CHAPTER 20

FIELD OBSERVATIONS OF WAVE PRESSURE, WAVE RUN-UP, AND OSCILLATION OF BREAKWATER

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INTRODUCTION

When a strong progressive wave collide against a shore structure, run-up and reflection of the wave take place on the front surface of the structure. At the same time, the structure is subjected to wave pressure resulting its oscillation or sometimes its sliding when the wave pressure is very large.

Studies concerning such wave phenomena related to structures have been conducted by numerous scientists and engineers in many laboratories. While only a few investigations in the field have been made on these phenomena. At the same time it is noted that very few investigations have been carried out on the oscillation of breakwater caused by wave forces.

The author performed some field observations on the wave pressure, wave run-up, and oscillation of breakwater at Haboro Harbor in Hokkaido, Japan, from 1957 to 1960 (Refs. 1,2 and 3). In this paper the main results obtained from these observations such as the frequency of occurrence of shock pressure, the relationships among the run-up height, wave pressure and incident wave height, and the rocking phenomenon of the breakwater caused by wave pressure are summarized.

EXPERIMENTAL PROCEDURE

DESCRIPTION OF HABORO HARBOR

Haboro Harbor, where the observations were carried out, is a small local harbor under Government jurisdiction, located at the north-western coast of Hokkaido, facing the Japan Sea. The construction work of this harbor is now in progress. Locations of this harbor and the breakwater at the time when the observations were made are shown in Fig. 1. The slope of the sea bottom is about 1/450 and the maximum tidal range is about 40 cm throughout the year in this area. The predominant direction of the stormy waves, which are wind waves generated from autumn to winter, is in a range of W to WNW. A cross-sectional configuration of the breakwater used for the experiments is shown in Fig. 2.

INSTRUMENTS USED FOR OBSERVATIONS

<u>Wave recorders for offshore wave</u> - Two types of wave recorders

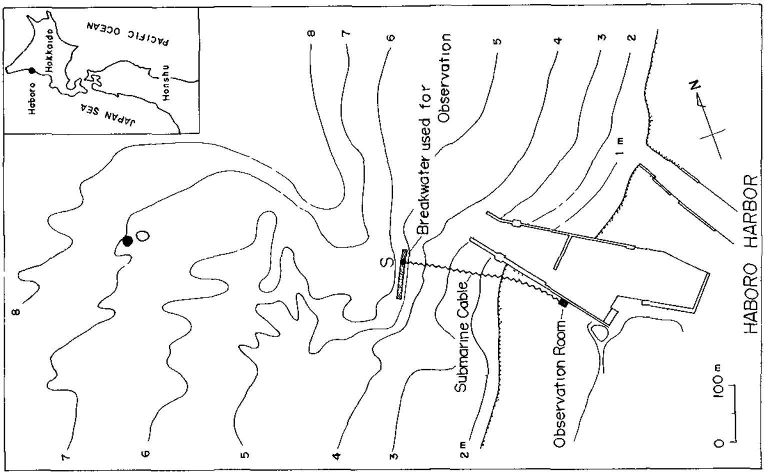


Fig. 1. Map of Haboro Harbor

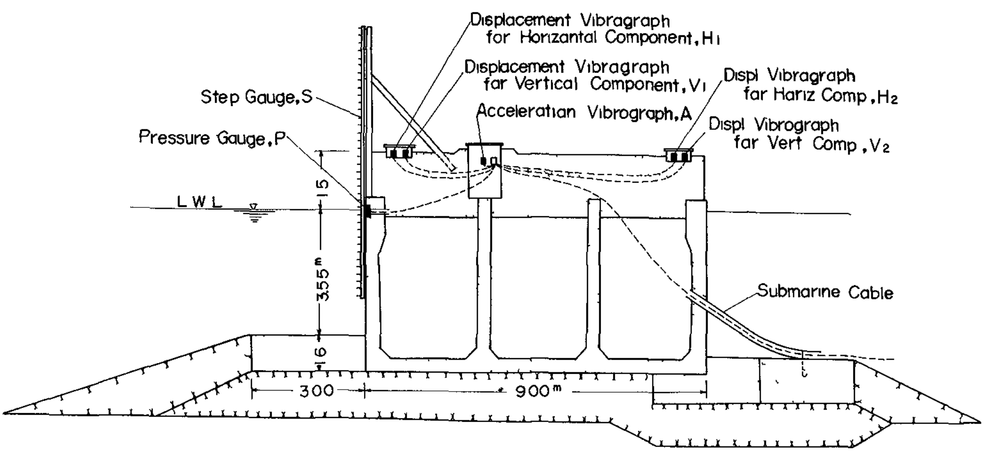


Fig. 2. Cross-sectional configuration of the breakwater used for observations, and positions of the installed instruments on the breakwater.

were used for observing the height and period of offshore wave. One is of a so-called underwater pressure type, and the other is of a stadia type using optical means. The former was designed by the Port and Harbor Research Institute, Japan, and the latter was newly devised by G. Udai (Ref. 1), a member of our Research Institute. The used data of the offshore wave characteristics were mainly obtained by the stadia type wave recorder.

Wave recorder for run-up wave - A step type wave recorder with relay circuits was used for observing the wave run-up height on the breakwater. This step type wave recorder was newly devised by the author (Refs. 1 and 4). The electrical circuit of this wave recorder is shown in Fig. 3. The characteristics of the devised step type wave recorder render the calibration test unnecessary and both sensitivity and linearity are maintained for a considerable length of time, although corrosion of electrodes by the sea water exists and clogging by marine creatures and dirts appear on the step pole.

Wave pressure gauge - The pressure gauge used for measuring the wave pressure against the vertical wall is of the electrical strain meter type pressure gauge with a carrier frequency of 1500 c/s, and with the final accuracy of ± 2 % for full scale.

Vibrographs - Two types of vibrographs were used for observing the oscillations of the breakwater caused by wave forces. One is of an electrical strain meter type and the other is of an electrodynamic type. The principal characteristics of the electrical strain meter type vibrograph are as follows; the natural frequency is 22 c/s, the capacity is ± 1 G, and the frequency of carrier wave is 5000 c/s. This vibrograph was used for measuring the acceleration of the oscillation to be investigated. The electrodynamic vibrograph consists of a so-called moving coil type transducer and a low frequency integrating amplifier. The main characteristics of the transducer are as follows; the natural frequency is 1 c/s, the sensitivity is 0.27 volt/kine, and the damping constant, h, is 0.64. This vibrograph was used for measuring the displacement of oscillation to be investigated.

