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LABORATORY SURFACE WAVE EQUIPMENT

A SUMMARY OF LITERATURE

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P R E F A C E

Contract Nonr-710(05) between the University of Minnesota St. Anthony Falls Hydraulic Laboratory and the Department of the Navy, Bureau of Ships, David Taylor Model Basin provides for an experimental investigation of certain types of laboratory equipment necessary for studies involving gravity waves.

This report presents the results of a survey of literature pertaining to wave generators, filters, absorbers, and instrumentation. It was undertaken in order to provide background information and to avoid duplication of effort in the experimental program.

The project is under the general direction of Dr. Lorenz G. Straub, Director of the St. Anthony Falls Hydraulic Laboratory, with C. E. Bowers, Research Associate, as project leader. Manuscript preparation was performed by Marilyn Larson and Joyce Chalmers under the general direction of Loyal A. Johnson.

A B S T R A C T

This report is a brief summary of selected literature pertaining to equipment and methods associated with laboratory studies of surface waves. It consists of four parts:

- (1) Summary or discussion section.
- (2) Selected abstracts.
- (3) Annotated bibliography.
- (4) Bibliography.

The summary section consists of a discussion of available literature on the subject of wave generators, wave filters, wave absorbers, and instrumentation. No attempt has been made to include reference material relating to equipment associated with field studies of waves.

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LIST OF SYMBOLS

- A - $H_i - H_r$.
- \bar{A} - Relative wave amplitude.
- a - Wave amplitude.
- B - $H_i + H_r$.
- b - Channel width.
- C - Wave celerity.
- C_g - Group velocity.
- c_0, c_n - Integral coefficients.
- D_f - Energy dissipation per unit area.
- d - Water depth.
- E - Wave energy per wave length.
- e - Maximum generator displacement from the mean position.
- F - Force.
- F_i - Inertia force per unit width.
- F_n - Normal force per unit width.
- F_v - Viscous force.
- g - Acceleration of gravity.
- H - Wave height.
- H_f - Friction wave height.
- H_i - Incident wave height.
- H_r - Reflected wave height.
- H_t - Transmitted wave height.
- h - Submerged distance beneath the free surface.
- J_1 - Bessel function of the first order and first kind.
- K - An integer.
- k - Friction coefficient.

- L - Wave length.
- l - Length of test section.
- l - Width or thickness of plunger generator body in the direction of propagation.
- l - Connecting rod length.
- M - Energy coefficient.
- m - $2\pi/L$
- m_0 - Positive real solution of Eq. 11.
- m_n - Positive real solutions of Eq. 12.
- N - Energy dissipation per cycle per unit length.
- n - Integers 1, 2, 3 . . .
- o - Refers to a distant region.
- $P_1, 2$ - Power of waves at stations 1, 2.
- p - Pressure.
- p - An exponent.
- p - Ripple pitch.
- p_H - Hydrostatic pressure.
- p_N - Normal pressure.
- p_i - Inertia pressure.
- q - Fluid velocity.
- R - Form factor.
- r - Crank length.
- s - An integer.
- T - Period.
- t - Time.
- u - Velocity component in the direction of x.
- u_y, v_y - Velocities at the depth y.
- V - Velocity of surface current.

- v - Velocity component in the direction of y.
- w - Specific weight = $\rho_w g$.
- w - $\phi + i\psi$
- X - Horizontal semi-amplitude of motion.
- X, Y - Horizontal and vertical particle displacements.
- x, y, z - Variables, coordinate axes.
- z - $x + iy$.
- α - Beach slope.
- α - A variable.
- β - Rate of damping.
- δ - Wave steepness.
- η - Surface elevation.
- θ - Crank angle.
- λ - Permeability coefficient.
- ν - Kinematic viscosity.
- $\xi(y)$ - Displacement function.
- ρ - Intrinsic coefficient.
- ρ_w - Water density.
- σ - $2\pi/T$
- ϕ - Velocity potential.
- Ω - Force potential.

L A B O R A T O R Y S U R F A C E W A V E E Q U I P M E N T
A S U M M A R Y O F L I T E R A T U R E

I. INTRODUCTION

The experimental study of oscillatory waves can be divided into studies in the ocean--or rather in nature--and studies in the laboratory. In general, the first is concerned with the nature of the phenomenon of ocean wave motion and the second with the possible explanation of the phenomenon. Because of the large number of uncontrolled variables effective in nature, definition of the character, behavior, and effect of ocean waves is difficult. Thus, the explanation of the natural phenomenon may best be determined by laboratory studies in which the variables are isolated and studied systematically. The value of these studies, however, is dependent upon the equipment and methods employed in the laboratory.

In an effort to determine the utility of some types of laboratory wave-study equipment, the David Taylor Model Basin, Department of the Navy, has contracted with the St. Anthony Falls Hydraulic Laboratory for an experimental investigation of selected types of equipment.

As an initial step in this investigation it was considered desirable to review earlier work pertaining to this field. This report is a brief summary of the references which have been reviewed to date.

It should be emphasized that the survey reported herein pertains to laboratory equipment. No attempt has been made to review the extensive literature pertaining to field studies.

It is felt that the bibliographical survey may be of interest to others performing wave studies for it presents a brief picture of the methods and equipment employed by a number of organizations active in this field.

II. WAVE GENERATORS

In laboratory studies involving wave phenomena, some type of machine must be utilized to create the waves which are to be observed. The number of possible forms which these generators may assume is as diverse as the wide variety of wave conditions which must be simulated. Fortunately, however,

wave generators may be loosely grouped in a few very different categories. Within each category, of course, there are as many different possible variations in the basic principle of operation as there are designers. These variations are usually employed to emphasize one or more of the basic criteria of generator performance as dictated by the particular wave problem involved.

A. Criteria of Generator Performance

1. Kinematics of the Generating Member

Presumably any periodic disturbance at the upstream section of a wave channel, if of sufficient strength, will eventually become the originator of a train of waves further downstream. However, the distance downstream may be extremely long, and the type of wave which results may be wholly undesirable. The wave generator then must approximate as closely as possible the particle motion for the particular wave desired in order to cause the correct particle motion to occur in the immediate vicinity of the generating member. Conformance to this kinematic criteria accomplishes two purposes:

(a) It allows a relatively short wave channel to be utilized, thereby lending economy and compactness.

(b) It conserves power required to generate the wave by forming only the wave which is desired.

2. Mechanical Simplicity

If the generating member is to impart the proper orbital motion to the fluid, some form of mechanical linkage may be necessary between the member and the power source. Good mechanical design requires a minimum of moving parts to accomplish the desired motion. Naturally, the more protection which is afforded to hinges, bearings, and adjustments, the less the maintenance expense. The primary step in protection of these vital parts is to remove them from the damaging effect of sediment-laden water. (Engineers at the Neyrpic Laboratory [10] have indicated that where bearings must be immersed their practice has been to decrease the bearing diameter, thus reducing friction. Such bearings are expected to be worn out or corroded and hence replacement is anticipated.) It is also necessary to restrict the mass and hence the inertia of the moving parts to a minimum in order to maintain the cyclic motion assigned and the economy of operation.

3. Reflective Action

Ideally a wave-generating member should not again reflect waves which are reflected to it from downstream. Unfortunately, however, the majority of machines are good reflectors. Mention will be made later of a machine which is designed to avoid reflection.

4. Simplicity of Control

Not only should a wave machine be capable of generating various types of waves, but the machine should be easily adjustable to perform this action. This feature may serve to reduce greatly the time necessary for experimental work.

5. Mobility

While some types of wave programs do not call for mobility of the wave machine, there are other programs which can be seriously hampered if the machine is not readily movable.

The usual method of making a wave machine mobile is to mount it upon a carriage which travels on rails located along the side of the wave channel, or, in the case of a large wave tank, to support the generator on a carriage mounted upon caster rollers which enable movement of the machine over the floor of the model. For quite deep tanks, however, a mobile unit devised by the Neyrpic Laboratory might be very useful. This unit has the wave generator mounted upon a caisson which may be filled with air to float the entire mechanism from one location to another.

6. Leakage and Friction

Side and bottom leakage of the water around and under the generating member can account for the following poor wave characteristics:

- (a) Decrease in the amplitude of the generated wave.
- (b) Creation of instability of the wave form.
- (c) Incorrect shape or profile.

On the other hand, if leakages are effectively sealed, the increased friction introduced by gaskets, etc., may promote undesirable operating characteristics.

The items enumerated above do not include all possible criteria for generator performance. They do, however, indicate the balance between economy

and versatility which seemingly must be drawn in the application of every generating mechanism. The next logical step in surveying generators would be to enumerate the types of machines in use and to evaluate their worth in the light of the previous criteria.

B. Methods of Wave Generation

1. Plunger Type

There are three main classes of operation into which most wave machines fall. The first may be known as the plunger-type machine. Its action is to cause a body to be periodically thrust into and withdrawn from the free water surface. The body may have various cross-sectional forms, the most common being either wedge-shaped or parabolically contoured with a vertical back. The longitudinal axis of the body ordinarily spans the entire width of the wave channel, although such is probably not the case for a large harbor model. Wave length and amplitude may be adjusted on this machine by varying the period and stroke of the wave generator.

This type of machine has been investigated theoretically by Schuler [119] for particular forms of plunger cross section in a fluid of infinite depth.

2. The Movable Wall or Rigid Flap Type

A second general category for wave machines includes those types whose wave-generating members are immersed in the fluid and oscillated back and forth in accordance with some established law. Generators falling in this classification are perhaps the most versatile types available, since by imposing an appropriate law of motion such machines will effectively generate waves of any desired characteristic.

Ordinarily the wave-generating member of machines in the second category is a rigid plate. It may be flat or curved; that is, having either a linear cross section or a concavity facing downstream. The plate width spans the wave channel. The method of imparting motion to such members varies from a flap simply hinged at the channel bed and driven by a crank and connecting rod at the surface, to a plate suspended in the channel by a linkage system so that the plate may move relative to the channel in any prescribed manner. The utility of the latter is to enable one machine to approximate the orbital motions of a variety of wave types.

