboratory conditions these recorders could determine wave height with a probable error of plus or minus 5 percent (MORISON, R.J. 1949).

In all cases the box was held in place by a cord and after the surface of the water had quieted the cord was cut, allowing the body to fall, or slide freely. A sloping beach was located at one end of the channel which effectively absorbed the waves. However, waves were reflected from the opposite end of the channel in the tests involving the vertically falling body. The reflected waves arrived after the initial disturbance had completely passed the recording elements and so presented no problem; in fact, it gave an opportunity to illustrate the dispersive qualities of the phenomenon.

Results and Discussion.

Vertically Falling Body of Constant Size: The simplest case studied was that of a box falling freely in a vertical direction. The variables were water depth, initial depth of submergence, and the weight, in water, of the box. The results are presented in Table I.

In Figure 2 are shown examples of the surface time histories of the waves generated under conditions of constant water depth (1.50 feet and zero submergence (the top of the box barely under the water surface), but with varying weights of boxes. It can be seen that the initial disturbance was a crest, followed by a trough and then another crest. This was also true for all the experiments which were conducted. By the time the disturbance reached Station 2 (4.82 feet from the leading edge of the body) several waves had formed due to dispersion. In Figure 3 are shown examples of the surface time histories of the waves generated: (1) in water of constant depth, but with the initial submergence depth of the body varying, and (2) with zero initial submergence, but with varying water depths.

The most interesting characteristic of the waves is their consistent "period" (see Table I). At Station 1 the time interval between no disturbance and the first crest varied between 0.2 and 0.[illegible] seconds, with the average being 0.23 seconds. The time interval between the first and second crest varied between 0.45 and 1.0 seconds, with the average being 0.77 seconds. At Station 2 the time interval between no disturbance and the first crest varied between 0.4 and 0.75 with the average being 0.67 seconds, and the time interval between the first and second crests varied between 1.1 and 1.25 seconds, with the average being 1.18 seconds. Within the limits of accuracy of the measurements and within the range of experimental conditions, it appears that the period of the waves in independent of the water depth, the initial depth of submergence of the body and the weight of the body.

In Figure 4 are presented the relationships among body weight, water depth, submergence, and wave amplitude. It can be seen that the greater the body weight, the higher the wave amplitude for the same values of depth and of submergence. The effect of depth of submergence is just as apparent, with the greater the submergence the lower the wave amplitude, for the same values of body weight and water depth. However the relationship between water depth and wave amplitude is not entirely consistent. The effects of varying body weights and varying depths of submergence were large effects, whereas the effect of water depth was relatively small, within the range of experimental conditions. In addition, the surface of the water usually broke above the body as it started to fall from its position of initial zero submergence, whereas the water surface did not break for the 0.50 foot submergence. The amplitudes of the waves which reformed thus were dependent upon the amount of energy lost in breaking as well as upon the other conditions. By the time the waves had reached Station 2 the effect of breaking had nearly disappeared. It can be seen that the amplitude of the waves decreased with decreasing water depth for given values of initial submergence and body weight.

In Figure 5 are presented the relationships between amplitudes of the first crests and troughs and the second crests, at Stations 1 and 2. In addition, the correlation of the amplitude of the first trough at Station 1 with the amplitude of the first trough at Station 2 is shown. With the exception of the relationship between the amplitude of the first crest and the first trough at Station 1, there was apparently no effect of initial depth of submergence, and in no case was there an apparent effect of water depth or body weight.

In addition to the main body of tests, two additional runs were made. One was to determine the surface time history over the center of the falling body. It was found that at this point a trough occurred first, followed by a crest of approximately the same amplitude. Following the crest, the surface rapidly resumed its still-water position. This tended to confirm the expectations that the disturbance, as measured a short distance from the source, was caused by the bottom of the body pushing water out, and the water having to move in over the box as it falls. The second test was made with ends mounted on the body so that when the body rested on the bottom the ends extended up through the water surface. In this case an entirely different type of wave was generated, which consisted of a single crest followed by a single trough. This wave traveled as an entity down the channel and did not disperse into several waves as was the case of the main body of tests.

Vertically Falling Bodies of Different Lengths: In Figure 6a are shown the surface time histories of the waves passing Station 1 for body lengths of 0.6, 1.0, 2.0 and 3.0 feet. The net submerged body weight, the water depth, and the initial depth of submergence were approximately the same for all lengths. In Figure 6b are shown the relationships between body length and "period" between no disturbance and the first crest, and between the first and second crests, for Stations 1 and 2. Within the range of experimental conditions, the initial period changed but slightly with increasing body length, while the period measured between the first two crests increased considerably with increasing body length.

It is interesting to note that if the curve for T_1 in Figure 6 is extrapolated to a far greater degree than is prudent, one sees that a disturbance a few thousand feet in length would produce waves with an initial period of the order of from ten to fifteen minutes.

Body Sliding Down Inclines: In Figure 7a are shown examples of the surface time histories of the waves passing Station 1 which were generated by a body sliding down inclines with slopes from 24.2 to 90 degrees. In all cases the body size and weight, the water depth, and the initial depth of submergence were kept constant. The data on amplitude and period are shown in Figure 7b (see also Table II). It can be seen that the period is related to incline slope, with the smaller the slope the greater the period. The period between no disturbance and the first crest is not nearly as sensitive to slope as the period between the first two crests. The amplitudes of the initial crests and troughs are smallest for the flattest slopes, increasing rapidly with increasing slope for the flatter slopes and becoming asymptotic to some maximum value as the slope approaches the vertical. Also shown are the relationships between the ratio of the amplitude of the initial trough to the initial crest and the incline slope for Stations 1 and 2. Although there is considerable scatter, it is evident that the ratio of the amplitudes of the initial troughs to the initial crests increases with increasing steepness of the incline.

In Figure 8 are presented some data from the earlier series of tests, Series I (see Table III), on the effect of initial depth of submergence and net body weight on waves generated by the body sliding down an incline of 45 degrees in water 2.5 feet deep. The relationships between amplitudes of initial troughs, crests and second crests are more complex than was the case for the vertically falling body. This is understandable, considering the relationship between amplitudes at Stations 1 and 2 for the vertically falling bodies, i.e., the effect, due to dispersion, of travel distance. In these earlier tests, the wave recorders were mounted at fixed distances from the intersection of the still-water line and the incline. Hence, for the different initial depths of submergence, the distances changed (as measured from the edge of the body at the start of the slide to the wave recorders at Station A and B).

In Figure 9 are presented the correlations between the amplitudes of initial troughs and the initial and second crests, as well as the correlation between amplitudes of the initial troughs at Stations A and B.

The periods (Table III) were not as consistent as those of the vertically falling body; however, a plot on statistical paper showed the scatter about the mean values to be due to normal error.

The limiting case of a body sliding down an incline might be that of a hydrofoil moving with constant velocity. Studies of this problem by LAITONE (1954) have shown that a single wave is formed which remains above the hydrofoil.

Dispersion: The waves formed by the vertically falling and by the sliding bodies were not "long waves"; that is, their velocities were dependent upon wave length as well as upon water depth. These waves, once they had traveled a short distance from the origin of the disturbance, exhibited characteristics of the Cauchy-Poisson waves, UNOKI, S. and NAKANO, M. (1953). In order to show the effect of travel distance, the disturbance was allowed to travel the length of the wave channel, reflect, and travel back again. As can be seen in Figure 10a and Table IV, the initial disturbance dispersed into at least twenty-four recognizable waves, the periods of which progressively shortened from a maximum for the first wave to a minimum for the last wave.

The height of the body used in the deeper water precluded its use in shallower water. In order to study the phenomena in shallow water, a lead plate of nearly the same plan dimensions as the body used in Runs 4-10 (Series II), but only 3/16 inch thick was dropped vertically in water 0.36, 0.24 and 0.14 foot in depth. In Figure 10b are shown the experimental set-up and the surface time histories at four stations for an initial zero submergence in the three depths of water. The data from the tests are presented in Table V. It can be seen that the periods of waves remained constant for the three water depths at each station, but that they increased with increasing distance from the origin; hence, apparently dispersion was still present to some extent. However, the velocity of wave crest propagation compared very well with the theoretical velocity as given by the equation for "long waves" ($\sqrt{gd}$, where g is the gravitational constant and d is the water depth).

From an examination of the surface time histories and the phase velocity of the initial crests, it is thought that the first wave was one of the "Airy" type and that the following waves were dispersive. This seems to be especially true for the wave formed in the shallowest water (0.14 foot) as it can be seen to be deforming with increasing distance from the origin. This conforms with the prediction of URSELL (1953) as the parameter ($HL^2/2d^3$) is in the neighborhood of thirty and hence it is not possible for a solitary wave to exist.

<u>Dimensional Analysis:</u> In many studies of this nature it is valuable to utilize dimensional analysis to organize the variables into the smallest possible number of significant groups of parameters. Use of BUCKINGHAM's (1915) Π theorem is the usual means of obtaining this end. By use of this theorem, it is possible to group variables of m dimensional units into n-m dimensionless Π terms. Several different groupings can be obtained, depending upon which initial combination is chosen from which to develop the Π terms.