OBSERVATION PROCEDURE

The positions of the observation points and the location of the breakwater used for the observation are shown in Fig. 1. The offshore wave height and period at the point O, which are named as the incident waveheight and period in this paper, were observed by the stadia type wave meter. The wave pressure, wave run-up, and oscillation of breakwater were observed at the same place indicated as S in Fig. 1. The positions of the points O and S are about 800 m and 300 m apart from the shore line, respectively. And also, the water depths at points O and S are about 7 m and 6 m respectively, and the slope of the sea bottom is about 1/450.

The pick-ups of the measuring instruments were installed on the same one caisson, the size of which is 6.5 m in height, 9 m in width

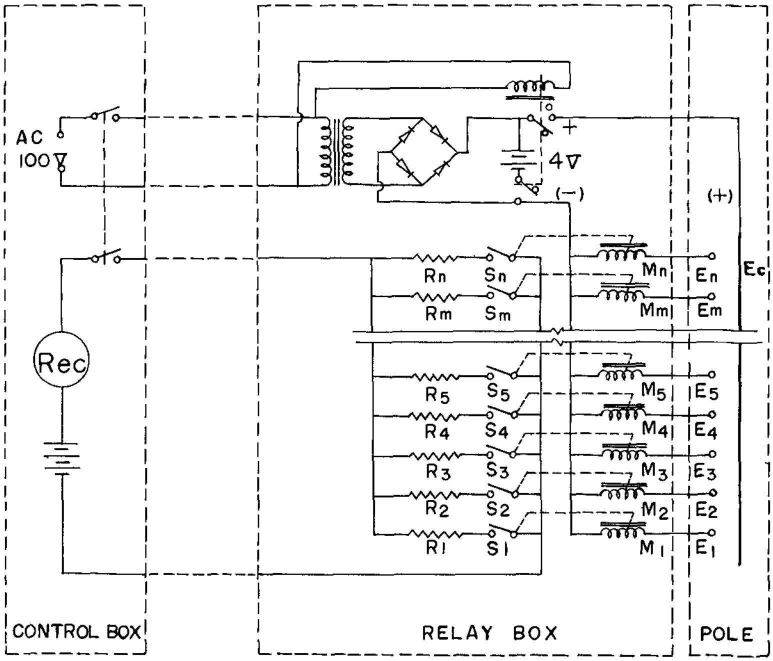


Fig. 3. Circuit of the devised step type wave recorder.

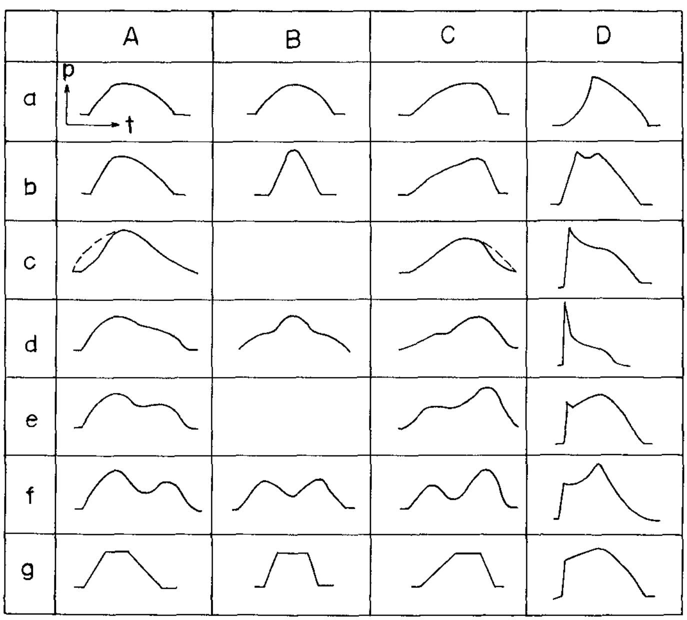


Fig. 4. Classification of wave pressure curves.

and 7.5 m in length as shown in Fig. 2. One step gauge (S), one pressure gauge (P), and one acceleration vibrograph (A) were installed at the front side, at the S.W.L. height of the offshore side wall and in a manhole near the center of the caisson, respectively. The two pairs of displacement vibrographs noted as (H_1, V_1) and (H_2, V_2) were installed at the offshore side and at the shore side of the caisson. Here, H_1 and H_2 represent the vibrographs for the horizontal components, and V_1 and V_2 represent those for the vertical components.

These pick-ups were connected to instruments such as control box, amplifier, and recorder in a observation room on land by means of a submarine cable of about 400 m in length. The wave pressure, wave run-up and oscillation of breakwater were simultaneously recorded with an electromagnetic oscillograph.

SHAPE OF WAVE PRESSURE CURVE

CLASSIFICATION OF WAVE PRESSURE CURVE

The discussion in this chapter on the wave pressure curve (pressure-time curve) is based on the data obtained from an observation for about three months from November, 1957 to January, 1958. During this period, many stormy waves, which involved wind waves and swells, appeared in this sea area. Considering the wave data obtained over the past several years, it can be said that the observed data involved almost all of the large scale waves throughout a year. And it also seemed that the observed data involved almost all types of wave pressure which could appear in any sea obstructed by a vertical wall.

The observed wave pressure curves could be roughly classified into four types of A, B, C and D as shown in Fig. 4. It is believed that all of the wave pressure curves in any sea can also be classified in this manner, although this type of classification is not always generalized. As will be seen in Fig. 4, the curves of any group of A, B and C are always smooth and simple, but the curves of group D have sharp angles. There are some differences among the groups of A, B and C. In type A the curves incline ahead, in type B they are symmetrical, and in type C they incline behind. The groups A, B and C are the so-called clapotis type wave pressures, and group D is the so-called shock type wave pressure.

THE MOST TYPICAL SHOCK TYPE WAVE PRESSURE OBSERVED

The most typical shock type wave pressure observed in our observation is shown in Fig. 5. The shape of this shock pressure is almost the same as that which is obtained in laboratory experiments. The time interval for shock (noted as τ in Fig. 5) was 0.07 seconds, the magnitude of the pressure was 11 ton/m^2 in "Gifle" and 3.2 ton/m^2 in "Bourrage" in our recording. It should be noted that the laboratory test and the field observation showed the similar shock type wave pressure.

FREQUENCY OF OCCURRENCE OF SHOCK TYPE WAVE PRESSURE

When the stability of a breakwater is to be discussed, it is, of course, important to know the intensity of the wave pressure, but it is also important to take into consideration the frequency of occurrence of each type of wave pressure in the natural sea. The frequency distribution of each type of wave pressure obtained from the observed data is shown in Fig. 6 and in Fig. 7. Fig. 7 shows the distribution of frequency in detailed classification.