Of course, the generating member may be flexible rather than rigid, as is the case with the Sines [123] machine, which is so designed in order to more nearly satisfy the kinematic criteria.

The theoretical work of Biéssel [10] has furnished the basis for evaluation of this second class of machine to a first approximation for a finite depth of water.

3. Pneumatic Type

The last general category includes machines of the pneumatic type. In its simplest form this type of device affords a means of altering the pressure above a limited region of the free water surface so that the fluid beneath the area rises and falls, the disturbance then being propagated at the wave celerity corresponding to the period and the depth of water involved. A further extension of this principle utilizes a discharge tube (Fig. 1), which allows the propagated disturbance to assume more rapidly the desired wave form. Such a discharge tube is primarily for the case of shallow water waves. This summary does not include a theoretical treatment of a pneumatic generator.

C. Brief Résumé of Existing Wave Generators

1. Plunger-type Machines

The plunger type of generating unit may be typified by the installations of the Waterways Experiment Station, Vicksburg, Mississippi, shown in Figs. 2 and 3. The figures shown are of both parabolically contoured and wedge-shaped plunger cross section. With regard to the slope of the forward face of a triangular-shaped plunger, an investigation was conducted by Reynolds [110] in the course of test work concerning wave action on sea walls. Plunger face angles were studied from 60° forward of the vertical to nearly vertical; the angle of 32° was finally used as an optimum. However, tests conducted on a machine at Fort Belvoir indicated that angles of 50° to 60° gave the best wave production [151].

Kempf and Hoppe [65] have described a method of computation of the profile shape of a contoured plunger generator. An abstract of this article is contained herein.

A noteworthy feature of the plunger-type machines is that they lend themselves readily to mobile installations. The Hamburg generator, for example, is mounted on track and carriage rollers, while the machine of the Waterways Experiment Station is supported by large varidirectional caster rollers. The mobility of these machines is of extreme helpfulness when used in harbor models or shoreline installations where the wave action simulated may be incident from different directions.

2. Movable Wall-type Generators

This class of wave machine seems to be the most versatile of the various types previously enumerated, and more variations of the basic theme appear to have been utilized.

The first machine to be considered in this group is the flexible-flap type (Fig. 4), which is of a rather special form, being of most use when the channel is of limited length. A flexible-flap machine should be capable of more nearly approximating the motion of particles immediately at the machine. The disadvantage is, however, that it is a complicated mechanism which is not readily adjustable. The machine's inertia is small. There are, unfortunately, many moving cranks and bushings located beneath the water surface. Sines [123] indicates that his machine generates true trochoidal waves and is able to develop maximum wave lengths of 10 ft and maximum heights of 1 ft in a water depth of 5 ft.

The rigid flap-type wave generator may be typically illustrated by Fig. 5. This machine is hinged at the bed of the channel and driven by a crank and rod near its upper limit. Since the motion imparted is that for a wave having a d/L value of approximately $1/2$, the machine's use should be restricted to cases of relative depths of about this order of magnitude. Such a machine is simple in construction, having only the undesirable feature of a hinge placed on the bed of the channel. The unit does not possess a large inertia characteristic and is easily regulated because of its simplicity of design.

Another generator falling within this category is the piston-type machine illustrated by Fig. 6. The generating surface moves forward and backward, usually with simple harmonic translation, and the form of motion is particularly adapted to waves whose length is very large with respect to the

depth of water. The mechanism is quite simple and no maintenance problems are evidenced. This machine is very reflective, as are all machines having a solid generating member extending to the channel bed.

Reference to the synoptic table will indicate several schematic diagrams of the forms which may be taken by this group of machines. Of these, perhaps the "swing type"---sometimes called the ballistic pendulum---will be of use in demonstrating the form of generators whose motion with respect to the channel may be made to approximate very closely any of the motions of the previously discussed rigid plate machines. Figures 7 and 8, respectively, show these types of machines as presented by Ransford [107], and Coyer [27]. The Ransford wave generator is suspended from above, while the Coyer machine is supported from below. Figure 9 is a characteristic diagram for the Ransford generator, showing wave height as a function of the angular rotation of the link DA. The parameter is the period, and the characteristics shown are for the link setting GII and a water depth of 10 cm (0.328 ft). Figure 10 shows the operating characteristics of the Coyer machine where the pivot setting refers to the calibrated pivot arc shown in Fig. 8, and the connecting rod setting is the radius of the driving crank arm.

Maintenance of these machines is slight because all moving machine parts are out of the water. The inertia characteristics of this form of machine are comparable to those of the plate hinged at the channel bed.

Figures 11 and 12 illustrate the pneumatic form of wave generators. In operation, the air dome of these machines may be valve-connected alternately to the suction and discharge side of an air compressor or blower, or it may be connected solely to the low-pressure side of the blower. (Each method decreases the dome pressure, drawing a water volume into the dome reservoir.) The water is then discharged by an increased head equal to that of the blower outlet in the first case, or by the gravity head of the water elevation in the second case. It would appear that the first type of machine is capable of larger amplitudes of motion and of shorter periods than the second arrangement. The water flow in and out of the pneumatic type of machine which has a discharge tube as shown in Fig. 12 is essentially uniform with regard to the vertical velocity distribution, hence the machine generates a motion corresponding more nearly to the case of waves whose length is long compared to the water depth.

One other wave machine may be of interest although it cannot be strictly classified in the preceding categories. The unique feature of this machine is its reported inability to reflect waves. Figure 13 illustrated the mechanical arrangement. While the author of the report on this machine indicates that the fabric curtains are an integral part of the wave machine, they might also be considered to be a form of wave filter located downstream of the actual generating member. In actuality, these pliable elements perform one of the essential functions required of wave filters. The partitions, which are suspended from the channel top, are pliable curtains weighted at the bottom. Actual initiation of the wave occurs at an upstream point, presumably by a vane hinged at the bed. This disturbance is transmitted through the successive pliable elements undergoing slight phase changes at each until it reaches the last element which actually generates the wave propagated downstream. This device is said to absorb completely all waves which are incident upon it from downstream. The weighting, spatial disposition, and number of the pliable elements seemingly would have to be altered for various wave characteristics desired. The designers of this equipment have stressed the low cost of such an installation for overcoming reflected wave energy [74].

A final wave-generating device may be mentioned because of its unique quality which permits the generation of a wave front whose crest profile is curved in plan view. The mechanism by which this can be accomplished is called the serpent-type wave generator and is shown schematically in the synoptic table. Such a generator has been built at the Neyrpic Laboratory [10]; it is 25 m wide and has 63 elements placed side by side. Each element is driven back and forth by cams mounted on a common shaft. The phase of one cam with respect to each of the others may be varied as desired. Since each unit produces an elementary wave, the envelope of the elemental waves composes the form of the generated wave system. The generator, however, is quite expensive to construct and rather difficult to control.

D. Theoretical Generator Studies

1. Plunger Machines

The problem of wave generation by bodies oscillating in the vertical plane has been dealt with by Schuler [119], who presents equations for the determination of the progressive wave amplitude. (Although it is not specifically mentioned by the author, it seems clear that the depth of water in the cases considered is very large.)

All cases reported may be represented two-dimensionally with the intersection of the coordinate axes located at the free water surface. The direction of wave propagation is toward the positive x-direction.

The first case considers a line of oscillating pressure lying on the surface of the water, its direction normal to the direction of wave propagation. The relative wave amplitude at a great distance downstream was obtained by Dimpker [34] for this case as

$$\bar{A} = \frac{2\pi}{L} \frac{1}{2g\rho_w} \quad (1)$$

where L is the wave length; ρ_w is the water density; and \bar{A} is the wave amplitude per unit plunger stroke, per unit magnitude of the disturbing pressure integral.

If the line is considered to be expanded in the direction of wave propagation to a finite width ℓ , an oscillating plate is obtained at the water surface; and if an elliptical pressure variation is assumed over the width ℓ ,

$$\bar{A} = \frac{\pi^2}{2} \frac{\ell}{L} J_1 \left(\pi \frac{\ell}{L} \right) \quad (2)$$

where J_1 is a Bessel function of the first kind and first order, and \bar{A} is the wave amplitude per unit plunger stroke. Dimpker's results above have been called the "plate theory."

Holstein [50] has investigated the cases of bodies oscillating at a distance h beneath the water surface. Where the width of the body in the direction of wave propagation was infinitely small, a breathing line source replaced the body (an image sink being necessary, of course, to satisfy the boundary conditions), and the wave amplitude per unit plunger stroke at a great distance was found to be

$$\bar{A} = \frac{4\pi^2}{L} e^{-2\pi h/L} \quad (3)$$

the symbols having been previously defined. If the source is distributed over

the width ℓ in the direction of wave propagation, a finite body of width ℓ is obtained and

$$\bar{A} = 2\pi \frac{\ell}{L} e^{-2\pi h/L} \quad (4)$$

The latter expression has been designated as the "source theory."

Holstein investigated another method of determining the wave amplitude caused by an oscillating body whose bottom edge was located at a depth h beneath the free surface. This was done by equating the energy transferred from the bottom surface of the prism body to the water, with the energy carried away by the wave at a great distance. This amplitude was evaluated as

$$\bar{A} = 2 \sin\left(\frac{\pi\ell}{L}\right) e^{-2\pi h/L} \quad (5)$$

and this expression is referred to as the "prism theory."

It may be seen that when ℓ/L is very small, Eq. (5) and Eq. (4) become identical. The relationships among the three theories may be seen from Fig. 14 for the case of $h = 0$ and $S = \pi\ell/L$. The dashed line represents the plate theory, the dotted line the source theory, and the solid line the prism theory.