The variables in the problem of the vertically falling body are the water depth, d; wave period, T; wave height, H; body length, l; body height, h; depth of submergence, z (as measured from the still-water level to the top of the body); horizontal distance from the body edge to the point of wave measurement, x; water density, ρ_w; body density, ρ_b; viscosity, μ; and gravitational constant, g. Two sets of dimensionless parameters were developed. One set was developed using ρ_b, g and d, and the second set was developed using ρ_b, g and T as the primary variables. The two sets of Π terms are as follows:

A.

$$\Pi_1 = \sqrt{g/d}\ T$$
$$\Pi_2 = H/d$$
$$\Pi_3 = l/d$$
$$\Pi_4 = h/d$$
$$\Pi_5 = z/d$$
$$\Pi_6 = x/d$$
$$\Pi_7 = \rho_w / \rho_b$$
$$\Pi_8 = \mu / \rho_b d \sqrt{gd}$$

B.

$$\Pi_1 = d/gT^2$$
$$\Pi_2 = H/gT^2$$
$$\Pi_3 = l/gT^2$$
$$\Pi_4 = h/gT^2$$
$$\Pi_5 = z/gT^2$$
$$\Pi_6 = x/gT^2$$
$$\Pi_7 = \rho_w / \rho_b$$
$$\Pi_8 = \mu / \rho_b g^2 T^3$$

An analysis of this sort is particularly valuable if it is found that certain of the parameters are of little importance. For example, within the range of experimental conditions, it is probable that the parameter containing viscosity can be neglected. Various combinations of the dimensionless parameters were plotted to determine whether certain of the other parameters could be neglected. It was found that they could not. In addition, it is known that certain of the parameters are related in such a manner that it is not possible in all cases to hold all but one constant in order to determine the individual effects. For example, the parameter H/d depends upon $\sqrt{g/d}\ T$ as well as x/d.

The solution is even more complicated for the case of a body sliding down an incline.

Energy: Another approach, and one which proved more fruitful, was to consider the energy of the waves which were generated as compared with the initial potential energy (net, submerged) of the body. The potential energy (net, submerged) is the product of the net weight, submerged, of the body, and the water depth less the height of the body (0.6 inch).

An approximation of the energy contained in the waves was obtained, using the equation for the energy per wave length of a periodic train of waves of uniform small amplitude:

$$E = wLH^2/8 = gwH^2T^2/16\pi \qquad (1a)$$

where g is the gravitational constant, w is the unit weight of water, H is the wave height (as measured from trough to crest), L is the wave length, and T is the wave period. In the case of a disturbance of the sort being studied, this equation gives only an approximate answer. As the disturbance was found to be dispersive, it was most convenient to compute the energy from measurements close to the origin (Station 1) where the total energy was nearly concentrated in one wave. Thus the energy of the wave disturbance was considered to be given by:

$$E = gw\,(H_1+H_1')^2\,T_1^2/16\pi\,. \qquad (1b)$$

The results are shown in Figure 11, excepting the few results of very low energy (order of magnitude of less than 10^{-3} ft-lbs). It can be seen that the energy of the waves correlates rather well with the initial potential energy (net, submerged) of the body. Within the band of results, it can be seen that two general trends exist: 1) for water of constant depth, the less the initial submergence the greater the energy of the waves for a given initial potential energy of the body; 2) for constant initial depth of submergence, the smaller the water depth the greater the percentage of energy transformed into wave energy. In addition, it can be seen that the amount of energy of the wave disturbance is of the order of magnitude of one percent of the initial potential energy (net, submerged) of the vertically falling body.

Conclusions

In general it was found that, within the range of experimental conditions, dispersive waves were generated by a body either falling vertically or sliding down an incline. An exception was the case of a flat plate falling in quite shallow water (0.1 to 0.2 foot) in which an "Airy" type of wave was generated, together with dispersive waves forming the tail. Surface time histories of the disturbance measured a short distance from the source showed that a crest always formed first, followed by a trough from one to three times the amplitude of the first crest (depending upon the slope of the incline primarily), followed by a crest with about the same amplitude as the trough. Due to the dispersive qualities of the waves, additional crests and troughs continued to form with increasing distance from the origin, while at the same time the amplitudes of the initial crests and trough decreased.

The magnitudes of the amplitudes depended primarily upon the submerged weight of the body, but also upon the depth of submergence, the water depth and other characteristics of the generation.

The "period" associated with the gravity water waves of the disturbance was found to be independent of water depth, initial depth of submergence, weight of the body, or time of the fall. It was, however, found to be related to the length of the body, with the period increasing with increasing length, and to the slope of the incline, with the smaller the incline, the greater the period.

Computations of the approximate energy of the wave disturbance generated by the vertically falling body indicated that about one percent of the initial potential energy (net, submerged) of the body was transformed into wave energy. Within the band of results it was seen that for water of constant depth, the less the initial depth of submergence of the body, the greater the percentage of energy transformed into wave energy; and for constant initial depth of submergence, the samller the water depth the greater the percentage of energy transformed into wave energy.

When the body was modified by adding ends to it, an entirely different type of wave was generated. It did not appear to be dispersive, but rather consisted of a single crest followed by a single trough.

It is interesting to note that the curves showing the correlation between the length of the body and the initial period of the waves, when extrapolated considerably, indicate that an underwater disturbance of the order of a few thousand feet in length would generate waves with an initial period of the order of ten to fifteen minutes. Because of the great length of such a wave, it could travel a considerable distance without being affected greatly by its dispersive qualities, because it would be traveling a short distance as measured in wave lengths. In fact, it would have the general appearance of the Tsunamis observed in nature.

Acknowledgment

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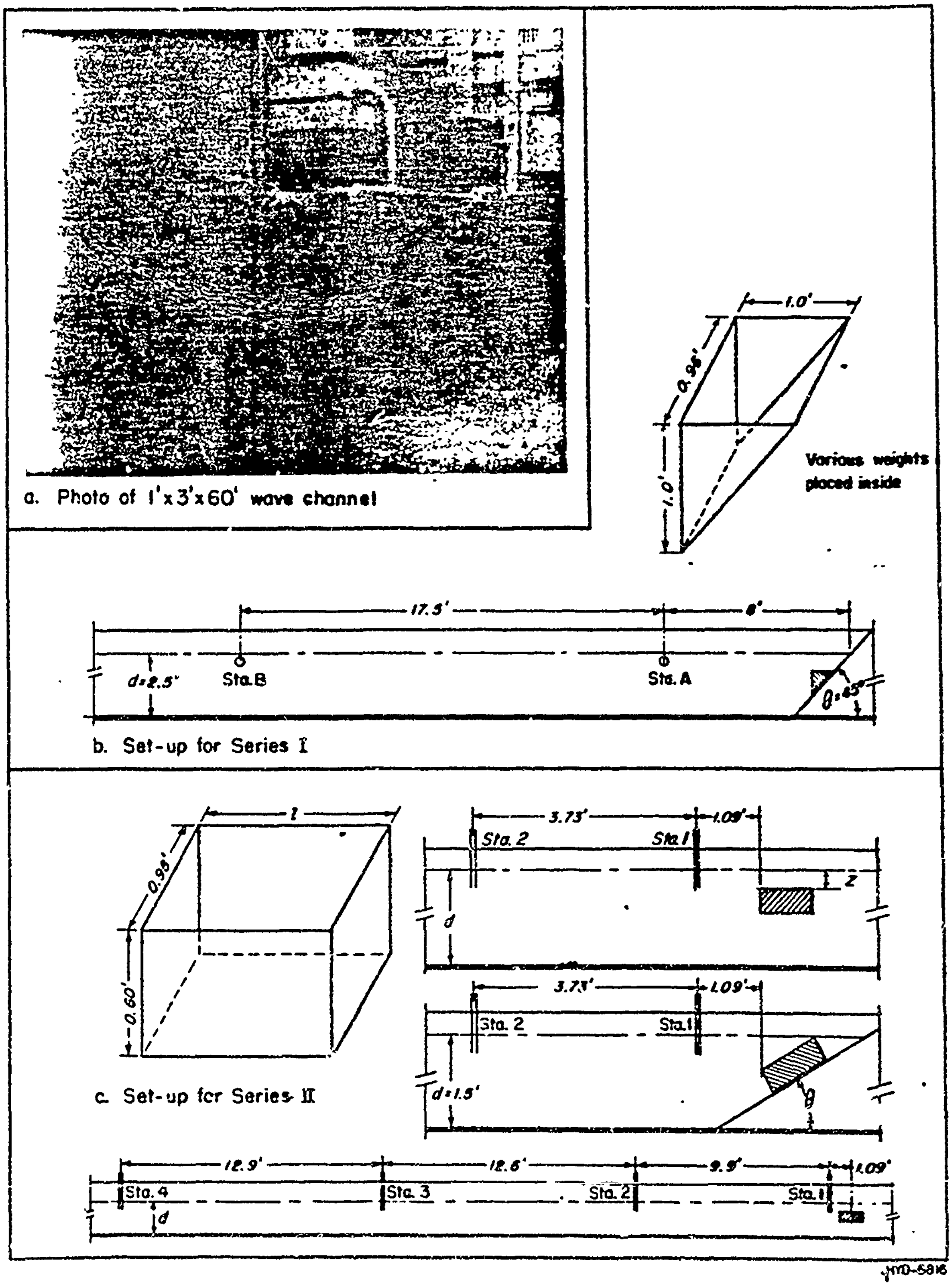
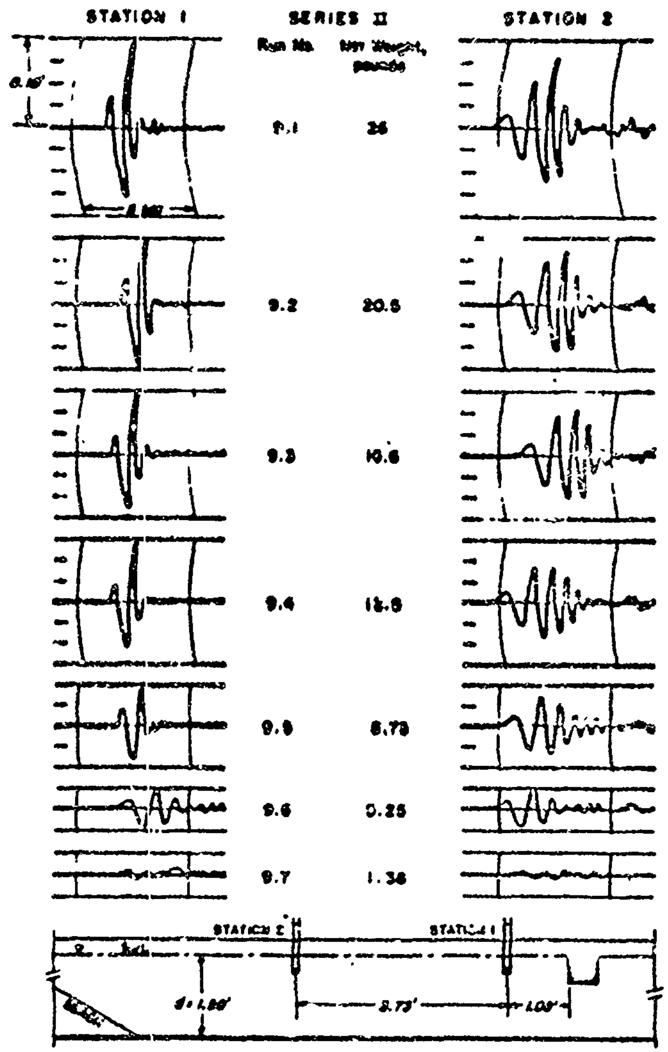