The full line in Fig. 6, and figure (a) in Fig. 7 show the average frequency of occurrence obtained from the entire data observed. In this case, the values of frequency percentage are respectively 45% in type A, 27% in type B, 24% in type C and 4% in type D. The dotted line in Fig. 6, and figure (b) in Fig. 7 show the distributions of frequency obtained from the single observation in which the shock pressures appeared in the highest frequency. In this cade, the values of frequency percentage are respectively 39% in type A, 28% in type B, 25% in type C and 8% in type D.

As may be seen from these results, the value of frequency percentage of occurrence of shock type wave pressure is very small under the conditions of our field experiments. The typical shock type wave pressures, indicated as D-c type and D-d type in Fig. 4, were found in only two or three cases in the entire data observed, which involved two thousand and several hundred waves.

WAVE RUN-UP HEIGHT

RELATIONSHIP BETWEEN RUN-UP HEIGHT AND WAVE HEIGHT

Symbols and definitions of the wave height, run-up height and other factors used in this paper are as follows:

- $H_o(m)$: Incident wave height in the sense of significant wave height defined by the average height of the one-third highest wave heights of a given wave group over a period of 20 minutes,
- $L_o(m)$: Incident wave length calculated by a theoretical formula using the values of the significant wave period and water depth,
- $H_T(m)$: Wave height at the breakwater front expressed by the average value of the 1/3 highest ones,
- $H_R(m)$: Run-up height above S.W.L. expressed by the average value of the 1/3 highest ones,
- H_o/L_o : Incident wave steepness,
- H_R/H_o : Relative run-up height,
- $P_o(ton/m^2)$: Wave pressure at S.W.L. on the breakwater, expressed by the average value of the 1/3 highest ones.

The relationship between the relative run-up height, H_R/H_o, and the incident wave steepness, H_o/L_o, is shown in Fig. 8. From this

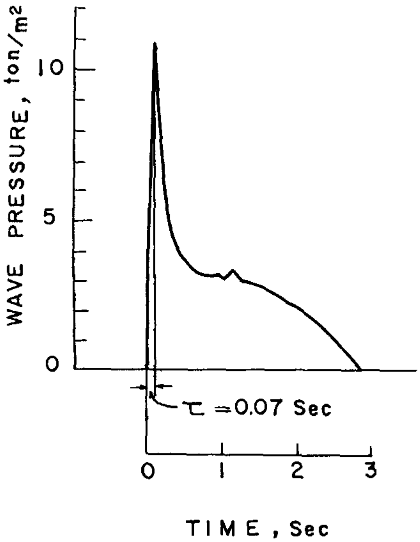


Fig. 5. The most typical shock type wave pressure observed.

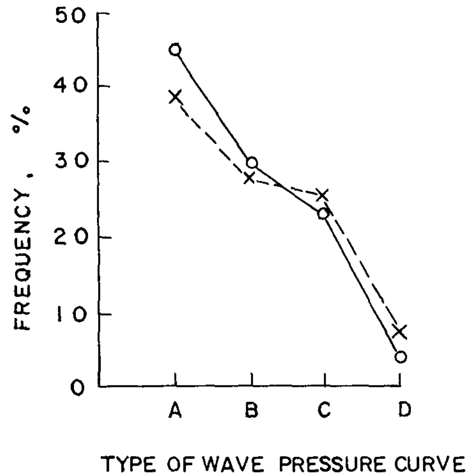


Fig. 6. Frequency percentage of each type of wave pressure.

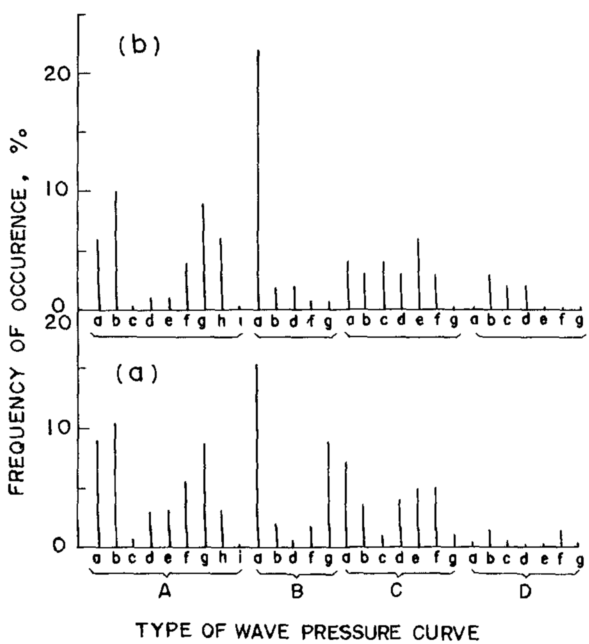


Fig. 7. Frequency percentage of occurrence of each type of wave pressure in detailed classification.

figure, it can be seen that the value of relative run-up height increases as the wave steepness decreases. For example, the value of H_R/H_o is 1.3 under the condition of $H_o/L_o = 0.04$, while $H_R/H_o = 1.9$ when $H_o/L_o = 0.02$. Where, the wave heights H_o are in the range of 0.9 m $< H_o <$ 2.1 m.

It has been reported in many papers that the increasing tendency of the relative run-up height is remarkable in model experiments with an inclined wall. It is also reported in these papers that the relative run-up height on a vertical wall located in deep water does not increase so remarkably as that of an inclined wall, and takes sometimes an opposite trend according to the results of the experimental studies. Our field observations show that the increasing tendency of the relative run-up height is also remarkable even in the case of a vertical wall in deep water.

The relationship between the total wave height at the breakwater front, H_T, and the incident wave steepness, H_o/L_o, is shown in Fig. 9. From this figure, it can be seen that the relative wave height also increases as the incident wave steepness decreases. For example, the value of H_T/H_o is 1.7 under the condition of $H_o/L_o = 0.04$, while $H_T/H_o = 2.4$ when $H_o/L_o = 0.02$.

It was also found that the ratio of the run-up height to the wave height at the breakwater front, H_R/H_T, was almost independent of the wave steepness in the range of $0.02 < H_o/L_o < 0.05$. The mean value of H_R/H_T was 0.75. Generally speaking, the ratio of the wave height above S.W.L. to the total wave height is 0.5$\sim$0.6 in deep water and 0.75 at the breaking water depth of progressive waves. Therefore, the value of H_R/H_T of wave run-up in deep water would be expected to be 0.5 $\sim$ 0.6 when a theoretical clapotis (standing wave) is assumed to be generated at the front of the breakwater. However, the value of H_R/H_T obtained in this observation under the condition of a relatively large water depth is considerably larger than the expected value. This discrepancy may show that the above theoretical assumption is unsuitable for this case.