The maximal and minimal values of the wave amplitude occur at somewhat different values of $\pi\ell/L$ for the plate and prism theories because the zero points of the sine function occur at smaller values of the argument than in the case of the Bessel function. These points represent frequencies at which no moving waves are generated. Figure 15 indicates the conformance of the various theories with experimental data.

Schuler's conclusions are as follows: The plate theory is valid for small immersion depths (wide bodies); the prism theory is valid for large immersion depths (slender bodies) and yields better approximations for very low ℓ/L ratios ($\ell/L < 1/10$); the source and prism theory agree well at small values of ℓ/L ; the source theory is not valid where h is small ($< \ell/5$).

Schuler [120] has also described an interesting phenomenon which may be grounds for fruitful analysis. When a plunger is generating progressive waves at low frequencies and the period is then decreased, a transition

point is reached where the progressive wave disappears and a standing wave occurs normal to the crests of the progressive wave train. The frequency of the standing wave is 1/2 that of the generator frequency, and there are an even number of standing wave lengths between the channel walls. Schuler indicates that this effect was first thought to be due to the walls of the channels or to the ends of the plunger. Experiments with a spherical plunger in a large tank, however, showed that the same phenomenon occurred even though no end or wall effects were present.

The conclusion reached was that the standing wave was purely a hydrodynamic happening, possibly due to a concentration of small vortices near the crests of the progressive waves whose strength became large enough to form the standing waves. No analysis was presented to substantiate this observation.

2. Movable Wall Machines

The most usable theoretical work for this class of wave generators appears to have been presented by Suquet and Biésel [10]; their analysis is based on first-order theory and the irrotational motion of an ideal fluid. Leakage beneath the machine is not considered.

The boundary conditions are

$$(a) \quad \frac{\partial \phi}{\partial y} = 0 \quad \text{for } y = 0, \quad x \geq 0 \quad (6)$$

where the origin of the coordinates is placed on the channel bed, and the \overline{ox} -axis extends along the bed in the direction of propagation; the \overline{oy} -axis is the mean position of the oscillating member.

$$(b) \quad \frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial y} = 0 \quad (7)$$

for the surface condition in a first-order theory.

$$(c) \quad \frac{\partial \phi}{\partial x} = \sigma \xi(y) \cos \sigma t \quad (8)$$

for the boundary condition at the moving wall and where $\sigma = 2\pi/T$ and the motion of the generator is $x = \xi(y) \sin \sigma t$.

The solution for this problem is shown to be

$$\phi = -\frac{\sigma}{m} c \cosh my \sin(\sigma t - mx) - \sum_{n=1}^{\infty} c_n \frac{\sigma}{m_n} \cos m_n y e^{-m_n x} \cos \sigma t \quad (9)$$

where

$$c = c_0 = 2m_0 \frac{\int_0^d \xi(\alpha) \cosh m_0 \alpha d\alpha}{\sinh m_0 d \cosh m_0 d + m_0 d} \quad (10)$$

and

$$c_n = 2m_n \frac{\int_0^d \xi(\alpha) \cos m_n \alpha d\alpha}{\sin m_n d \cos m_n d + m_n d}$$

and where m_0 is the positive solution of the equation in α ,

$$\sigma^2 = \alpha g \tanh \alpha d \quad (11)$$

and m_n represents the positive solutions of the equation in α

$$\sigma^2 = -\alpha g \tan \alpha d \quad (12)$$

When this velocity potential is used, the displacements of the particle whose mean position is x and y are found to be

$$X = c \cosh my \sin(\sigma t - mx) + \sum_{n=1}^{\infty} c_n \cos m_n y e^{-m_n x} \sin \sigma t \quad (13)$$

$$Y = c \sinh my \cos(\sigma t - mx) + \sum_{n=1}^{\infty} c_n \sin m_n y e^{-m_n x} \sin \sigma t$$

The wave amplitude then becomes

$$a = c_0 \sinh md \quad (14)$$

The pressure fluctuations may also be obtained from the potential since

$$\frac{p}{\rho_w} = -\frac{\partial \phi}{\partial t} + g(d - y) \quad (15)$$

at the generating member $x = 0$, and the pressure when separated into three parts becomes

(a) A hydrostatic pressure

$$p_H = \rho_w g (d - y) \quad (16)$$

(b) A pressure fluctuation

$$p_n = \rho_w g a \frac{\cosh my}{\cosh md} \cos \sigma t \quad (17)$$

because of the generated wave. It is in phase with the generator speed, and the power consumed in overcoming this pressure is recovered in the wave itself.

(c) A pressure fluctuation

$$p_i = \rho_w g \sum_{n=1}^{\infty} c_n \tan m_n d \cos m_n y e^{-m_n x} \sin \sigma t \quad (18)$$

which is in phase quadrature with the generator speed. It is an inertia pressure which does no work, on the average, and which acts in the same fashion as the inertia of the wave generator.

The fluctuating pressures above are deduced for a single train of waves generated in one direction only. Where the machine sets forth wave systems upstream as well as downstream these pressure effects are additive.

In actual computations the curves of Fig. 16 may be used to evaluate $m_n d$.

The analysis presented may be applied to several typical cases, one being the piston-type machine where $\xi(y) = e$, a constant which is the semi-amplitude of the piston motion. Using the expression previously determined for c_0 , the wave amplitude is found to be

$$a = c_0 \sinh md = \frac{2 \sinh^2 md}{\sinh md \cosh md + md} e \quad (19)$$

and the vertical amplitude of the transient oscillation near the generator $x = 0$ is

$$\eta_n = c_n \sin m_n d = 2e \frac{\sin^2 m_n d}{\sin m_n d \cos m_n d + m_n d} \quad (20)$$

Similarly, the pressures existent upon the generating member become

$$p_H = \rho_w g (d - y)$$

$$p_n = 2e \rho_w g \frac{\cosh my}{\cosh md} \cos \sigma t \quad (21)$$

$$p_i = g \sum_{n=1}^{\infty} c_n \tan m_n d \cos m_n y \sin \sigma t$$

The resultant forces acting on the piston become

$$F_n = \int_0^d p_n dy = \frac{2e \rho_w g}{m} \tanh md$$

(22)

and

$$F_i = \int_0^d p_i dy$$

This analysis may be used not only to evaluate the wave profile and the pressure forces existent upon the generator, but also to determine the applicability of a particular generator for originating a given wave characteristic. For example, determination of the η value for the piston generator shows that the disturbance generated at the piston for very long waves is small compared with the wave amplitude. On the other hand, the disturbance at the generator for very small waves is large when compared with the wave amplitude. Thus, a great deal of energy must be wasted if the piston-type unit is to generate short waves.

Similarly, it is of interest to compare the values of the pressure ratios for two machine types generating the same wave. Such comparison indicates the structural advantages of one generator over another.

The ratio of the inertia force to the normal force may be taken as a criterion of the wave machine performance. Large values of the ratio ($F_i/F_n > 1$) indicate that the undesirable inertia force is considerably in excess of the force necessary to cause wave propagation. This condition may

indicate that the machine is being used improperly. Since F_i/F_n is a function of the relative depth d/L , the value of the pressure force ratio may be reduced by using the piston-type generator to create waves which are long relative to the depth.

Havelock [47], Kennard [66], and Burgers [18] have each treated phases of this problem theoretically; the most usable work, however, is described above.

The foregoing summary may be of particular assistance in the selection and design of wave-generating equipment where use may be made of the Biésel theory for the movable wall-type generator. This work may be of utility in anticipating the necessary wave machine stroke for the limiting design steepnesses. Too, it may yield an evaluation of the forces to be exerted upon the machine so that design computations can be made to determine the component machine members. There is no experimental evidence to verify this theory or to indicate the error to be expected when making use of the theory. Such data would be of singular help in applying this work.

In the case of the somewhat limited theory for plunger-type machines, a certain amount of experimental data is shown for verification purposes. The theory may be useful in estimating the plunger dimensions necessary for the proposed wave steepness in relatively deep water.

In the case of a comprehensive wave program where it may be deemed necessary to study waves of both deep and shallow water characteristics, the use of a pendulum-type machine is highly recommended. This is because the pendulum-type machine can adapt the motion of the suspended blade to agree approximately with the particle orbital motion for most varieties of wave characteristics. While it appears likely that the construction of this machine would involve a larger initial expense and a greater amount of design work than would some of the simpler types of generators, it also seems that the resulting generating facility would be sufficiently superior to the simple type to warrant the additional construction cost and effort.

The foregoing discussion has been limited to devices having simple harmonic motion. However, periodic movements of the generating member may be desired which follow another form of motion with respect to time. It is possible to produce such motion by use of a double actuated member, as shown in the synoptic table. In this instance the wave generator motion is composed

of two sinusoidal motions, one having the frequency of the wave (the fundamental), and the other having twice the wave frequency (the second harmonic). This device was not found practical by engineers of the Neyrpic Laboratory [10].

A second method of regulating the motion with respect to time utilizes a motor controller which instantaneously alters the generator motor speed in accord with the law established. A similar method makes use of a cam-regulated oil servo-motor system wherein the cam profile yields the input signal for the generator motion. Any such system, of course, increases the complexity and cost of the installation. The only published information on machines of this type discovered to date is published in reference [10].

III. WAVE FILTERS

A. General Remarks

Laboratory models of wave action upon maritime structures fail to simulate the prototype conditions because the model waves are generated at a finite distance from the model structure. The prototype waves, however, may be considered to originate an infinite distance from the structure upon which they act. Similarly, reflections which are propagated seaward have a large expanse of the ocean in which to decay and disappear. In the laboratory, however, reflections from the model become incident upon the wave-generating device which, in turn, acts as a reflector and returns the reflected wave to the model structure. This process continues until the sum of energy losses during reflection consumes the energy of the reflected wave. Such continued reflection allows superposition of each reflected wave and the incident wave to form a test profile which may be entirely different from that desired.