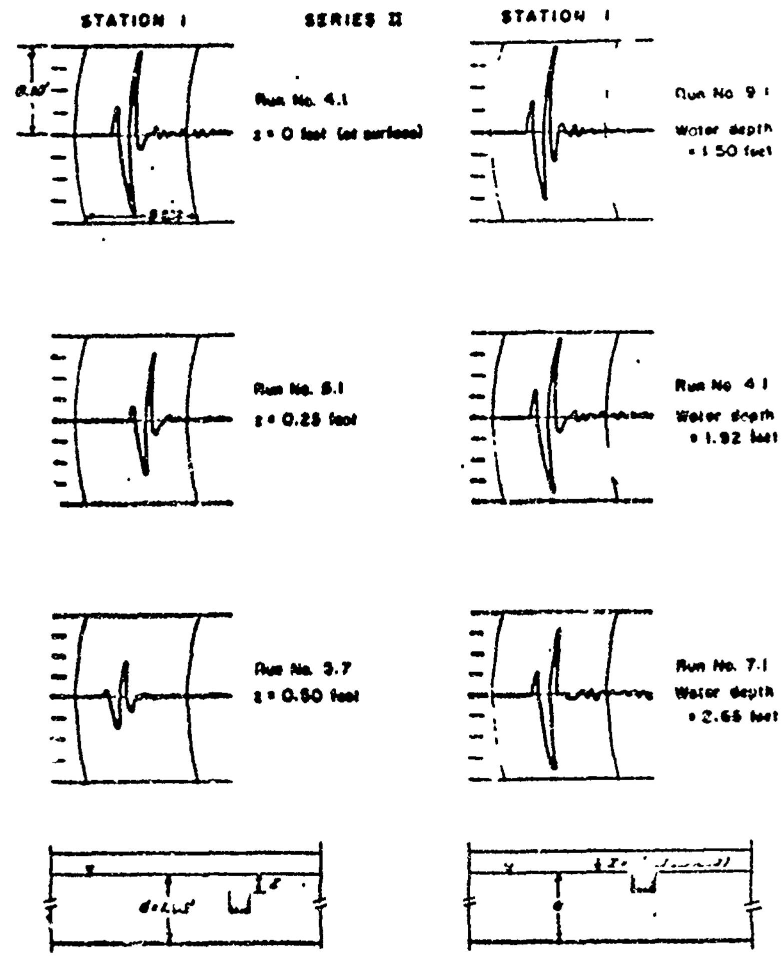
GENERAL LABORATORY SET-UP

FIGURE 1



SURFACE TIME HISTORIES FOR SEVEN DIFFERENT WEIGHTS FOR CONSTANT WATER DEPTH AND CONSTANT INITIAL SUBMERGENCE OF BODY

WES-6614 FIGURE 2



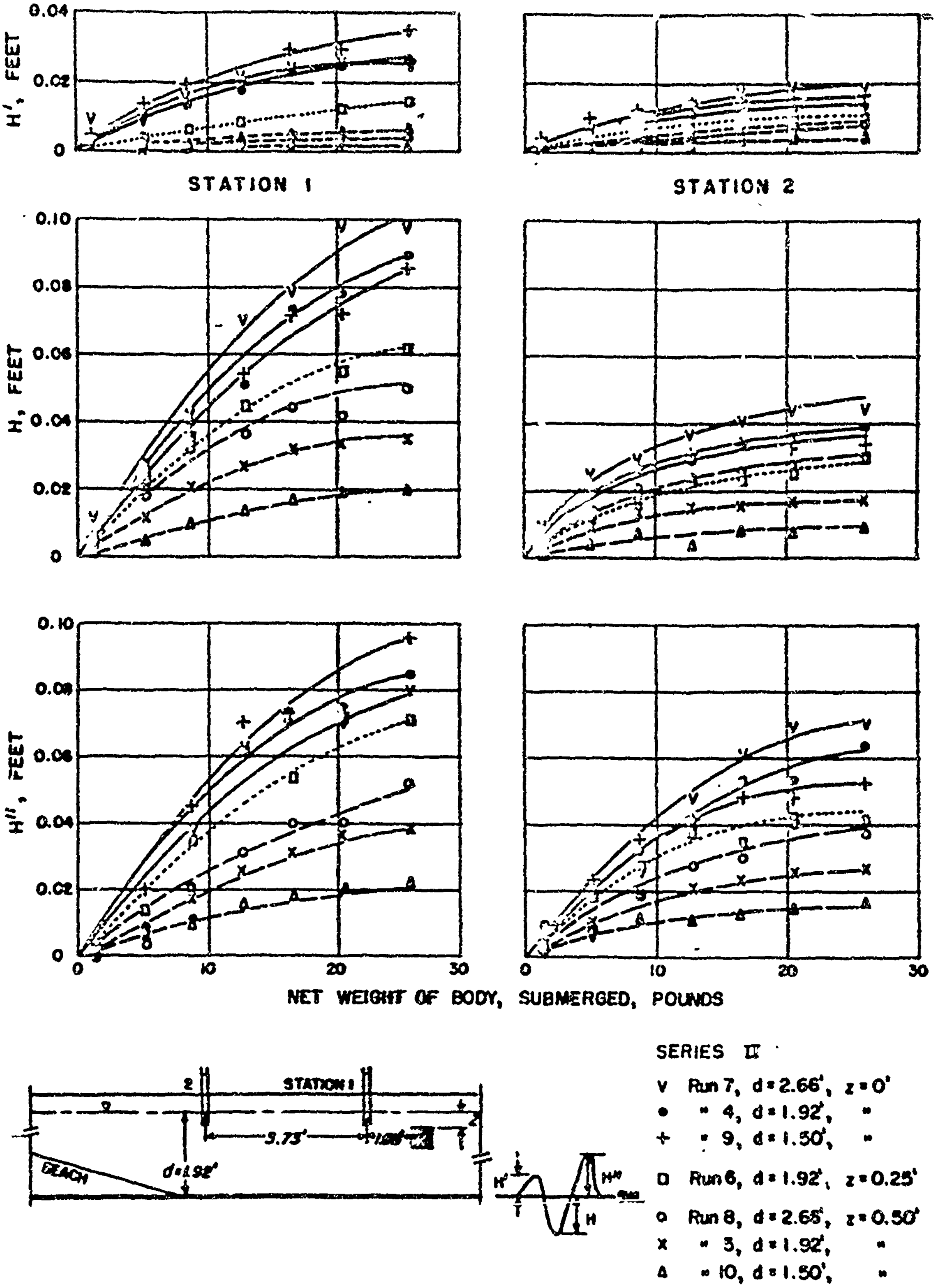
a. Effect of initial submergence of body in water of constant depth