SOME CONSIDERATIONS ON RUN-UP HEIGHT

The required crown height of the breakwater with a vertical wall may be obtained by applying the ratio of $H_R/H_T = 0.75$ mentioned above to the theoretical clapotis given by reflection theory at the front of the wall. If it is assumed that the coefficient of reflection is 100%, H_R can be obtained by the formula of $H_R = 2H_o \times 0.75 = 1.5H_o$ (i.e. $H_R/H_o = 1.5$). The value of $H_R/H_o = 1.5$ is nearly equal to the value of H_R/H_o obtained from Fig. 8 under the condition of $H_o/L_o = 0.03$. If the coefficient of reflection is 70%, $H_R = 1.27H_o$ can be obtained. This value is nearly equal to the value of H_R/H_o in Fig. 8 under the condition of $H_o/L_o = 0.04$. In the actual sea, the coefficient of reflection is usually 70$\sim$80% and can not be 100%. Therefore, H_R/H_o becomes 1.27$\sim$1.35.

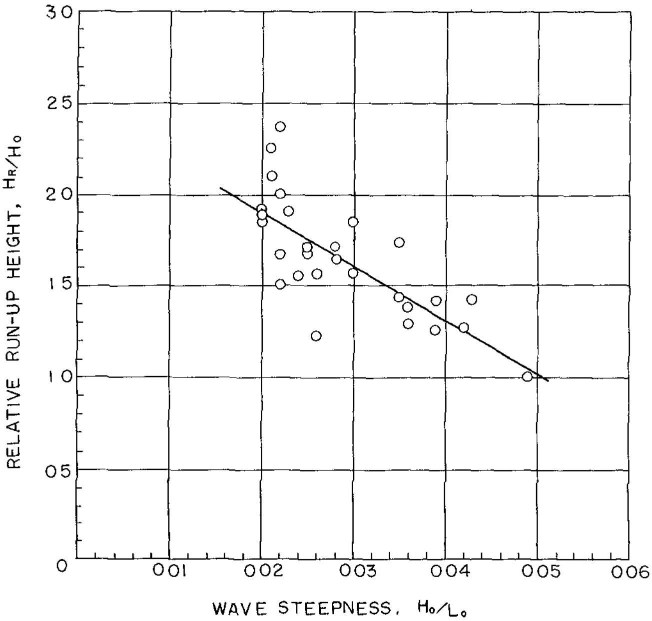


Fig. 8. Relationship between the relative run-up height and the wave steepness.

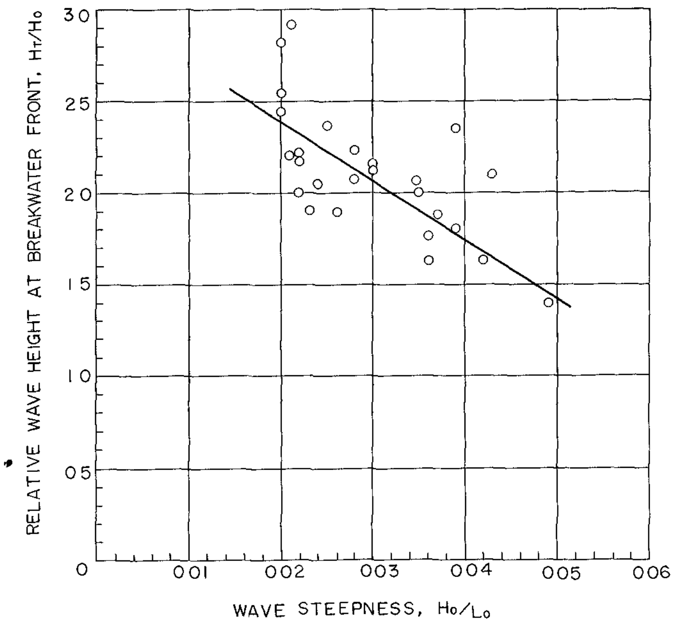


Fig. 9. Relationship between the relative wave height at the breakwater front surface and the wave steepness.

As will be seen in Fig. 9, the value of H_T is larger than $2H_o$ (height of theoretical clapotis) in the range of $H_o/L_o < 0.03$. This means that the wave run-up phenomenon has other properties in addition to the clapotis. J. J. Stoker's theory deals with the reflection of a shock wave on a vertical wall (Ref. 5). When Stoker's theory is applied to the wave run-up phenomena, H_R becomes $1.65H_o$ and $1.78H_o$ when H_o is 0.5 m and 2 m, respectively. These values correspond to the values of H_R/H_o which can be obtained from Fig. 8 in the range of $0.02 < H_o/L_o < 0.03$.

From the above consideration, it can be seen that the clapotis theory with $H_R/H_T = 0.75$ is approximately applicable to the run-up phenomena of the waves which have relatively large steepnesses, and that Stoker's reflection theory gives a good approach to the run-up phenomena of the waves which have relatively small steepnesses.

RELATIONSHIPS AMONG WAVE HEIGHT, RUN-UP HEIGHT, AND WAVE PRESSURE

RELATIONSHIP BETWEEN RUN-UP HEIGHT AND WAVE PRESSURE

The relationship between the run-up height above S.W.L. and the wave pressure at S.W.L. is shown in Fig. 10 and Fig. 11. The points plotted in these figures are given by individual waves obtained from other observation different from that which was applied in the previous chapter. Fig. 10 is a sample record of clapotis type wave pressure, and Fig. 11 is a sample record of shock type wave pressure. According to Fig. 10, the magnitude of the clapotis type wave pressure at S.W.L. is equivalent to 75% of the statical pressure due to water, the elevation of which is equal to the run-up height above S.W.L. On the other hand, in the case of the shock type wave pressure, the equivalent percentage decreases to 65% owing to the results of Fig. 11.

RELATIONSHIP BETWEEN WAVE HEIGHT AND WAVE PRESSURE

The relationship between the initial wave height, H_o, and the clapotis type wave pressure at S.W.L., P_o, is shown in Fig. 12. In this figure, the mark o is for the waves with steepnesses of $0.02 < H_o/L_o < 0.03$, while the mark • is for the waves with steepnesses of $0.03 < H_o/L_o < 0.04$. The points plotted in this figure show a relatively large scattering. However, by using a parameter of wave steepness, a fairly linear relationship was seen. The average relationship between H_o and P_o, which is obtained by using all plotted points, is given by full line (a) of $P_o = 1.2H_o$.

The relationship between H_o and P_o can be derived indirectly by using the two relationships above mentioned i.e. the relationship between the wave steepness and the relative run-up height, Fig. 8, and the relationship between the run-up height and the wave pressure, Fig. 10. If it is assumed that the initial wave steepness H_o/L_o is 0.03, a formula of $H_R = 1.6H_o$ is obtained from Fig. 8. Then, $P_o = 1.2H_o$ can be obtained by using $P_o/H_R = 0.75$ of Fig. 10 with $H_R = 1.6H_o$.