This difficulty may be avoided by restricting test periods to the time interval necessary for the reflection of the initial incident wave to return to the generator. However, such a program is tedious and costly since test runs must be separated by the time required for quiescence of the water surface. This scheme, furthermore, does not permit tests on the effect of wave action of long duration. In addition, the tests are conducted upon transient wave motions which may differ from the equilibrium condition of motion.

Another remedy is furnished by utilizing a wave generator which is nonreflecting. Development of such a generator has been claimed and is described previously in this report [74]. A third method--one which appears to be extremely difficult--may also be cited [10].

The generating machine may be controlled to give not the desired incident wave but, rather, one which when combined with its own reflection will give the specified incident wave.

There is, however, a more practical way of eliminating the difficulties due to reflection. This is through the use of a wave filter between the model area and the generating device. Such a device when placed between the generator and the model should absorb a portion of the wave energy passing through it; it should reflect none. In regard to the nonreflecting characteristics of wave filters, Biésel has indicated that results obtained at the Neyrpic Laboratory show reflections due to the filter to be negligible where the sectional area of the filter occupies about 10 per cent or less of the sectional area of the channel [8].

A wave which is incident upon and reflected from the model must pass through the filter to the generator and after reflection from the generator again pass through the filter before it gains access to the model region. Thus, for an incident test wave of unit height and for a filter of $2/3$ damping capacity, the height of the reflected wave present after being twice reflected through the filter is of $1/9$ unit. This is true if the wave is fully reflected both at the model and at the machine. Actually the machine is not likely to be fully reflecting and the model generally reflects considerably less than 100 per cent of the incident wave.

A second beneficial effect of filters is the characteristic of more severely damping the shorter length harmonics of the fundamental wave. These harmonic components cause the initial wave to appear rough and distorted, but when eliminated they leave the pure fundamental which is desirable for study.

B. Experimental Studies

The types of filters which have been utilized to date are those of the Neyrpic Laboratory [parallel perforated plates and cellular wire mesh structures (Figs. 17 and 18)], the Waterways Experiment Station [parallel perforated plates (Fig. 19)], and those used by Costello at the University of California [vertical circular cylinders (Fig. 20)]. Actually the nonreflecting generator elements of the French Central Hydraulic Laboratory might be considered as another form of filter device (Fig. 13). Experimental data concerning the effects of filters have been found only for tests reported by Meyer [86] and Costello [26]. The test data reported on by Meyer are prefaced

by remarks to the effect that the filter length used appeared to be too short to yield satisfactory results. The data (Fig. 62) indicate that the filter action obtained was extremely unsatisfactory. Low values of damping were noted, the value of the transmission coefficient (exit to incident wave height ratio) varying to make the effect of various depths indeterminate. The tests were apparently conducted with a constant period and variable depth and with increasing incident wave height. An increase in the depth would correspond to an increase in wave length. The period used was 1 sec with depths ranging from 1.25 ft to 2.0 ft, giving wave lengths of the order of 5 ft. The filter length was 2 ft, only $2/5$ of the wave length. As Meyer suggests, wave reflections appear to have existed which gave incorrect records of the incident wave height and, consequently, poor estimates of the filter action. It seems likely that this factor may account for the apparently erratic behavior of the filter.

The tests of Costello were primarily concerned with the effectiveness of several geometric configurations of vertical circular cylinders in reducing wave amplitude through the array. The tests were designed to determine the effects of several piling arrangements on various incident wave forms. The test data were graphically presented in the form of plots of the transmission coefficient versus incident wave steepness, the parameters being depth-to-wave-length ratio d/L , and cylinder array geometry. The most notable feature of these several curves is that the transmission coefficient diminishes very regularly with increasing values of wave steepness. The rate of change of the coefficient is different for various geometries, as might be expected. Of interest also is the fact that variation of the parameter d/L causes a scatter of values for H_t/H_i of no greater degree than might have been expected because of experimental error. Costello observed from this that the effect of d/L may be neglected when considering the effect of the transmission coefficient as a function of wave steepness.

A further presentation of the data indicated the time history of wave transmission through the filter body. These data were determined by observing the height of the wave at several stations through the filter. The tests were undertaken for values of d/L varying from 0.203 to 0.392 and for wave steepnesses of from 0.0775 to 0.0291. These tests indicated that for the particular array of vertical circular cylinders considered, between 40 and 80 per cent of the total decrease of the transmission coefficient occurred

within a distance from the leading edge of the filter of about $L/6$. More generally, for this type of filter, about 80 per cent of the total decrease occurred within a distance of $L/4$ from the seaward face of the filter.

Special note was not made concerning the reflective characteristics of the cylinder arrays considered, although it appears that because of the relatively dense configurations a considerable amount of reflection must have occurred in some instances.

C. Theoretical Studies

Two analyses are available which may be applied in the use of wave filters. The first was performed by O'Brien [101] who determined the energy lost from gravity waves due to the effects of channel wall friction. It appears that in the case of parallel-plate type filters, this analysis should allow determination of the damping which might be expected from the filter. O'Brien's method was to determine the velocities existent in the boundary layer by applying the analysis of Lamb for the case of an infinite plate oscillating parallel to itself with periodic motion and in contact with a semi-infinite fluid. The velocities outside the boundary layer were determined from the theory of gravity waves on the surface of a frictionless liquid. Thus, if velocities are known at any point as a function of the distance from the channel walls, use may be made of the dissipation function in order to determine energy loss due to viscous action.

The energy loss per unit time occurring in a channel length of ℓ may be equated to the difference in entrant and exit power to and from the channel length considered, or

$$P_1 - P_2 = \int_0^{\ell} \frac{N}{T} dx \quad (23)$$

where P_1 is the power transported into the reach at $x = 0$,
 P_2 is the power transported from the reach at $x = \ell$, and
 N is the energy dissipation per cycle per unit length of channel

$$N = \left(\frac{\rho_w}{2} \right) \sqrt{\pi \nu T} \left[\int_0^b (\bar{u}_{y=d})^2 dz + 2 \int_0^d (\bar{u}_y^2 + \bar{v}_y^2) dy \right] \quad (24)$$

where the origin of coordinates is at the water surface with the axis \overline{ox} in the direction of propagation and the axis \overline{oy} positive upward and normal to the water surface. The z-axis forms a right-handed system and is normal to the plane x, y . The maximum horizontal and vertical velocities are \overline{u}_y and \overline{v}_y for any depth y , T is the wave period, ν is the kinematic viscosity, b is the breadth of channel, and d is the depth of water.

A step-by-step method of determining H_2 and P_2 may be used with the previous equations. This method, however, is quite tedious and is susceptible to cumulative error. The right-hand member of the first equation may be evaluated if the incident wave height is known. If the evaluation is performed for a very small length, P_2 and H_2 may be determined. The process can then be repeated for another very small portion of the channel length, and ultimately this method will predict P_2 and H_2 for a finite value of ℓ .

However, for the purpose of comparing theory with experiment, values of N may be computed at various stations along the channel length using the measured values of wave height, period, and depth at these points. Graphical integration then may be used to evaluate $\int_0^\ell (N/T) dx$. When this value is obtained, the power P_2 and the wave height H_2 may be determined.

O'Brien indicates experimental data which differ from the theoretical results by an average value of 11 per cent.

The second theoretical analysis was performed by Biésel [9], who assumed the viscous force which dissipates energy to be linearly related to the velocity. While this assumption allowed the particular physical geometry of the filter to remain undefined, its accuracy became dependent upon the exactness with which energy-dissipating forces follow a linear law with velocity. Biésel remarks, however, that a proportionality coefficient may be utilized to account for deviations from a linear relationship.

For analytical purposes this work considers a fluid which is viscous with respect to friction against the filter body but regarded as inviscid with respect to internal friction. The resulting theory does not indicate the internal mechanism of wave attenuation, nor is it self-sufficient in the determination of damping when only the filter geometry is known.

In the analysis, Biésel has set forth the boundary condition which must be satisfied by the complex potential developed to represent the damped wave motion. The boundary conditions are

$$(a) \quad \nabla^2 \phi = 0 \quad (25)$$

$$(b) \quad \frac{\partial \phi}{\partial y} = 0 \quad \text{for } y = -d \quad (26)$$

$$(c) \quad p = \text{constant} \quad \text{for } y = \eta(x)$$

$$\text{or} \quad \frac{\partial \phi}{\partial t} + \lambda \phi + g \int_0^T \frac{\partial \phi}{\partial y} dt = 0 \quad (27)$$

which are the usual conditions for wave motion, and where λ is a constant and is equal to the viscous force which dissipates energy divided by the fluid velocity.

It is shown that the velocity potential chosen,

$$\begin{aligned} \phi = & \frac{a_0 \sigma e^{-\beta mx}}{m \sinh md} \cos \beta m (y + d) \cosh m (y + d) \sin (mx - \sigma t) \\ & + \frac{a_0 \sigma e^{-\beta mx}}{m \sinh md} \sin \beta m (y + d) \sinh m (y + d) \cos (mx - \sigma t) \end{aligned} \quad (28)$$

does satisfy the boundary conditions if the following relationships exist:

$$\sigma^2 = mg \tanh md \frac{1 - \frac{\beta \sin 2 md}{\sinh 2 md}}{1 - \frac{\sin^2 \beta md}{\cosh^2 md}}$$

and

$$\lambda = \beta \sigma \frac{1 + \frac{\sin 2 \beta md}{\beta \sinh 2 md}}{1 - \frac{\beta \sin 2 \beta md}{\sinh 2 md}} \quad (29)$$

where $\sigma = 2\pi/T$, $m = 2\pi/L$, d is the water depth, β is the rate of damping, and λ is the permeability coefficient, a constant for a given filter.