b. Effect of water depth with initial submergence of body at water surface

EFFECT OF INITIAL SUBMERGENCE AND WATER DEPTH

WES-6616 FIGURE 3

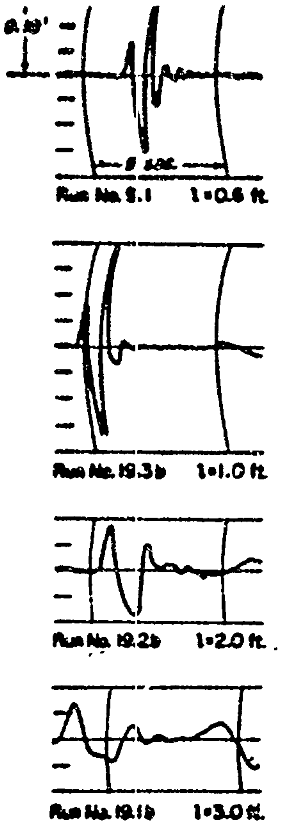
FIGURES 2 & 3



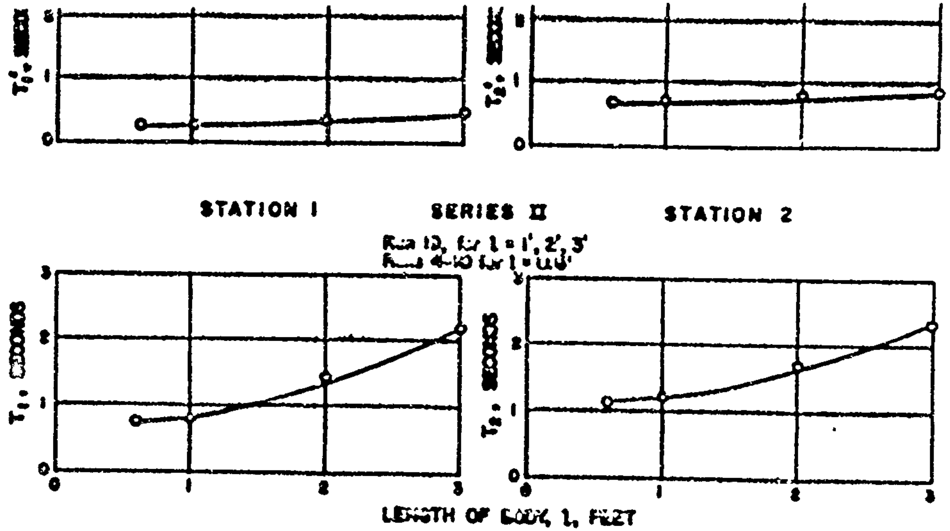
RELATIONSHIPS AMONG WATER DEPTH, SUBMERGENCE, AND AMPLITUDE OF INITIAL CREST AND TROUGH AND SECOND CREST, FOR VERTICALLY FALLING BODY

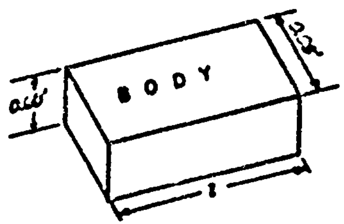
HYD-6817

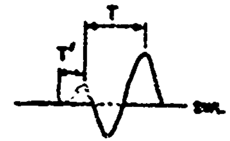
FIGURE 4

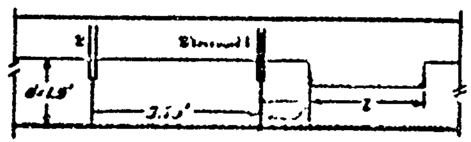


a. Effect of length of body on wave characteristics, constant water depth; net weight varied from 30 to 32 1/2 pounds; Series II.









l feet	T' seconds		T seconds	
	Sta. 1	Sta. 2	Sta. 1	Sta. 2
0.6	0.23	0.67	0.77	1.16
1.0	[illegible]	0.72	[illegible]	1.2
2.0	[illegible]	[illegible]	1.45	1.7
3.0	0.42	[illegible]	2.2	2.3

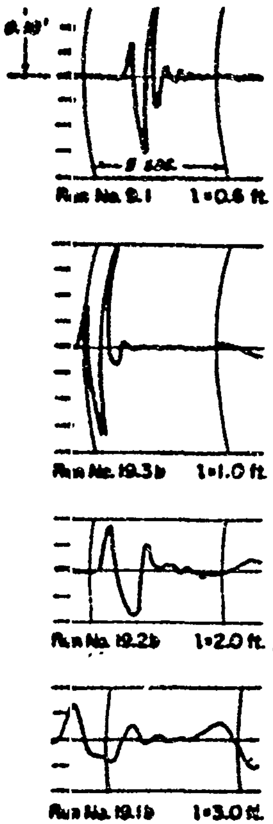
* d = 1.8' ** d = 1.43'

b. Relationship between length of vertically falling body and wave period.

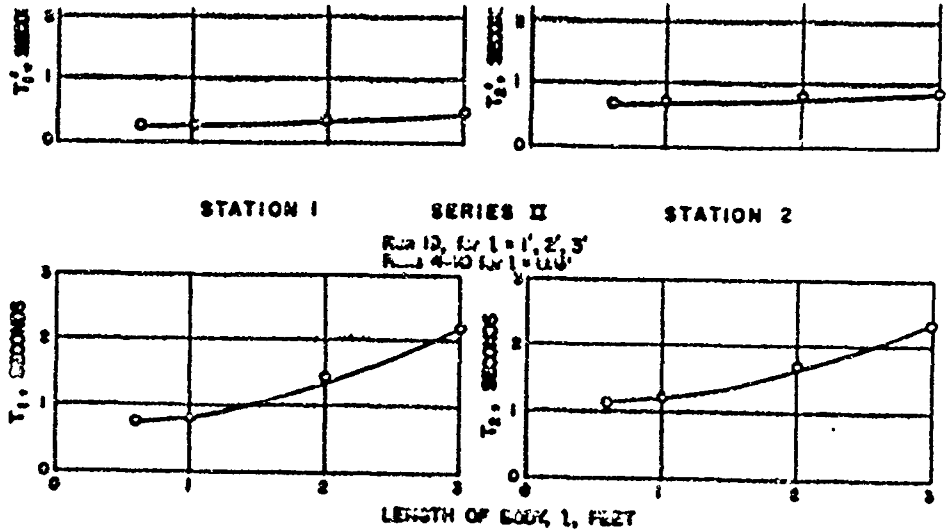
EFFECT OF BODY LENGTH

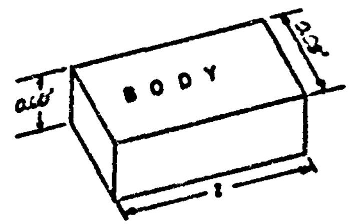
FIGURE 6

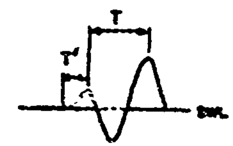
HYD-328

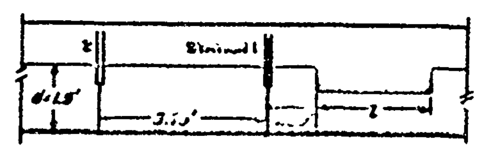


a. Effect of length of body on wave characteristics, constant water depth; net weight varied from 30 to 32 1/2 pounds; Series II.









l feet	T' seconds Sta. 1	T' seconds Sta. 2	T seconds Sta. 1	T seconds Sta. 2
0.6*	0.23	[illegible]	0.77	1.16
1.0**	[illegible]	0.72	[illegible]	1.2
2.0*	[illegible]	[illegible]	1.45	1.7
3.0**	0.42	[illegible]	2.2	2.3

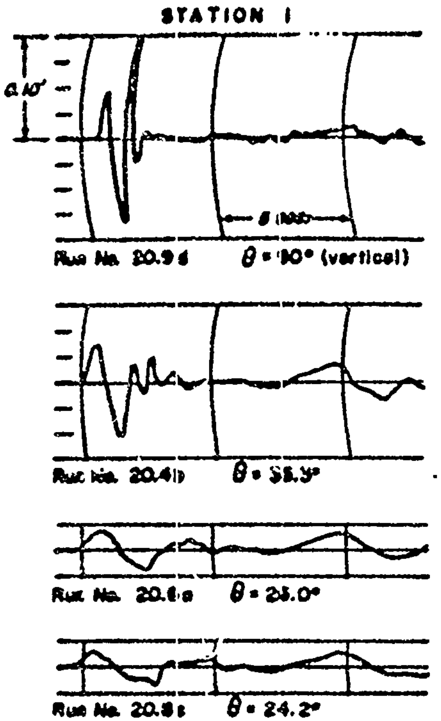
* d = 1.8' ** d = 1.43'

b. Relationship between length of vertically falling body and wave period.