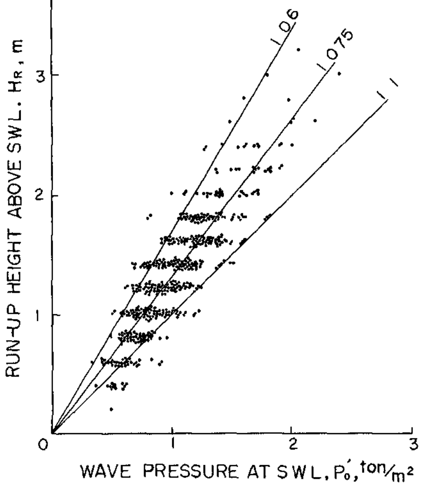


Fig. 10. Relationship between the run-up height and the clapotis type wave pressure at S.W.L.

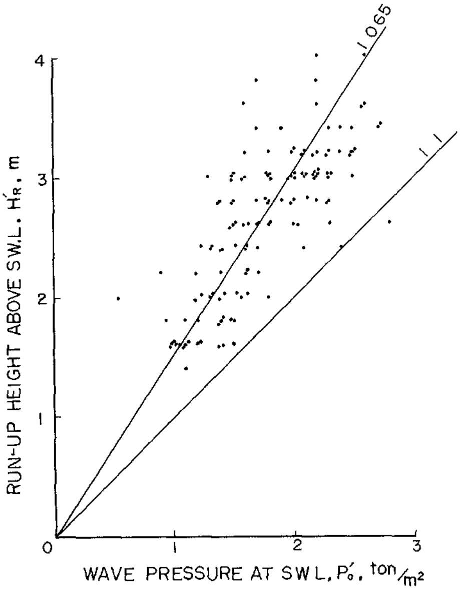


Fig. 11. Relationship between the run-up height and the shock type wave pressure at S.W.L.

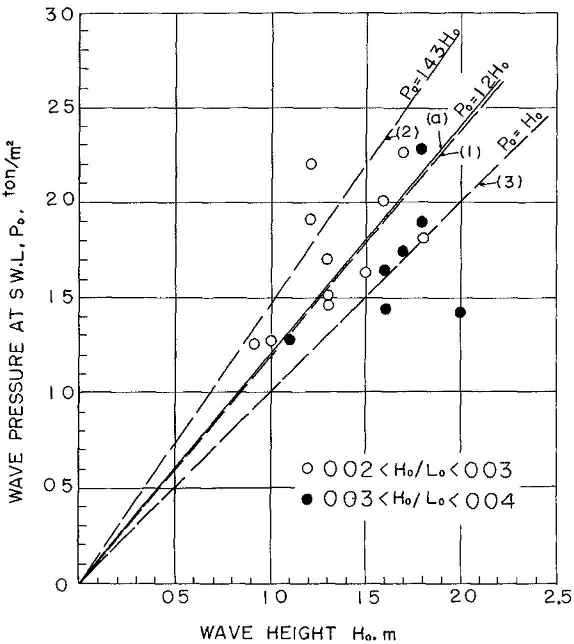


Fig. 12. Relationship between the wave height and the clapotis type wave pressure at S.W.L.

This result, which is shown by the broken line of (1) in the mixed domain of points o and •, is in accordance with the average relationship shown by the full line (a) in Fig. 12.

Following the same procedure in the case of $H_o/L_o = 0.02$, a formula of $P_o = 1.43H_o$ can be obtained as shown by the broken line of (2) through the upper group of points o. When H_o/L_o is 0.04, $P_o = H_o$ is obtained and this result is indicated by the broken line of (3) through the lower group of points •. As mentioned above, the results obtained through the indirect procedure agree fairly well with the results obtained directly from the observed data.