Now it seems apparent that use may be made of the potential function developed by Biésel to determine the form of the surface profile, since for a theory of the first order

$$\eta = \frac{1}{g} \frac{\delta \phi}{\delta t} \quad (30)$$

or by making use of the potential function developed

$$\begin{aligned} \eta = & \frac{-a_0 \sigma^2 e^{-\beta mx}}{gm \sinh md} \cos \beta m (y + d) \cosh m (y + d) \cos (mx - \sigma t) \\ & + \frac{a_0 \sigma^2 e^{-\beta mx}}{gm \sinh md} \sin \beta m (y + d) \sinh m (y + d) \sin (mx - \sigma t) \end{aligned} \quad (31)$$

where a_0 is the incident wave amplitude, and the other terms are as previously defined.

Note may be taken that the latter factor of Eq. (31) describes the variation of the profile with time and position. The first factor indicates the variation of the profile as a function of the filter-to-wave-length ratio. For the case of the wave height this can be written

$$\frac{H_t}{H_i} = e^{-\beta mx} \quad (32)$$

where H_t is the wave height transmitted, H_i is the incident wave height, x is the length of the filter, and $m = 2\pi/L$.

Now for the case of small values of k (i.e., for long waves), Biésel defines β as

$$\beta = \frac{\lambda}{\sigma [1 + (2 md / \sinh 2 md)]} \quad (33)$$

where $\sigma^2 = mg \tanh md$, the symbols having been previously defined.

To make use of the expressions developed, there remains only the determination of λ . Since λ is defined in the following manner,

$$\lambda = \frac{F_v}{q} \quad (34)$$

where F_v is the viscous force which dissipates energy and q is the velocity. It would appear that values of λ could be determined for a given filter geometry. Another method of determining λ would be by solving for β from Eq. (32), when the transmission coefficient H_t/H_i is known. Biésel's assumption that λ is constant for a given filter could then be followed and determination of the β value for the same filter subject to various wave characteristics could be made through use of Eq. (33). Biésel's work is, of course, a first approximation theory.

There is little theoretical help available in attempting to design a wave filter for a given wave installation. If the filter design were for a "plate" type of installation, the theory of O'Brien and Chaffin would, of course, be of great help in determining the size and characteristic of the filter.

The theory of Biésel, on the other hand, is of no help to the designer unless some experimental work has been done toward evaluating the constants for the filter media. However, the Biésel theory is not limited to any particular filter type as is the O'Brien development. Of course, it is taken for granted that evaluation of the filter constants would include the consequence of assuming the energy loss to be purely viscous in nature.

The experimental work of Costello would provide excellent information for constructing a piling type of filtering device but this is scarcely believed practical. In the absence of further experimental proofs, it is felt that due use may be made of Biésel's description of wave filters in constructing one of a similar type.

IV. WAVE ABSORBERS

The wave absorber as well as the wave filter is of great importance in attempting to reproduce prototype wave conditions in the laboratory. In order to prevent energy from being reflected back into the test channel from its ends, some form of wave absorber must be placed at the channel extremities. The function of such absorbing units is to transform the energy contained in the wave motion so that it cannot be returned to the test channel in the form of reflected wave action.

If this can be accomplished the effect of an endless wave channel is achieved; thus, natural circumstances are more closely approximated. The form and the varied conditions of wave motion make solution of the problem difficult.

In attempting to review absorbers in use at this time and to present briefly the theoretical works, it would appear helpful to define the criteria for a successful wave absorber:

- (a) Nonreflecting.
- (b) Completely absorbing.
- (c) Of as short a length as is consistent with efficiency.

It is easily imagined, for example, that a series of filters with good characteristics might be combined to form a reasonably efficient absorber.

A. Sloping Beaches

Although several other devices have been explored for possible use as wave absorbers, the majority of organized test work appears to have been concerned with the utilization of sloping beaches for energy absorbing devices.

Schoemaker and Thijsse have conducted such a study [116] upon walls of both continuous and discontinuous slope. The discontinuous slopes were formed by a lower vertical wall and an upper sloping section. The point of juncture was at a variable depth beneath the still water surface. Another variable studied was the slope of the upper section of the barrier. These types of structures were studied to evaluate the effect of lengthy beaches as opposed to relatively short, discontinuous beaches.

The data shown in Fig. 21 indicate the trend of the reflection coefficient as a function of the ratio of the horizontal slope distance to the wave length. For the discontinuous slope, the curves of Fig. 22 show the reflection coefficient as a function of t/L , the ratio of horizontal slope projection to wave length; and the parameter h/d , the ratio of submergence of the transition point to water depth. These data, of course, do not include the loss of energy due to viscous action upon a rough and permeable beach and therefore may indicate the worst reflection conditions obtainable by use of a sloping beach.

The Beach Erosion Board, however, has made use of solitary wave studies to determine how the reflective characteristics of various simple structures are affected by alterations of the body porosity and orientation [144]. The test program was divided into four parts:

(a) Permeable rock structures with vertical seaward face and impermeable vertical rear wall. The composition was altered by varying the size of the rock and the thickness of the structure.

(b) Same as the above, except the anterior face was permeable and backed by open water.

(c) Impermeable smooth structures at variable slopes.

(d) Permeable sloping structure backed by open water.

Use was made of the solitary wave theory to avoid the necessity of distinguishing between reflected and incident oscillatory waves.

Note may be taken of Figs. 23 and 24, which show the per cent of energy absorption plotted versus the beach slope for the case of impermeable and permeable sloping barriers. A comparison shows that for the tests presented the permeable sloping barrier is an extremely more efficient damping device than the impermeable sloping barrier. It may also be seen that the per cent of energy absorbed at a given slope increases as the ratio of rock size to water depth increases. More experimental verification of this point would be welcome. Figure 25 from the same source shows the effects of the width of a vertical, impermeably backed structure on wave absorption. It would appear that a width of about 2-1/2 times the depth would yield the maximum wave absorption. This maximum is not, however, as great as the absorption by the sloping barrier. It can be seen again that the increased rock size produces greater values of damping (Fig. 26).

An interesting curve is shown in Fig. 27, wherein the per cent of energy absorbed is given as a function of the per cent of voids in the vertical crib. The indications from this curve are that the most efficient permeable absorber would be one having from 60 to 80 per cent voids.

The presentation of Healy [48] yielded interesting results concerning the damping effect of beaches as shown in Figs. 28, 29, and 30. The tests were run upon a smooth plywood beach of variable slope. Various wave steepnesses were used, varying from about 0.005 to 0.025. The effect of wave

steepness with a 10° beach slope may be seen from the first figure above. As is to be expected, the reflection coefficient rapidly increases for very small wave steepnesses.

The curves of Figs. 29 and 30 show the effect of beach slope on the reflection coefficient and the energy absorption in per cent. An interesting comparison may be seen between the data of Healy and that of the Beach Erosion Board by noting that Healy's curve for the per cent of energy absorption as a function of beach slope in general gives good agreement with the studies of the Beach Erosion Board for the case of an impermeable sloping barrier.

A theory has been developed by Miche to determine the reflective capacity of beaches by considering both the slope and beach roughness or permeability. This was done by evaluating the reflection coefficient H_r/H_i in terms of the slope angle of the beach. The following relationships are presented:

$$\frac{H_r}{H_i} = R\rho, \quad R = \frac{\delta_m}{\delta_o}, \quad \delta_m = \sqrt{\frac{2\pi}{\alpha}} \frac{\sin^2 \alpha}{\pi} \quad (35)$$

where R is a form factor,

ρ is the intrinsic coefficient,

α is the beach slope,

δ_m is the maximum wave steepness in deep water that could be reflected from a smooth slope, and

δ_o is the incident wave steepness in deep water.

The equation for evaluating δ_m was derived by Miche in an analytical treatise on the movements of the sea [89]. A later work by Miche [88] indicates values which may be used for the intrinsic coefficient under various circumstances. It is also stated that if $\delta_m > \delta_o$, then $R = 1.0$. The coefficient ρ is said to be "apparently independent of the barrier slope." Figure 31 shows the results obtained when using $\rho = 0.8$ and applying the theory to the data of Schoemaker and Thijsse [116]. The slopes used were smooth and impermeable.

Miche studied data of the Beach Erosion Board and deduced that ρ may be taken to be 0.68 for rough slopes and 0.9 to 1.0 for smooth surfaces. In the case of a rubble structure, a value of 0.31 was determined for the

intrinsic coefficient by estimating the other factors involved. Figure 32 is presented to show the agreement between the theory (using $\rho = 0.33$) and experimental studies of slopes formed by enrockment and artificial blocks.

Laurent and Devimeux [75] have made investigations of three styles of discontinuous slopes as shown in Fig. 33. Figure 34 represents the test data for the first type of barrier. The conclusions reached from this study were that the reflection capacity of a structure increases as the steepness of the incident wave decreases, and in general for a discontinuous slope the wave reflection decreases as the form approaches that of a sloping beach and increases as the form approaches a vertical barrier. The need for further study of this type of structure seems well indicated.

Other studies have been made which allow the determination of the energy absorption characteristics of beach slopes by virtue of bottom friction and of flow within the permeable media. Putnam and Johnson [106] have investigated the first case. The curves of Fig. 35 show a comparison of their results with waves acting over a nonfrictional slope. The examples chosen were for typical ocean waves. The method involved makes use of an equation developed for the average rate of energy dissipation per unit area of the bottom which is

$$D_f = k \rho_w H^3 \left\{ - \frac{4\pi^2}{3T^3} \left[\frac{1}{\sinh \left(\frac{2\pi d}{L} \right)} \right]^3 \right\} \quad (36)$$

where k is a friction coefficient equal to

$$0.072 (X/p)^{-0.75}$$

X being the horizontal semiamplitude of particle motion at the bottom and p the pitch of ripples formed in the bed.