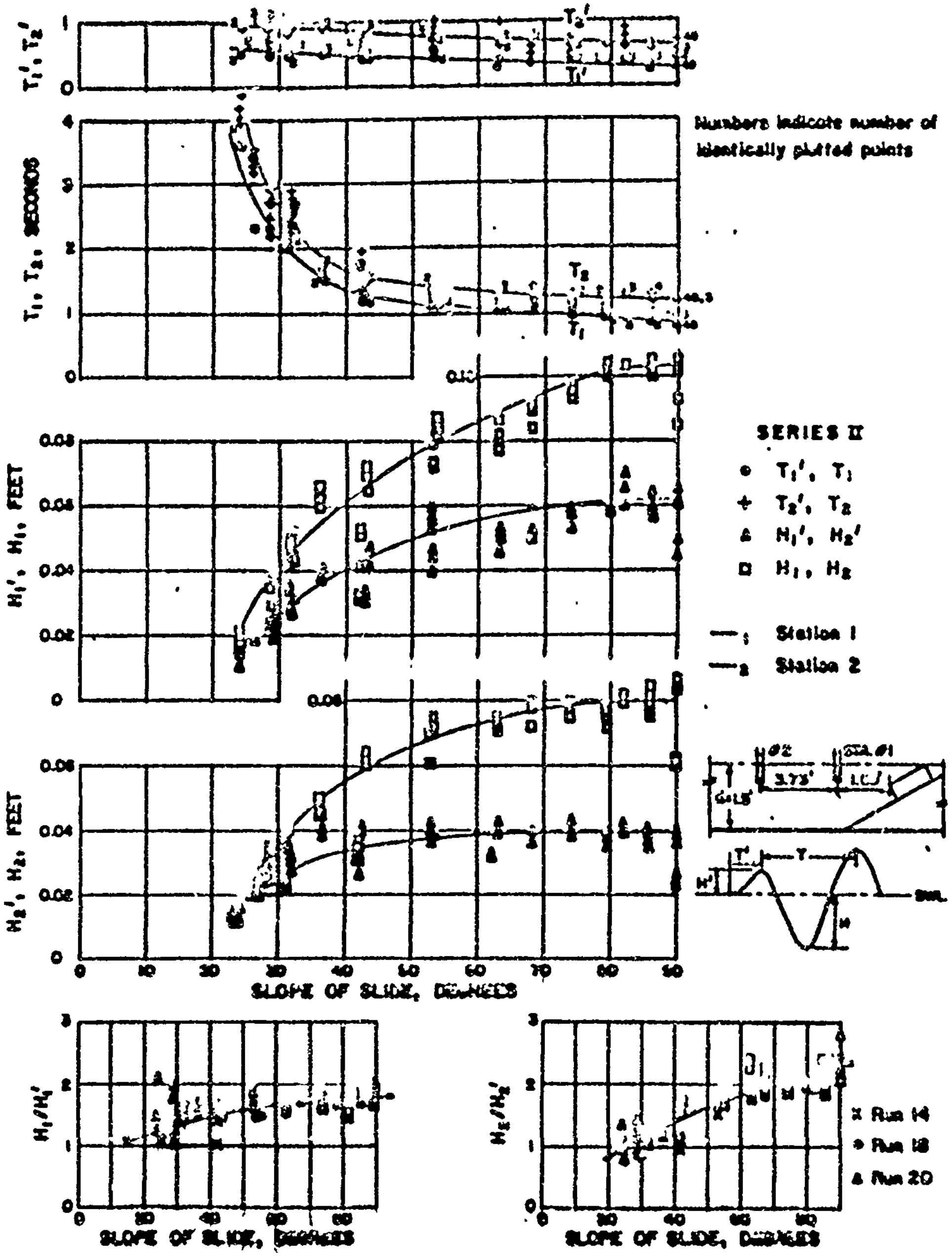
EFFECT OF BODY LENGTH

HYD-[illegible]

FIGURE 6



a. Effect of slope on wave characteristics, constant water depth and constant body dimensions; Series II.

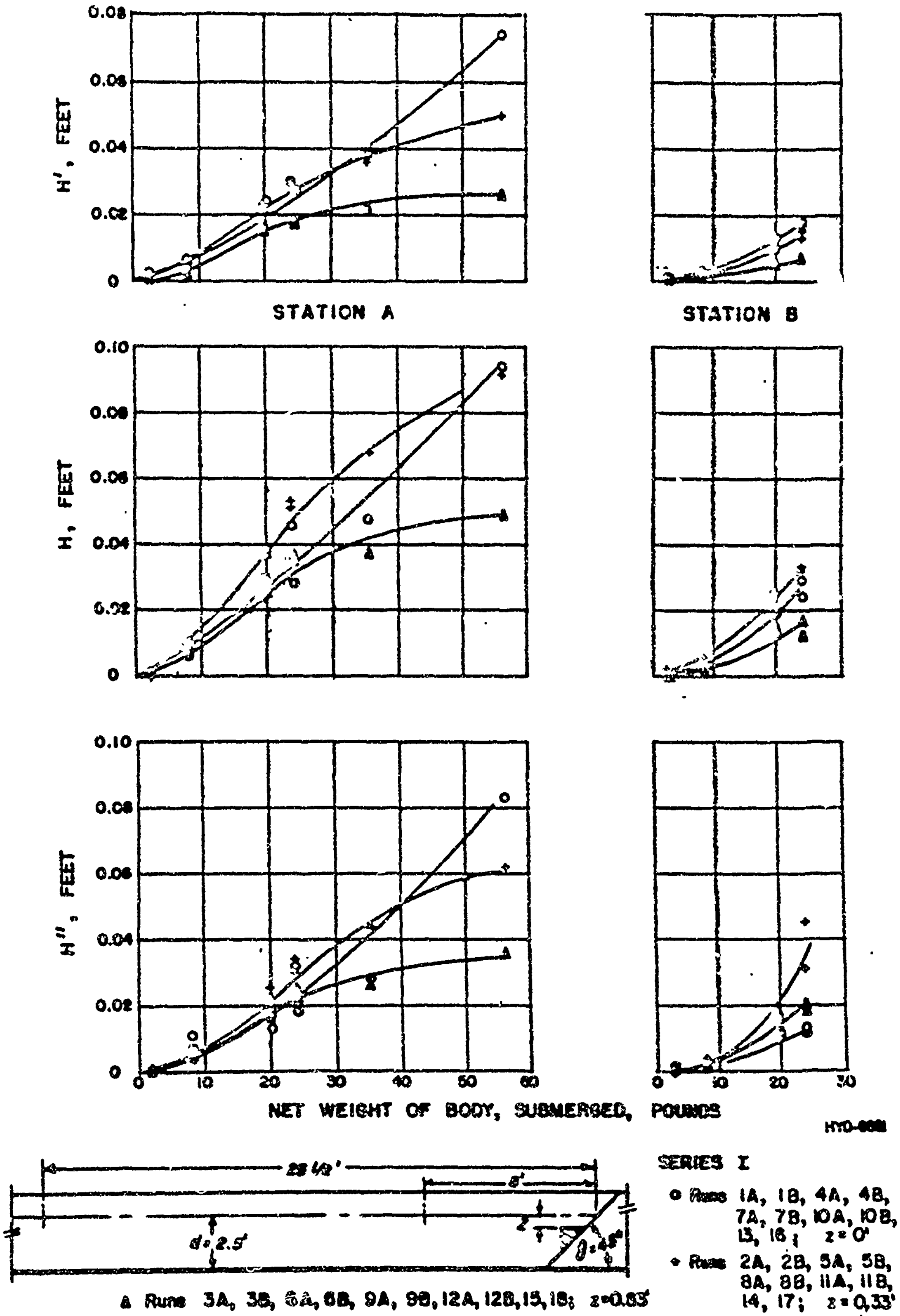


EFFECT OF INCLINE ANGLE

b. Relationships among slope of sliding body, period and amplitude of waves.

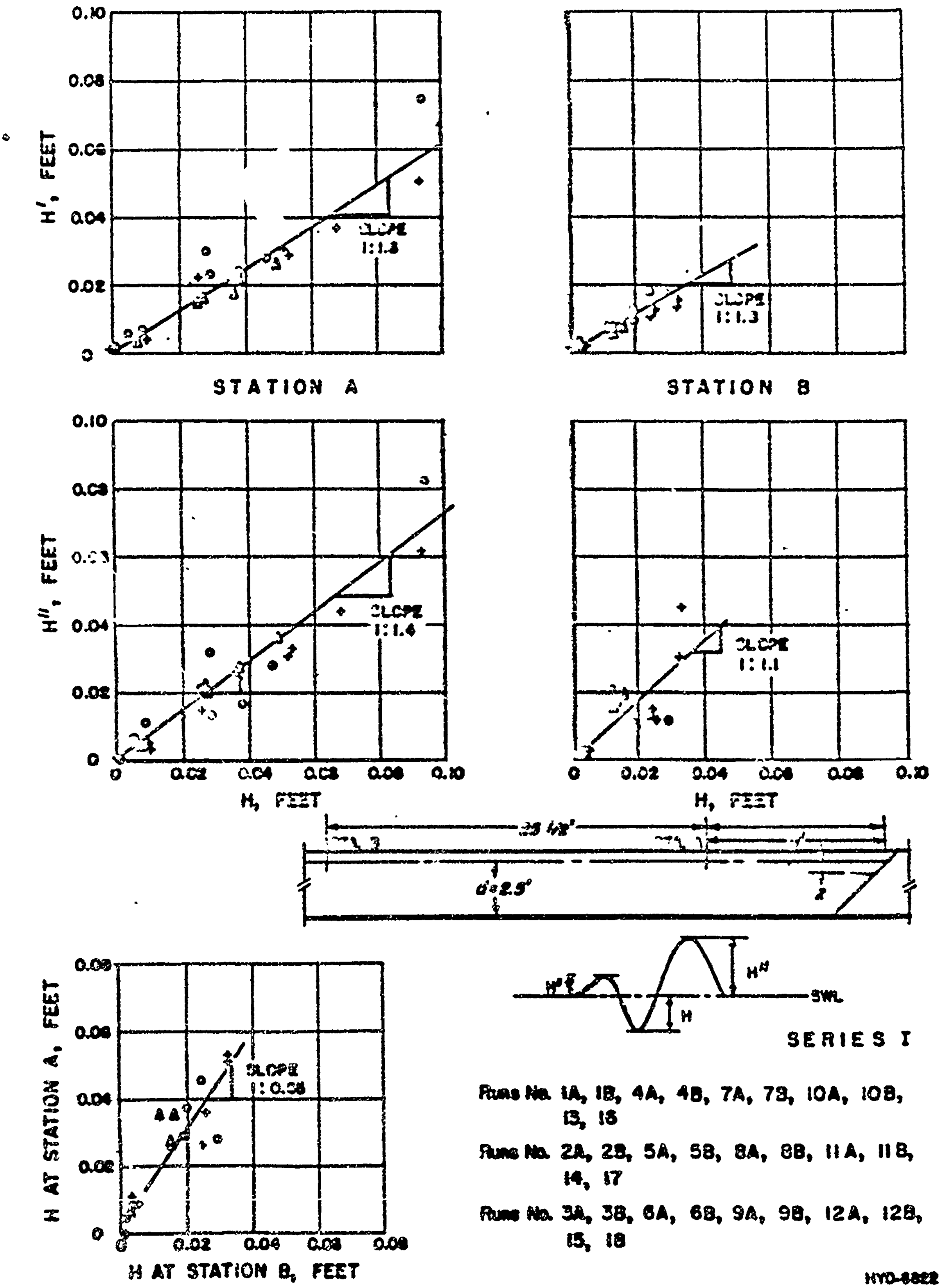
HYD-5420

FIGURE 7



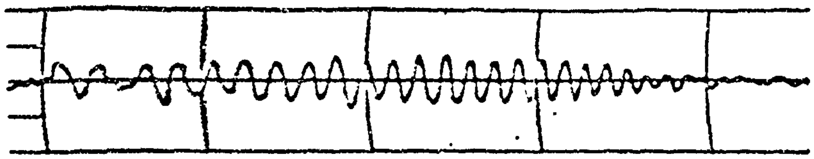
RELATIONSHIPS AMONG INITIAL ELEVATION OF BODY, WEIGHT OF BODY AND AMPLITUDE OF INITIAL CREST AND TROUGH, AND SECOND CREST