OSCILLATION OF BREAKWATER CAUSED BY WAVE PRESSURE

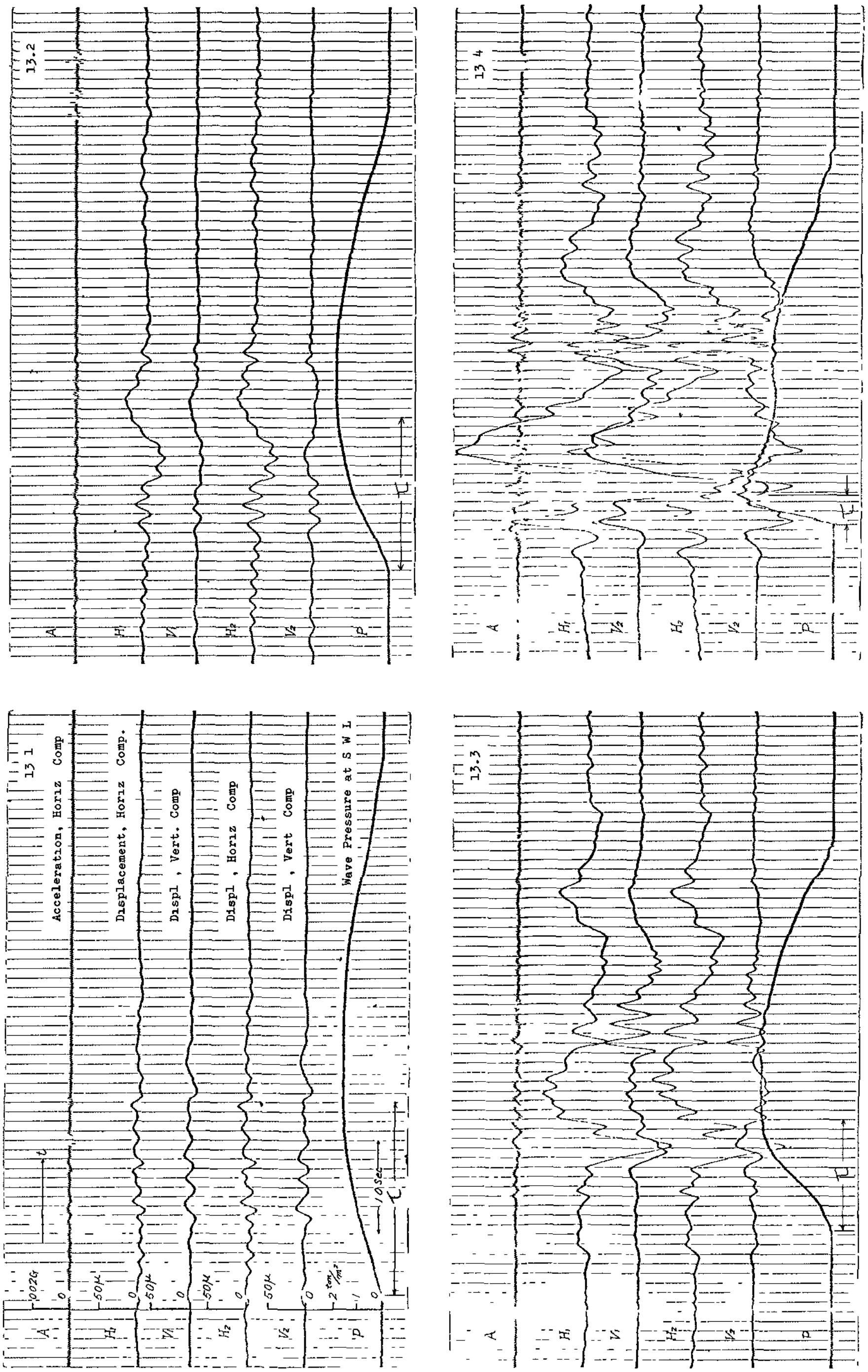
DESCRIPTION OF OBTAINED RECORDS

Figures 13.1 through 13.4 show the examples of the records of oscillation of breakwater for various types and magnitudes of wave pressure. As seen from these records, in which the pressure and the oscillations appear with time, two types of oscillation i.e. one with a relatively long period of $1\sim2$ sec. and another with a relatively short period of about 0.2 sec. can be found. The oscillation of the long period does not appear while the pressure-time curve is gently rising or the magnitude of wave pressure is fairly small, but it begins to appear as the curve commences to lean forward. This long period oscillation is considered to be the secondary or tertiary natural motion of the pendulum of the vibrograph induced by the initial motion of the caisson. No further discussion, therefore, will be made concerning this type of oscillation in this paper.

On the other hand, the oscillation of a short period is almost always found when the magnitude of wave pressure exceeds a certain value. This type of oscillation can be seen in every record of the examples. The periods of these oscillations are small enough compared with the natural period of the electrodynamic vibrograph used in the present investigation. Therefore, it is believed that the recorded oscillation curves of the short period, noted as H_1, H_2, V_1 and V_2 in the records, show the actual oscillatory displacement of the breakwater. Very close correlations in forms and phases can be seen among the recorded curves of A, H_1, H_2, V_1 and V_2, which represent the acceleration, the horizontal components and the vertical components of the oscillation of breakwater, respectively.

PREDOMINANT PERIOD OF OSCILLATION OBSERVED

Among a series of oscillations caused by a single wave pressure, those generated before the peak of the wave pressure seem to be somewhat different in their behavior from those generated after it. Therefore, the predominant period of the oscillation is examined for each of the above two groups of oscillation. Figs. 14 and 15 show the frequency percentages of occurrence of the period of oscillation, and also show the relationship between the period of oscillation and the time interval from the rising point to the peak of wave pressure, noted as τ in Figs.



Figs. 13.1-13.4. Examples of observation records of oscillations.

13.1 through 13.4. Fig. 14 is for the oscillations appearing before the peak of wave pressure and Fig. 15 is for those appearing after it.

As seen from these figures, no relation can be found among the period, the time interval, τ, and the magnitude of the wave pressure, i.e. the period of oscillation observed depends neither upon the type of wave pressure nor the magnitude of wave pressure. In both figures, the plotted data are scattered in a range of 0.1 to 0.3 seconds. The comparison between Fig. 14(b) and Fig. 15(b) show that the distribution of frequency shows little difference between these two groups. The predominant period obtained is approximately 0.2 sec. for each group. This value coincides with that of the oscillation obtained in the previous observation (Ref.1), where an acceleration vibrograph was used.

POSITION OF ROTATION AXIS

In order to know the position of the rotation axis of the oscillation, the phase relation among the horizontal and the vertical motions at the front and at the back of the caisson is examined. The results obtained from a number of records of oscillation are shown in Table 1. As shown in Table 1, the position of the rotation axis of oscillation seems to exist at any one of the three positions, namely the front edge, central portion and back edge of the bottom of the caisson. The frequency of occurrence of each position is highest in the central, next in the front edge and least in the back edge of the bottom of the caisson. In a series of oscillation caused by a single wave pressure, the rotation axis frequently changes its position from one to the other of the three positions.

Table 1

Position of rotation axis	Oscillations generated before the peak of wave pressure	Oscillations generated after the peak of wave pressure
Central portion	76%	48%
Offshore side edge	10	36
Shore side edge	6	8
not clear	7	8

AMPLITUDE OF OSCILLATION OBSERVED

The relationship between the amplitude of horizontal oscillation and the time interval, τ, is shown in Fig. 16 and Fig. 17. Fig. 16 is the figure for the oscillations generated before the peak of wave pressure and Fig. 17 is for those generated at the "Bourrage". From these figures it can be seen that the amplitude of the oscillation of short period increases as the time interval, τ, decreases i.e. as the

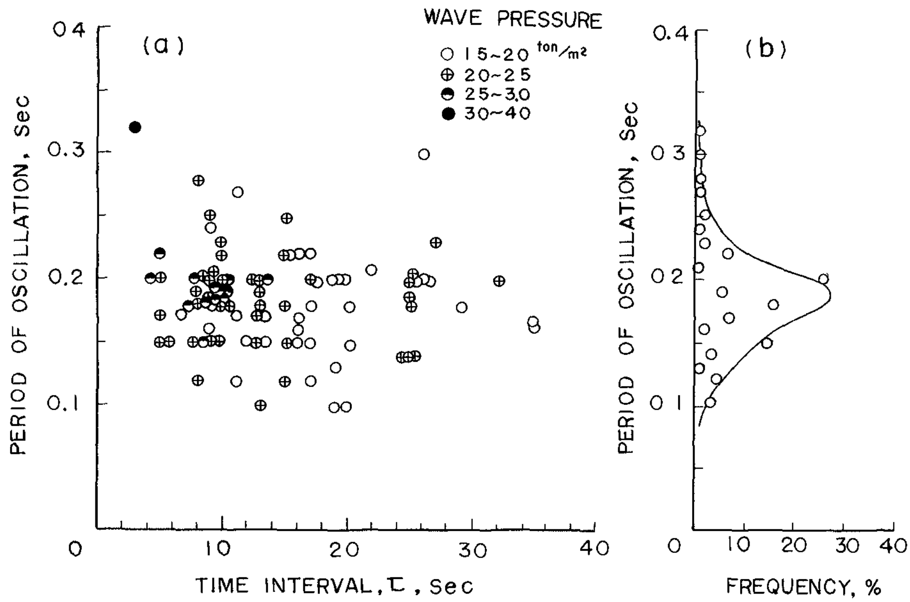


Fig. 14. (a) Relationship between the period of oscillations generated before the peak of wave pressure and the time interval τ. (b) Frequency distribution of the period of oscillations generated before the peak of wave pressure.