If the origin of the coordinate axes is located at the point where the depth equals $1/2$ the wave length, the power entering this region can be computed from the incident wave characteristics. Then, assuming the bottom friction negligible, the wave height may be computed for increasing values of x (i.e., in the direction of decreasing depth). These first approximations of the wave height may then be used in the equation for energy dissipation to determine dissipation as a function of x . Graphical integration of a

plot of D_f versus x yields the energy loss per unit width up to any desired value of x . If the loss is then deducted from the incident power at $x = 0$, the remainder is the energy available at x . From this the wave height H_f at x may be computed; H_f denotes "friction wave height" or the wave height on the beach after considering the dissipation of wave energy. Putnam indicates that in general several approximations must be employed.

The ratio of the wave height H_f (considering friction) to the wave height H (excluding friction) becomes

$$\frac{H_f}{H} = \sqrt{\frac{P - \Delta P}{P_0 (1 - MH^2/L^2)}} \quad (37)$$

where P_0 is the rate of wave energy entering the section at $x = 0$,

ΔP is the rate of loss of energy equal to $\int_0^x (D_f b) (dx)$,

$M = 4.935/\tanh^2 (2\pi \frac{d}{L})$, and

$$H = \sqrt{16 b_0 P_0 T/wbL (1 - MH^2/L^2)}$$

where the latter is determined by equating the energy of wave motion in deep water to the energy of wave motion in shallow water.

The method developed assumes (a) horizontal motion which is sinusoidal at the channel bottom, (b) a plane surface of constant slope, (c) a constant friction coefficient, and (d) negligibly small percolation at the permeable bed. The assumption of a constant friction coefficient may be serious, although the authors remark that since k enters the dissipation equation only to the first power, its value could be in error by ± 50 per cent without appreciably changing the order of magnitude of the results . . . "

The effect of percolation currents at the bed has been discussed separately by Putnam [104]. The bed, however, is assumed to be horizontal; therefore, the analysis should properly not be applied to relatively steep slopes such as permeable absorbers at the extremities of wave channels. Putnam has indicated, however, that the order of wave height reduction due to sea bed permeability is very small compared to bottom friction unless the slope of the beach is quite flat.

The transmission coefficients of a sloping barrier which does not reach to the bed of the channel have been investigated by Hamilton [46] for varying degrees of submergence and slope of the barrier. The barrier used by Hamilton was a board whose width spanned the channel and whose length was of the order of the wave length. The board was suspended in the channel with the upper edge at, slightly above, or slightly below the free surface. The results of Hamilton's study are shown in Fig. 36. The presence of upstream reflections due to the sloping barrier was noted in some instances although it is presumed that upstream amplitude measurements were taken prior to the time reflections reached the measuring station.

Within the limits of the wave heights tested it was found that the transmission coefficient depended chiefly on the wave length and upon the board elevation. For example, long waves apparently passed underneath the barrier with relatively little loss of energy. The wave height and the slope of the barrier exerted secondary influences. From the first figure it can be seen that the submerged barrier does little to reduce downstream wave height, average reduction being about 20 per cent. The barrier with small slope, its upper edge at the water surface, appears to be more effective for short wave lengths.

B. Other Devices

In 1931 experiments were carried on at the U. S. Experimental Model Basin to determine the most effective method for destroying wave energy at a reflecting wall [160]. Figure 37 indicates the types of absorbing devices tested. In addition, cylinders of No. 16 wire mesh were tested. Remarks concerning this study indicate that circular cylinders located parallel to the reflecting wall performed best when the ratio of cylinder diameter to wave length was of the order of 1 to 5. This type appeared to be the best of the sections tested, followed by the U-type trough. From observation, the mechanism of energy dissipation with the circular section was said to be due to

(a) Part of the incident energy being divergently reflected in the vertical direction.

(b) Part of the wave energy simultaneously passing beneath and over the cylinder resulting in turbulence between the wall and cylinder.

(c) The remaining energy being reflected and subjected to the same action in passing out to the open water.

The results of studies developing transmission and reflection coefficients for various underwater barriers are presented by Johnson, et al [63] at the University of California. These California tests are indicated by Fig. 38, while Figs. 39, 40, 41, and 42 represent the effect of the various parameters upon the transmission coefficient. Underwater barriers of the types shown in Fig. 43 were tested by the Beach Erosion Board and reported in the preceding reference. The curves of Fig. 44 indicate the transmission coefficients for the trapezoidal and triangular submerged barriers. No information was given concerning the reflection coefficients of these barriers; such studies would be of much interest.

The curves of transmission and reflection coefficients determined by Ursell [132] and Dean [32] are also shown for vertical barriers beneath the water surface (Fig. 45).

Dean [31] has also investigated the case of a plane barrier inclined at an angle of $\pi/2s$ to the free surface. Solutions for the equations of wave motion to the first order of approximation are presented for the case of $s = 1, 2, \text{ and } 3$. For the case of $s = 3$ (30°), the form of the free surface is calculated and the resulting wave profile is given.

Devices which were tried at the NACA Towing Tank to calm disturbances following a tow run have been described by Truscott [131]. These suppressors were wooden frames covered by fine copper screening and placed horizontally just beneath the surface of the water. Cloth screens and floating screens were indicated to be unsuccessful upon application. Truscott also describes the towing tank of the University of Michigan, which has the tank walls covered near the surface of the water to "turn the crests back upon the waves," a procedure which apparently was successful in decreasing the wave action following a tow run.

The action of a sheet of air bubbles released near the bed of a wave channel in dissipating wave energy is discussed by Carr [22], who concludes

(a) Such an air screen induces vertical water currents which separate into upstream and downstream currents at the water surface.

(b) The bubble screen cannot be a reflecting barrier. The only momentum change at the screen is the slight change in wave

velocity in the aerated region, since the screen cannot resist horizontal forces. This indicates only very small height changes at the bubble screen.

(c) A pneumatic barrier can dissipate energy only through surface current action.

(d) Practically only deep water waves can be appreciably reduced by a surface current.

Yu [139] has shown that the effect of surface currents on wave action in deep water causes complete breaking of the wave if the velocity of the current is $-1/4$ the velocity of the wave front. Also shown is the ratio of the wave height following the opposing current, to the initial wave height for the case where the stream velocity is less than $1/4$ of the wave velocity. This ratio is given by

$$\frac{H}{H_0} = \left[\frac{2}{1 + 4 (V/C_0) + \sqrt{1 + 4 (V/C_0)}} \right]^{1/2} \quad (38)$$

where V is the velocity of the surface current, C_0 is the wave celerity at a distant region, H is the wave height in the current region, and H_0 is the wave height at a distant region. The wave length alteration is also shown to be

$$\frac{L}{L_0} = \left(\frac{C}{C_0} \right)^2 = \frac{[1 + \sqrt{1 + 4 (V/C_0)}]^2}{4} \quad (39)$$

where L is the wave length in a distant region, L_0 is the wave length in the current region, and the steepness ratio is

$$\frac{H/L}{H_0/L_0} = \frac{\left[\frac{2}{1 + 4 (V/C_0) + \sqrt{1 + 4 (V/C_0)}} \right]^{1/2}}{\frac{[1 + \sqrt{1 + 4 (V/C_0)}]^2}{4}} \quad (40)$$

It is possible by use of the foregoing to determine the maximum steepness which the initial wave may have and yet not break upon entrance into the surface current region. To determine this value of H_0/L_0 , the term H/L should be set equal to $1/7$. This defines the maximum wave steepness which can exist in the surface current region. These results may also be found in reference [22], as well as an extension of the theory to be applicable to either deep, transition, or shallow water waves. Experimental work at California has verified the above theory.

Bagnulo and Burlin [3] have reported some work on absorbing devices in connection with their thesis study. Various absorbent materials tested were perforated brick, cement and tile building blocks, wooden baffles, wooden floats, metal screening devices, and sand and rock beaches. These materials were placed at the channel end in various configurations. Only the sand and rock beaches, however, were said to be effective enough to warrant their use (Fig. 46). The stone sizes used were 1- to 3-in. diameter and placed on a slope of 30° . Although the sand beach was felt to be slightly superior for absorbing purposes (about 85 per cent energy absorption), the stone beach was used for the thesis work because it could be built by placing individual stones and because the channel water remained clearer than it would have if sand had been used.

From the viewpoint of the designer who wishes to install an effective wave absorbing system in his laboratory wave channel, the foregoing information indicates that only rather limited knowledge is available on which to base the design. However, it should be noted that for this purpose the most promising method of energy absorption appears to be through use of a permeable sloping beach.

Evidence indicates that the sloping permeable barrier is a better energy-dissipating device than the sloping impermeable barrier alone. It is not possible on the basis of existing experimental data to evaluate separately the effects of slope and of permeability. Consequently, no statement can be made as to which of the two parameters is the more important in energy dissipation. Experimental work is therefore necessary in order to evaluate the relative effects of permeability and of slope.

V. INSTRUMENTATION

The problem of recording wave action and its effects in an experimental laboratory has likely been the source of more difficulty than has any other facet of such a program. Since measurement of wave action in model installations requires rather precise degrees of accuracy for a phenomenon which is transitory in nature, it has been only with the application of electronic instrumentation that satisfying results have become available.

The various quantities which are often desired are

- (a) Wave profile.
- (b) Wave amplitude.
- (c) Wave celerity.
- (d) Orbital velocities.
- (e) Orbital paths.
- (f) Wave length.
- (g) Forces exerted by waves on objects.

A. Methods Used in the Determination of Variables

A wide variety of methods have been used for the determination of the seven variables listed above; a brief summary of the methods is as follows:

1. Wave Profile and Wave Amplitude

- a. Float-actuated tracing mechanisms.
- b. Surface-seeking servo-mechanisms and recorders.
- c. Resistance-type probes and recording systems.
- d. Step resistance probes and recording systems.
- e. Optical reference devices.
- f. Hook and point gage methods.
- g. Capacitance-type probes and recording systems.
- h. Photographs with calibrated grids.

2. Wave Celerity

- a. Computed from wave-length and period measurements.
- b. Measured by timing wave passage over a known distance.