FIGURE 8

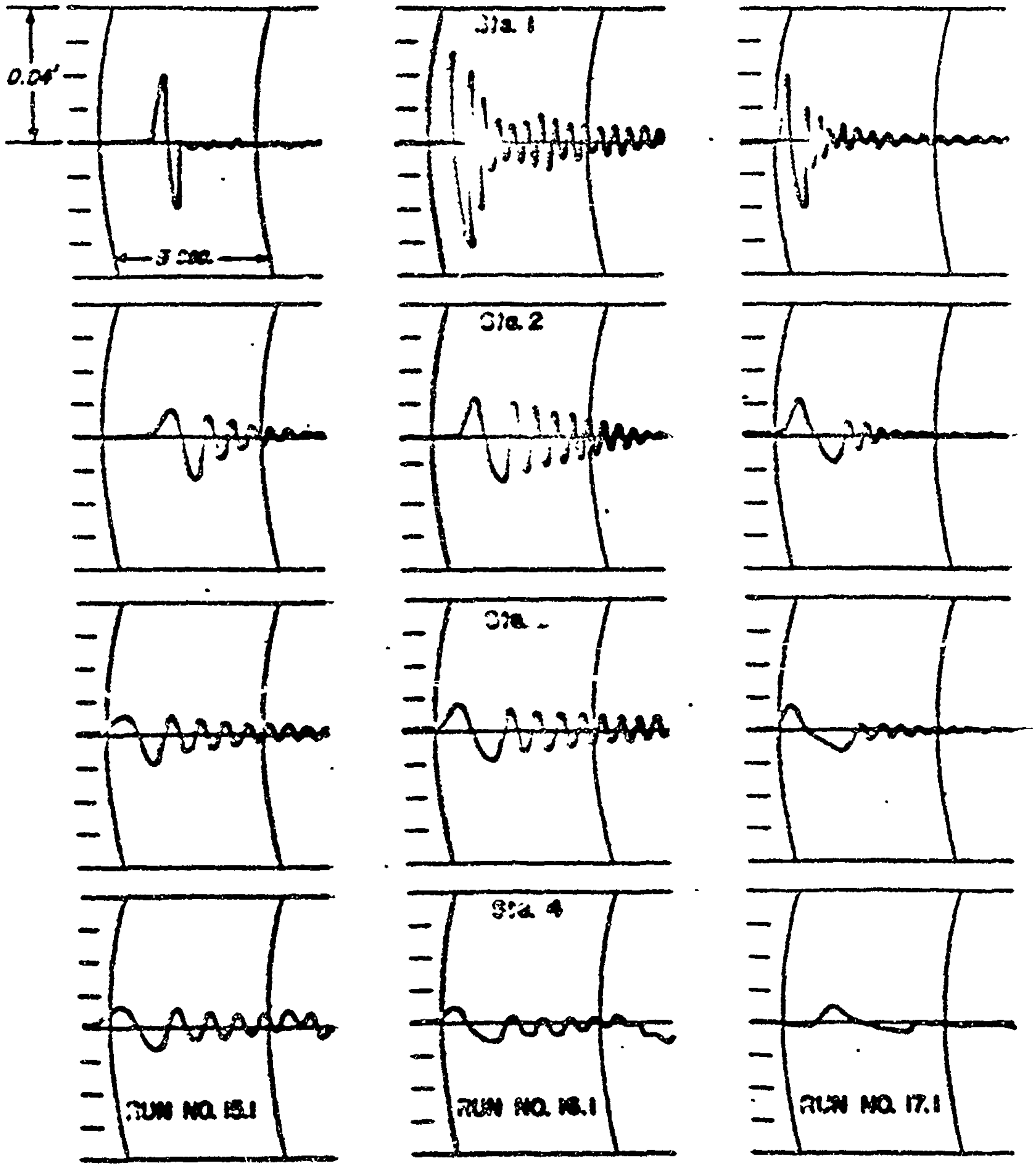


RELATIONSHIPS AMONG THE AMPLITUDE OF THE INITIAL CREST, TROUGH AND SECOND CREST FOR A BODY SLIDING DOWN A 1:1 SLOPE

FIGURE 9



a. Series II, Run 9.1; train of waves reflected from far end of channel

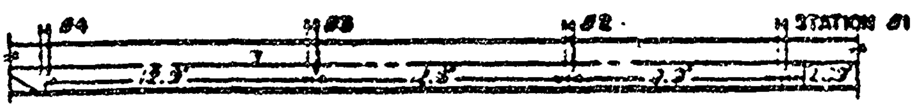


Water depth = 0.38 foot
z = 0'

Water depth = 0.24 foot
z = 0'

Water depth = 0.14 foot
z = 0'

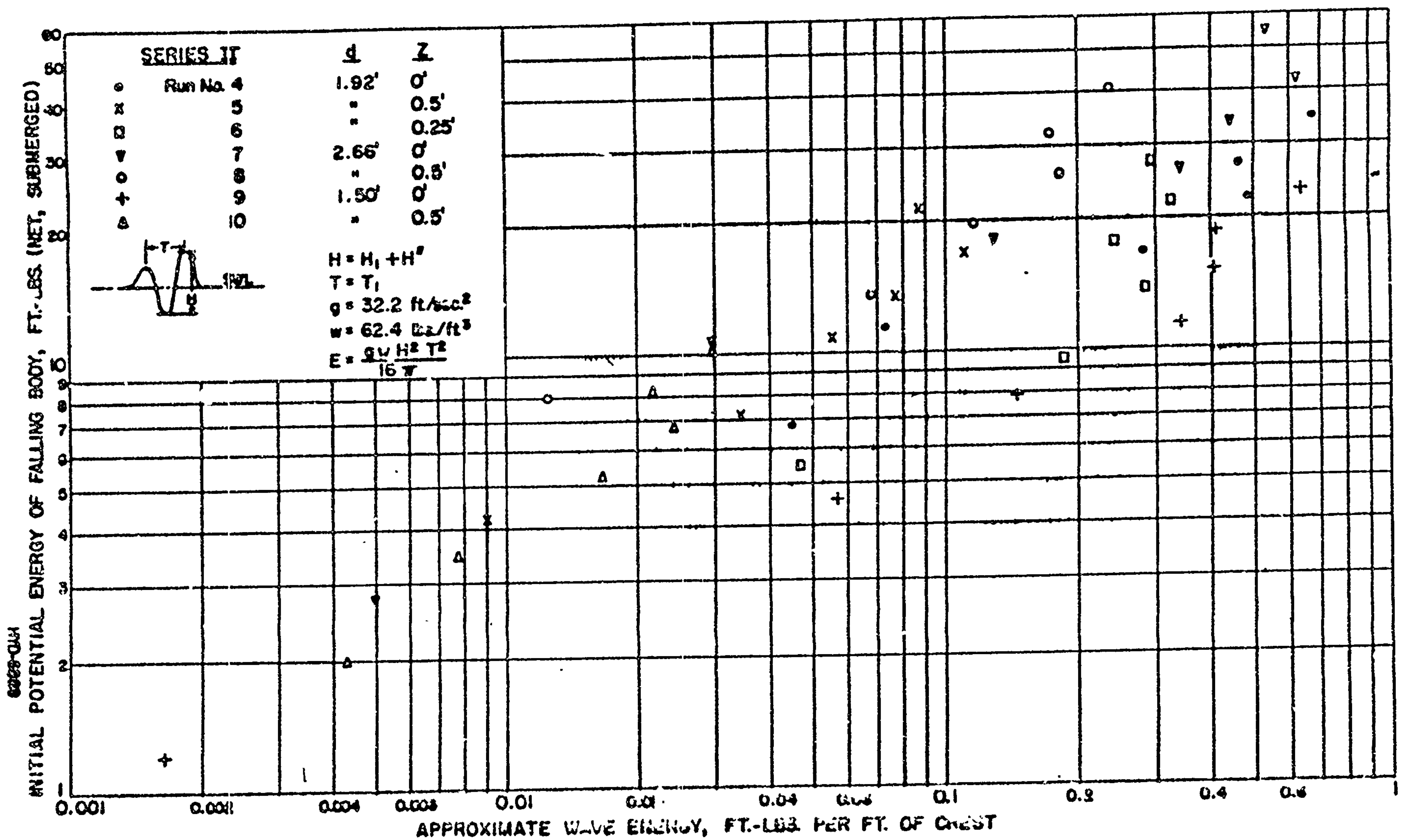
b. Series II; waves in water of various depths



HYD-0923

WAVE DISPERSION

FIGURE 10



RELATIONSHIP BETWEEN ENERGY OF WAVE DISTURBANCE
AND INITIAL POTENTIAL ENERGY (NET, SUBMERGED) OF A VERTICALLY FALLING BODY