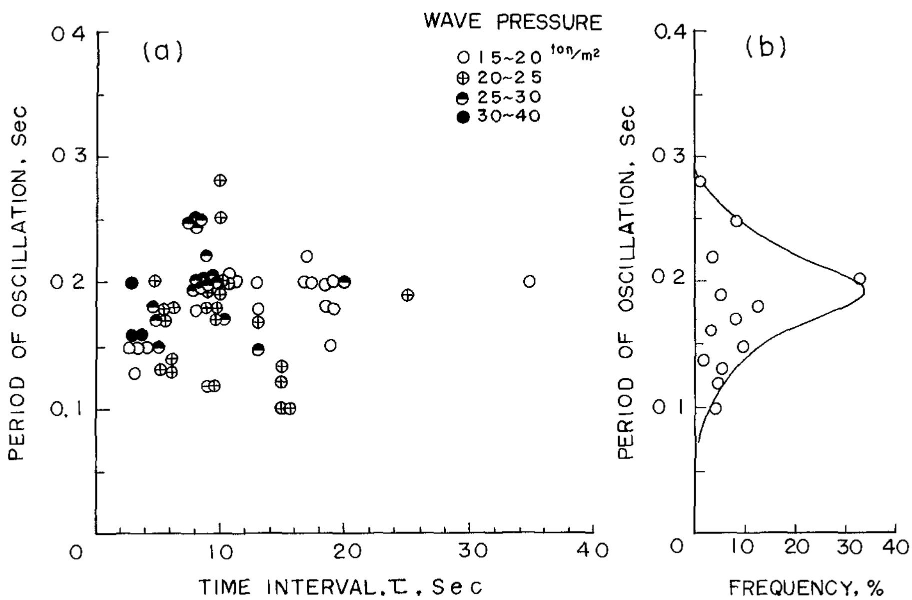


Fig. 15. (a) Relationship between the period of oscillations generated after the peak of wave pressure and the time interval τ. (b) Frequency distribution of the period of oscillations generated after the peak of wave pressure.

impulsive tendency of the wave pressure increases, and also it can be seen that it increases as the magnitude of the wave pressure increases.

Fig. 18 shows the relationship between the amplitude of the oscillatory acceleration and the magnitude of wave pressure at S.W.L. Fig. 19 shows the relationship between the amplitude of the oscillatory displacement and the magnitude of wave pressure. The full lines shown in these two figures represent the enveloped curves covering the observed data. From these enveloped curves, it can be seen that the lowest critical value of the wave pressure, which is required to oscillate the caisson under the present conditions, is about 1.3 ton/m^2 at S.W.L.

SOME CONSIDERATIONS ON OSCILLATION OF BREAKWATER

As mentioned above, the oscillation of breakwater with the relatively short period of 0.2 sec. was invariably found regardless of the type and the magnitude of the wave pressure, when the magnitude of wave pressure exceeds the value of about 1.3 ton/m^2. This type of oscillation is believed not to be a forced oscillation itself caused by the wave pressure, but is a type of free oscillation of the breakwater induced by the wave pressure. This free oscillation is the so-called rocking phenomenon of the breakwater perhaps generated from a system consisting of a fairly elastic foundation (rubble-mound) and a rigid body (caisson).

The author has already made a brief report on the rocking phenomenon based on the data obtained from the previous observation conducted with the acceleration vibrograph (Ref. 1). In the present paper, some detailed behaviors of the rocking phenomenon have been presented.

Since T. Hayashi published his noteworthy theory in which the stability of breakwaters is dynamically treated by introducing the rocking phenomenon (Ref. 6, 7 and 8), the rocking phenomenon has come to be recognized as a very important factor for discussing the stability of a breakwater dynamically.

When T. Hayashi's theory is applied to practical problems, it becomes necessary to know theoretically the period of rocking of the breakwater. For the above reason, and also, in order to check the propriety of the observed period of rocking, the coefficient of bearing resistance of the rubble-mound is calculated from the observed period with special reference to the paper by T. Hayashi (Ref. 6). The calculated value of the coefficient of bearing resistance of the rubble-mound under the present conditions is about 1.6×10^7 dyne/cm^2.

Lastly, the author intends to present briefly on the resonance phenomenon between the wave pressure and the rocking of the breakwater. As shown in Fig. 5, the time interval, τ, of the highest shock type wave pressure observed was about 0.07 seconds. On the other hand, the half period of the rocking is about 0.1 sec. as mentioned above. And, Fig. 16 shows that the amplitude of the oscillation of the breakwater increases as the time interval, τ, decreases. Considering the facts that the smallest value of the time interval, τ, of the observed

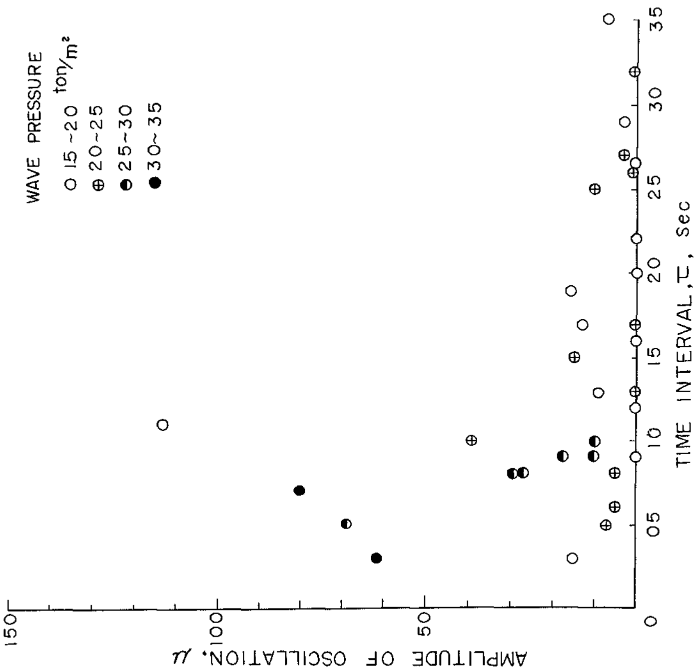


Fig. 17. Relationship between the amplitude of oscillations generated at the "Bourrage" and the time interval τ.