3. Orbital Velocities and Orbital Paths

From photographic traces of droplets of $SG = 1$.

4. Wave Length

- a. Measured by synchronous flashing point gages.
- b. Determined from celerity and period measurements.

5. Forces Exerted by Waves on Objects

- a. Deflection of cells containing strain gages.
- b. Piston cells, preloaded by calibrated springs.
- c. Cells containing linear differential transformer.

Since the above methods have little in common, there seems to be no point in comparing their relative merits save in the instance of methods for determining wave profile and amplitude.

B. Summary of the Disadvantages of Methods

Each of the methods enumerated appears to have certain inherent disadvantages; a short summary of these might be of interest.

1. Float-type Devices

Float-type devices depend on a system where inertia of the mechanical linkages connecting float and scribe may become of importance. Similarly, friction of the connecting devices may serve to modify the true record of the float movement. A float also cannot be depended upon to follow precisely the elevation of the water surface for all wave periods and amplitudes. Such a system is, however, economical to construct and may produce acceptable data for some conditions.

2. Surface-seeking Servo-mechanisms

Surface-seeking servo-mechanisms seem particularly well adapted to lower frequency oscillations where inertia effects are not overly pronounced. These devices appear, however, to be of rather complex construction.

3. Resistance-type Probes and Recorders

A relatively simple electrical circuit may be used with resistance-type probes and recorders, although these systems may not be linear for large amplitudes of motion. A further complication is that the system calibration must be dependent upon the conductivity of the medium and the proximity of the probe to ground.

4. Step Resistance Probes and Recorders

Step resistance gaging methods, while extremely useful for field work, appear to be too cumbersome in general for rather small-scale laboratory studies. Also, they do not report continuously but rather in a number of discrete steps.

5. Optical Reference Devices

Optical reference devices appear to be useful in large area model work--the "starred sky" method, for example--but for general wave study these methods yield only the amplitude of motion and appear to require slow and painstaking steps in use.

6. Hook and Point Gage Methods

Hook and point gage records yield only amplitude or height measurements and for exactness must depend upon a train of exactly similar waves. It becomes extremely difficult to determine the characteristic of a wave train with reflections superimposed when using such a system.

7. Capacitance-type Probes and Recorders

Capacitance-type probes and recorders are linear devices over any range of amplitude and are unlimited in frequency response for water waves. Their characteristic is not dependent upon the probe position nor upon the resistivity of the medium in which the probe is immersed. The attendant circuit is, however, quite complex.

8. Photographs with Calibrated Grids

Photographs of waves passing by calibrated grids are very useful, but errors in measurement may occur if care is not taken while photographing. More important, the records of a given run are not immediately available for reference.

The following abstracts describe in more detail some of the methods for laboratory wave measurements. Further discussion of these widely deviant methods seems unwarranted here.

APPENDIX A
(Abstracts and Annotations)

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ABSTRACTS

1. Biésel, F. "Équations de l'écoulement non lent en milieu perméable—application au calcul des filtres à houles" (Equations of Relatively Rapid Flow Through Permeable Media; Application to the Analysis of Wave Filters). La Houille Blanche, No. 2, pp. 157-160. 1950.

This article was written in an attempt to provide a theoretical background for the operation of the wave filter. An admitted fault of the thesis is that it assumes the energy-dissipating force to be proportional to the first power of the flow velocity.

The theory developed is to the first order of approximation and the fluid is considered viscous only with respect to friction against the filter.

In the equation of motion

$$\nabla \frac{p}{\rho_w} + \nabla \frac{\delta \phi}{\delta t} + \nabla \frac{q^2}{2} - F = 0 \quad (41)$$

the assumption is made that

$$F = \nabla \Omega - \lambda \nabla \phi \quad (42)$$

where Ω is the external force potential equal to $-gy$ and λ is a positive constant. The force dissipating energy within the filter is F .

The resulting form becomes

$$\frac{p}{\rho_w} + \frac{\delta \phi}{\delta t} + gy + \lambda \phi = \text{const.} \quad (43)$$

The boundary conditions are

$$\begin{aligned} (a) \quad \nabla^2 \phi &= 0 \\ (b) \quad \frac{\delta \phi}{\delta y} &= 0 \quad \text{for } y = -d \\ (c) \quad p &= \text{const.} \quad \text{for } y = \eta(x) \end{aligned} \quad (44)$$

where the origin of the coordinate axis lies on the free surface of the water and the positive x -axis extends in the direction of wave propagation. The y -direction is vertical and the system formed is right-handed.

$$\begin{aligned}
 d &= \text{water depth} \\
 \phi &= \text{velocity potential} \\
 \rho_w &= \text{fluid density} \\
 \eta(x) &= \text{equation of the free surface}
 \end{aligned}$$

From the equation of motion and the boundary conditions the complex potential is obtained

$$w = \frac{a\sigma}{m \sinh md} e^{-\beta m(z + id)} \sin(mz - \sigma t + imd) \quad (45)$$

where the complex variables are $z = x + iy$ and $w = \phi + i\psi$, and where a is the wave amplitude, $\sigma = 2\pi/T$, $m = 2\pi/L$, and β is the rate of damping; and the relationships among β , σ , and λ are

$$\sigma^2 = mg \tanh md \frac{1 - \frac{\beta \sin 2 \beta md}{\sinh 2 md}}{1 - \frac{\sin^2 \beta md}{\cosh^2 md}} \quad (46)$$

$$\lambda = \beta \sigma \frac{1 + \frac{\sin 2 \beta md}{\beta \sinh 2 md}}{1 - \frac{\beta \sin 2 \beta md}{\sinh 2 md}}$$

Thus, if the "permeability coefficient" λ , the wave characteristic md , and σ are known; the damping rate β may be determined.

2. Biésel, F. "Filtre à houles" (The Wave Filter, Neyrpic Method). La Houille Blanche, May-June, 1948.

This article describes the Neyrpic wave filter and is the only generalized discussion of wave filters, their use, and their characteristics known to the reviewers.

Great difficulties are encountered when a channel is used for model tests on wave motion if no provision is made to absorb the wave energy at one end of the channel. This is so because the incident waves are reflected and the reflected waves return toward the generator which reflects them once more.

Therefore, the profile of the incident wave is disturbed, often having no relation whatsoever to the phenomenon which must be reproduced. To surmount this difficulty the Neyrpic Laboratory has developed the wave filter which attenuates waves passing through it.

The principle is well illustrated by considering an incident wave of unit height which is fully reflected at the model and which upon passing through the filter to the generator is diminished to $1/3$ -unit height (for a filter passing only $1/3$ of the entrant wave height). Upon reflection from the wave machine the wave is diminished to $1/9$ -unit height upon reentering the model test zone. Thus the addition of a filter has, for the extreme case of full reflection, allowed a disturbance of only $1/9$ unit to be superimposed upon the incident wave. The difficulty of this system is that a wave of 3-unit height must be generated at the machine. However, this effect can be counteracted by constructing a convergent channel which amplifies the wave height obtained from the machine. (Reference [153] describes such a convergent channel.)

Considerable benefit may be gained from the selectiveness of the filter, which more stringently attenuates the shorter length harmonics of the fundamental wave. Biésel indicates that if for waves of length L the reduction of amplitude is $1/n$ through the filter, then for waves of length L/K the reduction in amplitude is $1/n^p$ where $p = K^{3/4}$.

Thus, for a wave machine which has periodic motion, the wave train generated is comprised of harmonics having periods of $T, T/2, T/3 \dots$; and lengths of $L, L/4, L/9 \dots$ etc. (This is for depths large enough so that $\tanh 2\pi d/L$ approaches unity.) Then if the fundamental were damped in the ratio of $1/2$, the second harmonic would be damped by $1/7.1$ and the third harmonic by $1/36.8$. Similarly, if the fundamental transmission coefficient were $1/3$, the second and third harmonics would be $1/22.4$ and $1/302$, respectively.

An analogy then is presented between the selective action of the wave filter and the natural regulatory action of immense spaces of the sea which cause the short harmonics to be rapidly decayed leaving the long smooth swell.

The application of wave filters appears to be particularly well suited for use in a wave channel or flume. Filters may also assume importance

in studies involving three-dimensional models such as harbors, jetties, and the like, although in these instances they may more often take the form of energy absorbers placed around the perimeter of the model area.

3. Biéssel, F. and Suquet, F. "Les appareils générateurs de houle en laboratoire." La Houille Blanche, Nos. 2, 4, and 5, 1951; No. 6, 1952.

This series of articles is a complete and thorough discussion of various wave-generating devices describing the various criteria desirable for a laboratory wave-making device. Many such machines which at present are in use at various hydraulic laboratories are described in detail. The factors of inertia, maintenance, reflective characteristics, regulation, mobility, leakage and friction, and the aspects of motion are evaluated for several different styles of machines.

A first-order theoretical study of generator performance is made with resultant equations which allow quite easy determination of the wave profile, wave amplitude, and the pressures exerted upon the machine. The amplitude of the wave generated is shown to be

$$a = c_0 \sinh md \quad (19)$$

where d is the water depth, $m = 2\pi/L$, and

$$c_0 = 2m \frac{\int_0^d \xi(y) \cosh my \, dy}{\sinh md \cosh md + md} \quad (10)$$

The function $\xi(y)$ defines the law of motion of the generating member with respect to the spatial coordinates x and y . In the case of a piston-type generator whose displacement from the mean is e , $\xi(y) = e$. In the case of a flap hinged at the bed whose displacement from the mean is e at the water surface, $\xi(y) = ey/d$.