FIGURE 11

TABLE I
BOX FALLING VERTICALLY
SERIES II

Run	d	s	W_{net}	$P.E._{net}$	Station No. 1					Station No. 2				
				ft	H_1'	H_1	$\bar{H}_1$	T_1'	T_1	H_2'	H_2	$\bar{H}_2$	T_2'	T_2
	ft.	ft.	lbs.	lbs.	ft.	ft.	ft.	sec.	sec.	ft.	ft.	ft.	sec.	sec.
II-4.1	1.92	0.0	26.	34.3	.027	.080	.085	.2	0.73	.013	.038	.034	.6	1.13
II-4.2	"	"	20.5	27.0	.026	.073	.073	.25	0.7	.012	.038	.034	.6	1.20
II-4.3	"	"	16.6	22.0	.024	.078	.071	.2	0.73	.012	.034	.034	.65	1.13
II-4.4	"	"	12.8	16.8	.018	.032	.030	.35	0.73	.012	.029	.041	.35	1.2
II-4.5	"	"	8.8	11.5	.014	.041	.012	.3	0.8	.009	.027	.032	.7	1.2
II-4.6	"	"	5.1	6.8	.011	.023	.009	.3	0.9	.007	.019	.017	.7	1.2
II-4.7	"	"	1.4	1.8	.0005	.004	trace	.3	0.45	.003	.002	.010	.4	1.2
II-5.1	1.92	0.5	1.4	1.1	trace	.002	.0005	-	0.7	.0005	.0005	trace	.7	1.13
II-5.2	"	"	5.1	4.2	.0005	.011	.004	.25	1.0	.003	.009	.010	.6	1.2
II-5.3	"	"	8.8	7.2	.001	.021	.013	.3	0.73	.004	.013	.019	.7	1.13
II-5.4	"	"	12.8	10.4	.002	.027	.026	.2	0.7	.005	.013	.021	.6	1.13
II-5.5	"	"	16.6	13.3	.002	.032	.031	.3	0.7	.006	.013	.024	.7	1.13
II-5.6	"	"	20.5	16.8	.002	.033	.037	.25	0.75	.006	.019	.026	.6	1.2
II-5.7	"	"	26.	21.3	.002	.034	.038	.2	0.83	.006	.017	.027	.3	1.1
II-6.1	1.92	0.25	26	27.3	.014	.062	.071	.2	.85	.010	.030	.041	.7	1.2
II-6.2	"	"	20.5	22.0	.012	.055	.075	.2	.7	.010	.025	.042	.65	1.2
II-6.3	"	"	16.6	17.8	.004	.044	.034	.3	.8	.008	.025	.036	.7	1.2
II-6.4	"	"	12.8	13.6	.008	.045	.031	.2	.8	.003	.023	.038	.6	1.2
II-6.5	"	"	8.8	9.4	.006	.036	.035	.2	.7	.008	.018	.023	.7	1.2
II-6.6	"	"	5.1	5.5	.004	.022	.014	.2	.95	.006	.014	.018	.7	1.2
II-6.7	"	"	1.4	1.5	.0005	.004	trace	.2	.9	.001	.0005	.002	.7	1.2
II-7.1	2.66	0.0	26.	53.6	.026	.098	.080	.2	.65	.018	.044	.070	.6	1.25
II-7.2	"	"	20.5	42.3	.025	.098	.070	.25	.7	.019	.044	.070	.7	1.25
II-7.3	"	"	16.6	34.2	.024	.078	.072	.25	.7	.017	.041	.061	.65	1.25
II-7.4	"	"	12.8	26.3	.022	.071	.061	.25	.7	.013	.037	.048	.7	1.25
II-7.5	"	"	8.8	13.0	.018	.042	.039	.25	.7	.003	.023	.027	.7	1.23
II-7.6	"	"	5.1	10.8	.009	.024	.006	.25	.9	.005	.015	.008	.7	1.25
II-7.7	"	"	1.4	2.8	.009	.012	.002	.25	.8	.003	.010	.008	.7	1.13
II-8.1	2.66	0.5	1.4	2.1	trace	.004	trace	-	.85	.0005	.002	trace	.7	1.15
II-8.2	"	"	5.1	8.0	.0005	.018	.004	.2	.8	.004	.013	[illegible]	[illegible]	1.2
II-8.3	"	"	8.8	13.6	.00[illegible]	.032	.020	.2	.8	.005	.021	.019	.7	1.25
II-8.4	"	"	12.8	19.9	.002	.036	.031	.2	.8	.006	.023	.028	.7	1.25
II-8.5	"	"	16.6	25.9	.002	.044	.040	.2	.8	.006	.026	.030	.7	1.25
II-8.6	"	"	20.5	32.0	.003	.042	.040	.2	.8	.008	.028	.041	.7	1.25
II-8.7	"	"	26.	40.5	.004	.050	.052	.2	.75	.008	.030	.037	.6	1.25
II-9.1	1.50	0.0	26.	23.4	.035	.086	.095	.2	.7	.015	.035	.052	.7	1.2
II-9.2	"	"	20.5	18.5	.029	.072	.073	.2	.7	.015	.033	.048	.7	1.1
II-9.3	"	"	16.6	15.0	.029	.072	.073	.2	.7	.015	.033	.048	.7	1.15
II-9.4	"	"	12.8	11.5	.020	.054	.070	.25	.75	.013	.030	.041	.7	1.15
II-9.5	"	"	8.8	7.9	.019	.036	.045	.2	.75	.012	.027	.036	.7	1.2
II-9.6	"	"	5.1	4.6	.011	.027	.020	.25	.8	.010	.020	.023	.75	1.15
II-9.7	"	"	1.4	1.2	.004	.006	.002	.25	.8	.003	.005	.008	.7	1.2
II-10.1	1.50	0.5	1.4	.6	trace	.0005	.002	.2	.8	trace	.0005	.003	.7	1.2
II-10.2	"	"	5.1	2.0	.001	.005	.008	.2	.8	.0005	.004	.008	.7	1.1
II-10.3	"	"	8.8	3.5	.002	.010	.010	.2	.7	.002	.007	.011	.7	1.2
II-10.4	"	"	12.8	5.1	.003	.015	.016	.2	.7	.002	.003	.011	.7	1.2
II-10.5	"	"	16.6	6.7	.004	.017	.018	.2	.7	.003	.006	.013	.6	1.2
II-10.6	"	"	20.5	8.2	.005	.019	.020	.2	.8	.004	.007	.015	.7	1.1
II-10.7	"	"	26.	10.3	.005	.020	.022	.2	.65	.004	.009	.017	.7	1.15

TABLE II

BODY SLIDING DOWN SLOPES OF VARIOUS ANGLES

SERIES II.

Run	Grade	Angle deg.	T_1' sec.	T_2' sec.	T_1 sec.	T_2 sec.	H_1' ft.	H_2' ft.	H_1 ft.	H_2 ft.	H_1/H_1'	H_2/H_2'
14.1*	1:1.59	32.1	—	—	—	—	—	—	—	—	—	—
14.2a	1:1.00	42.1	.4	.75	1.4	1.33	.033	.032	.051	.038	1.54	1.19
.2b	"	"	.5	.7	1.4	1.33	.032	.035	.053	.035	1.65	1.00
.2c*	"	"	—	—	—	—	—	—	—	—	—	—
.2d	"	"	.5	.6	1.5	1.33	.030	.028	.042	.031	1.40	1.19
.2e	"	"	.5	.7	1.73	1.35	.032	.028	.032	.028	1.00	1.00
14.3a	1:075	53.1	.43	.8	1.1	1.33	.048	.042	.080	.070	1.74	1.57
.3b	"	"	"	.7	1.25	1.4	.039	.038	.073	.081	1.87	1.70
.3c	"	"	"	.7	1.2	1.4	.044	.040	.072	.080	1.33	1.30
13.1*	1:2.08	25.7	—	—	—	—	—	—	—	—	—	—
13.2a	1:1.30	32.0	.8	.9	2.83	2.7	.027	.030	.044	.037	1.35	1.23
.2b	"	"	.6	.9	2.5	2.8	.031	.031	.043	.037	1.39	1.20
.2c	"	"	.53	1.0	2.5	2.9	.027	.027	.044	.037	1.33	1.37
13.3a	1:1.08	42.8	.53	.9	1.35	1.3	.041	.038	.084	.080	1.38	1.71
.3b	"	"	.5	.9	1.33	1.33	.047	.040	.070	.082	1.49	1.35
.3c	"	"	.4	.9	1.33	1.3	.047	.040	.072	.064	1.34	1.30
13.4a	1:0.74	53.5	.3	.9	1.23	1.3	.055	.040	.082	.070	1.43	1.75
.4b	"	"	.33	.85	1.2	1.4	.053	.039	.087	.075	1.38	1.72
.4c	"	"	.33	1.0	1.1	1.3	.052	.040	.086	.072	1.35	1.30
.4d	"	"	.33	.9	1.2	1.25	.059	.041	.084	.070	1.43	1.71
20.1*	1:2.40	22.7	—	—	—	—	—	—	—	—	—	—
20.2a	1:1.33	23.7	.3	1.0	2.7	2.9	.022	.023	.024	.025	1.08	0.39
.2b	"	"	.7	1.0	2.3	2.9	.024	.023	.029	.023	1.21	0.38
.2c	"	"	.3	1.0	2.3	2.7	.020	.023	.039	.033	1.95	1.27
20.3	1:1.23	23.7	.5	.9	2.3	2.2	.019	.024	.034	.035	1.79	1.45
20.4a	1:1.37	36.3	.5	.9	1.6	1.7	.040	.040	.066	.050	1.65	1.25
.4b	"	"	.5	.9	1.8	1.7	.038	.038	.060	.046	1.58	1.21
.4c	"	"	.5	.9	1.5	1.7	.039	.040	.062	.046	1.39	1.15
20.5a	1:1.64	31.5	.5	.8	2.1	2.1	.035	.033	.049	.040	1.40	1.21
.5b	"	"	.5	.9	2.1	2.2	.033	.034	.048	.034	1.45	1.00
.5c	"	"	—	—	2.0	2.1	.032	.032	.048	.033	1.50	1.03
20.6a	1:2.06	25.9	.6	1.0	2.3	3.3	.018	.020	.021	.020	1.17	1.00
.6b	"	"	.6	1.0	3.4	3.5	.020	.020	.021	.021	1.05	1.05
.6c	"	"	—	1.0	—	3.2	—	.020	—	.020	—	1.00
20.7 *	1:2.44	22.3	—	—	—	—	—	—	—	—	—	—
20.8a	1:2.24	24.2	.5	.9	4.0	4.4	.010	.012	.021	.016	2.10	1.33
.8b*	"	"	—	—	—	—	—	—	—	—	—	—
.8c	"	"	.5	.8	3.6	4.0	.014	.015	.020	.015	1.43	0.94
.8d	"	"	.5	—	4.0	4.2	.014	.016	.017	.012	1.22	0.75
20.9a	1:0	90.0	.3	.7	.9	1.13	.044	.022	.085	.061	1.93	2.78
.9b*	"	"	—	—	—	—	—	—	—	—	—	—
.9c	"	"	—	.7	—	1.15	—	.025	—	.060	—	2.40
.9d	"	"	.25	.7	.85	1.2	.048	.026	.093	.062	1.94	2.38