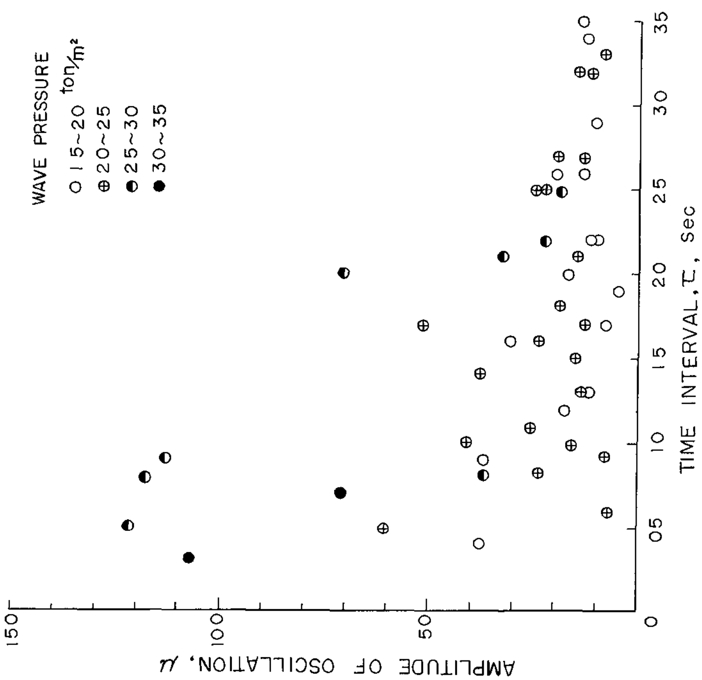


Fig. 16. Relationship between the amplitude of oscillations generated before the peak of wave pressure and the time interval τ.

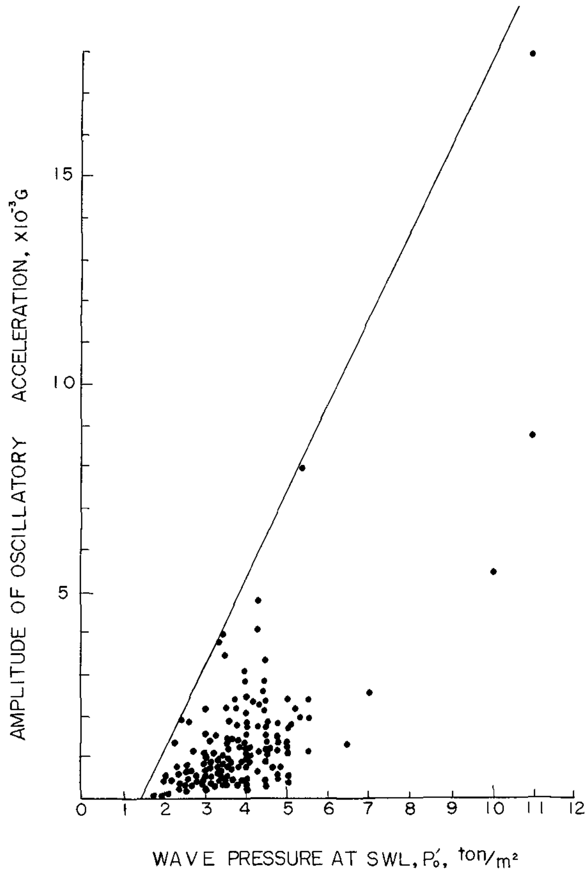


Fig. 18. Relationship between the amplitude of oscillatory acceleration and the wave pressure at S.W.L.

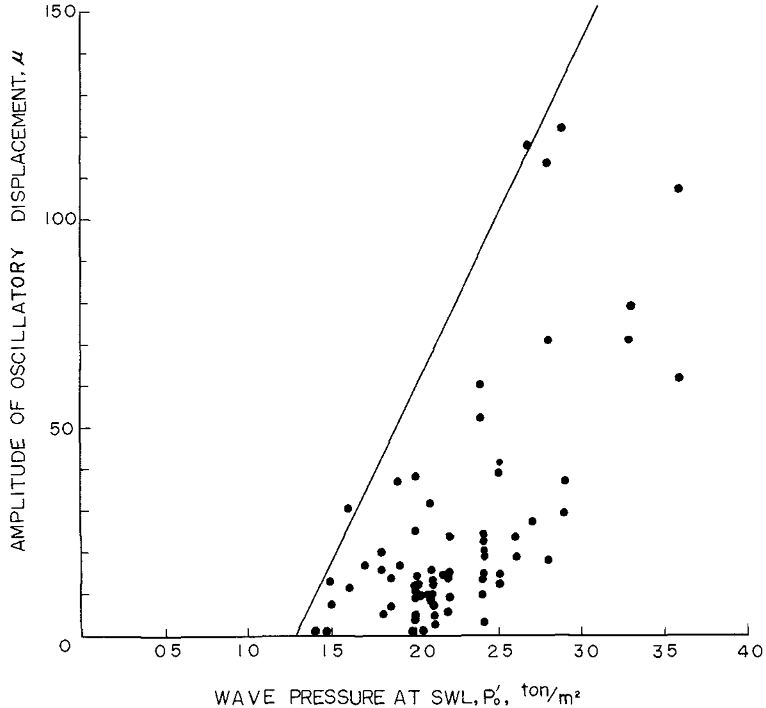


Fig. 19. Relationship between the amplitude of oscillatory displacement and the wave pressure at S.W.L.

pressure is very close to the half period of the rocking, and that the amplitude of oscillation increases as τ decreases, it may be said that a resonance-like phenomenon between the rocking of breakwater and the impact wave pressure on breakwater may occur.

CONCLUSIONS

The main results of the field observations presented here on the characteristics of wave related to the breakwater are as follows:

1. A considerably wide variety of wave pressure curves were found. However these could be roughly classified into clapotis type and shock type. A typical shock type wave pressure such as generated in laboratory tests was also observed in field experiments, but its frequency percentage of occurrence was very small.

2. The average relationship obtained shows that the value of the relative run-up height increases as the wave steepness decreases. The clapotis theory with $H_R/H_T = 0.75$ is approximately applicable to the run-up phenomena of the waves which have relatively large steepnesses, and the Stoker's reflection theory gives a good approach to the run-up phenomena of the waves which have relatively small steepnesses.

3. Plotted points which show the relationship between the incident wave height and the clapotis type wave pressure showed a relatively large scattering. However, by using a parameter of wave steepness a fairly linear relationship was seen.

4. The relationship between the wave height and the wave pressure coule be derived indirectly by using the two relationships i.e. the relationship between the wave steepness and the relative run-up height, and the relationship between the run-up height and the wave pressure. The results obtained by the above method agree fairly well with the observed values.

5. The oscillation of the breakwater was invariably found when the wave pressure exceeded a critical value of about 1.3 ton/m^2. The predominant period of this oscillation was about 0.2 seconds. This oscillation is believed to be a so-called rocking phenomenon of the breakwater caused by the wave pressure from a system consisting of a fairly elastic foundation (rubble-mound) and a rigid body (caisson).

6. Considering the fact that the smallest value of the time interval from the rising point to the peak of wave pressure observed is very close to the half period of rocking, it may be said that a resonance-like phenomenon between the rocking of breakwater and the impact wave pressure may occur.

7. The value of the coefficient of bearing resistance of the rubble-mound calculated from the observed period is approximately 1.6×10^7 dyne/cm^2.

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