* Run was no good as the body stuck for a short time during slide

Note: Water depth varied from 1.43 feet to 1.50 feet. -

TABLE III

BODY SLIDING DOWN A SLOPE OF 1:1

Series I

Run	d ft.	z ft.	W_{net} lbs.	$P.E._{net}$ ft/lbs.	t sec	V ft/sec	Station A H'_A ft.	H_A ft.	H''_A ft.	T'_A sec.	T_A sec.	Station B H'_B ft.	H_B ft.	H''_B ft.	T'_B sec.	T_B sec.
I-1A	2.5	0.00	2.3	3.5	7.6	0.20	.001	.0005	trace	1.1	1.3	.001	trace	.001*	1.2	1.8*
I-1B	"	"	"	"	7.7	.20	.002	.0005	"	0.8	1.3	.001	"	trace	"	1.8*
I-2A	"	0.33	"	2.7	4.7	.25	.001	trace	.0005*	1.0	2.0*	.0005	"	.0005	1.0	1.5*
I-2B	"	"	"	"	4.9	.24	.001	"	"	1.2	1.7*	.0005	"	.0005*	1.0	1.6*
I-3A	"	0.83	"	1.5	3.1	.22	.0005	"	trace	0.9	0.9*	.0005	"	.010*	0.8*	1.1*
I-3B	"	"	"	"	3.3	.20	.0005	"	"	1.0*	1.7*	.0005	"	trace	1.2*	1.8*
I-4A	"	0.00	8.1	12.1	4.1	.37	.007	.009	.011	1.1	1.5	.003	.003	.003	1.2	2.0
I-4B	"	"	"	"	4.1	.37	.003	.005	.007	1.0	1.6	.003	.002	.002	1.1	1.9
I-5A	"	0.33	"	9.5	3.1	.38	.004	.010*	.005*	1.2	2.1*	.002	.005*	.003*	1.2	3.1*
I-5B	"	"	"	"	2.9	.40	.004	.010*	.004*	1.2	2.1*	.002	.004*	.002*	1.2	3.1*
I-6A	"	0.83	"	5.4	2.1	.32	.003	.007	.004*	1.0	2.3*	.002	.003	.001*	1.2	2.6*
I-6B	"	"	"	"	2.1	.32	.003	.007	.004*	1.2	2.0*	.002	.003	.001*	1.1	3.8*
I-7A	"	0.00	20.0	30.0	2.1	.72	.023	.029*	.013*	1.0	2.8*	.013	.019*	.011*	1.2	3.5*
I-7B	"	"	"	"	2.3	.65	.024	.038*	.017*	1.1	2.8*	.009	.020*	.010*	1.4	3.5*
I-8A	"	0.33	"	25.1	1.5	.70	.022	.026	.015	1.1	2.1	.011	.025	.015	1.2	2.5
I-8B	"	"	"	"	1.5	.73	.022	.036	.025	1.0	2.1	.012	.028	.012	1.2	2.3
I-9A	"	0.83	"	13.4	1.1	.61	.018	.027	.020	1.0	1.8	.007	.013	.017	1.2	2.1
I-9B	"	"	"	"	1.1	.61	.015	.026	.022	1.0	1.9	.005	.013	.018	1.2	2.2*
I-10A	"	0.00	23.9	35.8	1.4	.79	.030	.028	.032*	1.2	2.6*	.018	.029*	.012*	1.2	2.7*
I-10B	"	"	"	"	2.1	.72	.028	.048	.018*	1.0	2.3*	.018	.024*	.013*	1.2	2.8*
I-11A	"	0.33	"	28.0	1.5	.78	.030	.052	.031	1.0	1.9	.014	.035	.031	1.2	2.4
I-11B	"	"	"	"	1.5	.78	.029	.063	.033	0.9	1.9	.015	.033	.046	1.2	2.3
I-12A	"	0.83	"	16.0	1.1	.61	.018	.036	.021	0.8	1.8	.007	.016	.019	1.2	2.2
I-12B	"	"	"	"	0.9	.75	.018	.033	.024	0.8	1.8	.007	.012	.020	1.1	1.9
I-13	"	0.00	35.3	53.2	1.3	.84	.038	.047	.028	1.1	1.7					
I-14	"	0.33	"	41.2	1.2	.97	.037	.038	.044	1.1	1.6					
I-15	"	0.83	"	23.8	0.8	.84	.028	.037	.027	1.0	1.7					
I-16	"	0.00	56.6	85.0	1.2	1.30	.075	.094	.083	1.1	1.8					
I-17	"	0.33	"	66.2	0.8	1.47	.050	.093	.062	1.1	1.7					
I-18	"	0.83	"	58.0	0.6	1.12	.026	.049	.038	1.0	1.5					

* Uncertain due to reflection from far end of channel.

TABLE IV
EFFECT OF DISPERSION

Series II, Run 9.1 Period of Train of Waves

Between crests	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13
Period T sec.	1.3	1.35	1.0	1.1	.95	.95	.95	.75	.80	.75	.70	.70

Between crests	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
Period T sec.	.75	.70	.65	.65	.60	.60	.60	.55	.55	.55	.55

TABLE V
EFFECT OF DISPERSION
Series II

Run	d ft.	s ft.	W_{net} lbs.	P.E.$_{net}$ ft. lbs.	between stations	Velocity of Disturbance Δx ft.	Δt sec.	C_x ft/sec	C_t ft/sec
II-15.1	0.36	0.0	3.5	1.3	1-2	9.87	3.2	3.1	3.4
	"	"	"	"	1-3	22.53	6.7	3.35	"
	"	"	"	"	1-4	35.40	10.5	3.0	"
II-15.2	"	0.14	"	0.8	1-2	9.87	3.2	3.1	"
	"	"	"	"	1-3	22.53	7.0	3.2	"
	"	"	"	"	1-4	35.40	10.7	3.2	"
II-15.3	"	0.29	"	0.25	1-2	9.87	3.1	3.2	"
	"	"	"	"	1-3	22.53	6.7	3.35	"
II-16.1	0.24	0.0	"	0.9	1-2	9.87	3.7	2.7	2.7
	"	"	"	"	1-3	22.53	8.2	2.75	"
	"	"	"	"	1-4	35.40	13.1	2.6	"
II-16.2	"	0.14	"	0.25	-	-	-	-	-
II-17.1	0.14	0.0	"	0.5	1-2	9.87	4.6	2.15	2.1
	"	"	"	"	1-3	22.53	11.3	2.0	"
	"	"	"	"	1-4	35.40	17.6	1.95	"
II-17.2	"	0.07	"	0.25	3-4	12.87	6.3	2.05	"

Run	T'_1	T'_2	T'_3	T'_4	T_1	T_2	T_3	T_4
15.1	0.4	0.7	0.8	0.9	0.6	1.15	1.5	1.7
15.2	0.3	0.7	0.9	0.8	0.7	1.1	1.55	1.7
15.3	-	-	-	-	-	-	-	-
16.1	0.3	0.7	0.7	0.6	0.7	1.2	1.6	1.7
16.2	0.3	trace	trace	trace	0.6	1.1	1.4	trace
17.1	0.25	0.7	0.5	0.6	0.7	1.3	2.1	trace
17.2	-	-	-	-	-	-	-	-
Ave.	0.31	0.7	0.73	0.75	0.66	1.17	1.63	1.7

Run	H'_1	H'_2	H'_3	H'_4	H_1	H_2	H_3	H_4	H''_1	H''_2	H''_3	H''_4
15.1	.019	.008	.008	.008	.019	.012	.018	.008	.0005	.006	.008	.008
15.2	.013	.005	.004	.002	.015	.010	.007	.004	.002	.005	.004	.004
15.3	-	-	-	-	-	-	-	-	-	-	-	-
16.1	.026	.012	.006	.004	.031	.014	.008	.006	.021	.011	.006	.002
16.2	.003	trace	trace	trace	.011	.004	.004	.002	.008	.002	.002	.002
17.1	.019	.010	.006	"	.019	.008	.007	trace	.010	.005	.002	trace
17.2	-	-	-	-	-	-	-	-	-	-	-	-

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