The pressures acting upon the generating blade are given by Biéssel as follows:

- (a) A hydrostatic pressure

$$p_H = \rho_w g (d - y) \quad (16)$$

(b) A pressure fluctuation

$$p_n = \rho_w g a \frac{\cosh my}{\cosh md} \cos \sigma t \quad (17)$$

(c) An inertia pressure

$$p_i = \rho_w g \sum_{n=1}^{\infty} c_n \tan m_n d \cos m_n y e^{-m_n x} \sin \sigma t \quad (18)$$

where

$$c_n = 2m_n \frac{\int_0^d \xi(y) \cos m_n y dy}{\sin m_n d \cos m_n d + m_n d} \quad (10)$$

and values of m_n are the positive solutions of the equation in

$$\sigma^2 = -\alpha g \tan \alpha d$$

This analysis is applied to several typical forms of generating devices. Such application was made to show that the extraneous disturbances of the water surface at the generating machine may be of the order of magnitude of the generated wave. The analysis further showed that these disturbances became negligible at a distance of three depths downstream.

Lastly, a group of engineers at the Neyrpic Laboratory discuss how use is made of the theory developed in their own wave studies. By way of illustration the authors describe three different laboratory installations for the study of waves or harbor problems. In conclusion they indicate the necessary and feasible improvements in design and construction of wave-generating machines, most of which have already been incorporated in prototypes and tested.

4. Blosset, M. Théorie et pratique des travaux à la mer. Paris: Eyrolles, 1951.

The accompanying sketch (Fig. 47) indicates the principle underlying the means of measuring surface heights described within this book. As the surface level changes, the immersion of the point gage makes a different sound in the phone set. The gage is then readjusted until the signal changes.

(It is deemed possible to introduce an electronic circuit to drive the point gage automatically in accordance with the signal from the gage. Although such a system appears more useful for tidal or other long-period studies, it seems that it can be used for work with oscillatory waves.)

5. Carr, J. H. "Long Period Waves or Surges in Harbors." Proceedings of the American Society of Civil Engineers, Vol. 78, Separate No. 123, April, 1952.

The system of a resistive type of model wave recorder is briefly described under the subtitle "Model Studies" of this work:

Wave heights were measured by electrical conductivity elements, consisting of a pair of spaced wires projecting into the water. A constant alternating-current voltage is applied across the two wires of an element. The resulting current flow depends on the immersion of the element and hence is a function of the wave height at any instant. The current signal, representative of the vertical water motion at the element location, is recorded on a galvanometer oscillograph.

6. Carr, J. H. Mobile Breakwater Studies. (Abstract of Section 4.2, "Laboratory Studies of Wave Damping by Uniform Current Flow.") California Institute of Technology, Hydrodynamics Laboratory Report No. N-64.2, December, 1950.

The studies reported in this paper deal with the effect of progressive waves entering a region of current flow. This section (4.2) first presents what is called the Scripps Institute of Oceanography theory for the damping of deep water waves by an opposing current. The development and equations are the same as those reported upon by Yu [139], and hence will not be repeated. Figures 48, 49, and 50, however, portray the variation of wave length, wave height, and steepness as a function of the ratio of current velocity to wave celerity.

The paper extends the SIO theory, however, to include the case of transition or shallow water waves entering a zone of current flow. Thus, utilizing the equivalence of periods at the boundary between the incident wave and the wave in the current regime, it is found that

$$\frac{L}{L_0} = \frac{\sqrt{gd}}{C_0} \sqrt{\frac{\tanh(2\pi d/L)}{2\pi d/L}} + \frac{V}{C_0} \quad (47)$$

where the zero subscript refers to the still water area and d is the water depth.

This equation is shown in Fig. 51 where the dotted line indicates an imaginary solution.

Making use of the fact that the slope of the curve of V/C_0 versus L/L_0 is zero at the critical value--i.e., the ratio of the current velocity to wave velocity at which the waves cease to be propagated into the stream--it is shown that the velocity of the opposing current is

$$V = - C'_g \quad (48)$$

or the opposing current velocity necessary to stop a given wave train is equal to the group velocity of the wave train in the current.

Through use of the equation for L/L_0 and the continuity of energy criteria

$$h_0^2 C_{g0} = h^2 C_g \quad (49)$$

a numerical solution may be found for the relationship of wave height and wave steepness within and without the current region for given values of the current-to-wave-velocity ratio. This procedure is given by example.

Discussing the mechanism of wave damping by adverse currents, the author states that,

In the case of deep water waves, the wave steepness is increased by a refraction process similar to that over a sloping bottom and wave breaking is so induced. In the case of shallow water waves, energy is stored at the current - still water boundary until the wave steepness is increased to the breaking point.

7. Carr, J. H. Mobile Breakwater Studies. (Abstract of Section 4.1, "Laboratory Studies of the Pneumatic Breakwater.") California Institute of Technology, Hydrodynamics Laboratory Report No. N-64.2, December, 1950.

This paper discusses the results of three theoretical treatments concerning the effect of a bubble screen on wave motion. Model observation, however, "quickly showed that very small air flow rates would indeed cause appreciable damping of deep water waves, but even with flow rates so high as

to cause violent surface disturbances, the air breakwater had no effect on transition or shallow water waves."

The experiments verified a theoretical assumption that the release of air from a submerged pipe produces a horizontal surface water flow. They further verified that the surface flow thus produced accounts for the total effect of the breakwater action. (This led to the next study, "Wave Damping by Uniform Current Flow.")

8. Costello, R. D. "Damping of Water Waves with Vertical Circular Cylinders." Unpublished M. S. thesis, University of California.

This paper reports a study of the effect of waves moving through a group of vertical circular cylinders which might be taken to represent piling groups. Considerable experimental evidence was recorded to evaluate the energy loss through the various cylinder groups.

The various test groupings studied are shown in Fig. 20. The variables tested were relative depth d/L , wave steepness H/L , and the filter geometry. Figures 52 and 53 are graphical representations of the test results.

The following conclusions were reached:

- (a) Variations of the wave transmission ratio H_t/H_1 are independent of the depth-to-wave-length ratio.
- (b) The dense configuration of Type I, Fig. 20, yields the greatest damping (58 per cent at $H/L = 0.100$, 24 rows; and 42 per cent at $H/L = 0.08$, 48 rows).
- (c) The test sections are highly selective in their damping ability, becoming effective only with increased wave steepness.
- (d) Between 40 and 80 per cent of the wave attenuation occurs in the first $1/5$ of the filter length.
- (e) Regardless of pile arrangement (as long as the spacing is uniform in each direction), increasing the number of rows by 100 per cent results in an average decrease in wave transmission of only 17 per cent.
- (f) For a given filter length l , the types of order of decreasing damping are I, II, V, IV, and III (Fig. 19).

9. Coyer, C. B. A Multi-Purpose Wave Generator. Bureau of Yards and Docks Technical Digest No. 22, February-March, 1952.

This report completely describes a versatile machine which can produce motion varying from pure horizontal translation of the blade to rotation of the blade about its lower end. The actuating linkages and members are self-supporting from the base, and the blade alone is immersed in the water.

Also included is a brief summary of types of machines in existence.

(a) The vertical oscillating plunger which does not produce the proper orbital velocities and which requires balancing.

(b) The pneumatic type, consisting of an air dome supplied with an alternating pressure. Coyer states that this machine does not give the correct particle motion and is difficult to control and operate.

(c) The hinged plate and roller hinged plate (Fig. 54).

10. Daily, J. W. and Stephan, S. C. The Solitary Wave. Massachusetts Institute of Technology, Hydrodynamics Laboratory Technical Report No. 8, June, 1952.

This study is concerned with the measurements of celerity, wave profile, internal velocities, and amplitude attenuation. It also presents a résumé of theoretical determinations of these quantities and correlates theory and experiment.

Wave profiles were finally measured by means of photographic techniques after little success had been achieved through the use of step resistance gages, wire-to-plate resistance elements, and capacitive probe methods. Photographic methods were also used for celerity measurement after other means were tried. Two recorders a given distance apart were tried; they were used in conjunction with a time marker. Also tried was a fork-shaped device which started and stopped a timing device whenever the successive probes were contacted. The difficulty experienced with these types of instruments was that very small attenuation of the moving wave or slight differences of succeeding waves in a train would cause different parts of the form to intercept the probes.

Orbital velocity measurements were made by a method employing a moving film and stroboscopic lights. Photos were taken of η -butyl thalate and xylene droplets against a grid. The droplets, of course, had $SG = 1.0$.

11. Hamilton, W. S. "Forces Exerted by Waves on a Sloping Board." Transactions of the American Geophysical Union, Vol. 31, No. 6, p. 849. December, 1950.

This report gives the results of a study which was undertaken to evaluate the forces exerted upon a sloping rigid board as a result of wave action, and to determine the disturbances produced by the board.

Specifically, for the board at or very close to the surface of the water and inclined at a given angle, the following were to be determined:

- (a) The increase in wave height upstream.
- (b) The ratio of transmitted to incident wave height.
- (c) Reaction of the board supports. The wave heights varied from 0.1 to 0.6 ft and the wave lengths from 1.3 to 20 ft.

Figure 36 illustrates the test results obtained and the conditions of testing. The various slopes appear not to affect the H_t/H_i ratios appreciably. The variation between points is large enough to make evaluation of the slope effect very difficult.

Curves are also presented which portray the forces exerted upon the supporting members of the board as a function of wave and board characteristics. An approximate solution for these forces has been developed and presented by the author.

12. Isaacs, J. D. and Wiegel, R. L. "The Measurement of Wave Heights by Means of a Float in an Open End Pipe." Transactions of the American Geophysical Union, Vol. 30, No. 4, August, 1949.

The phenomenon reported upon was a study of the usefulness of a float type of wave meter for sea use. The model study, however, is indicative of the feasibility of this instrument for laboratory use.

The effect of wave periods near the natural period of the tube and float was determined and is shown graphically by the magnification-factor - period-ratio curve (Fig. 55). The theoretical magnification curve was determined analytically from the differential equation of motion of the float subject to the forcing wave function. Experimental data showed excellent agreement with the analytical results.

The tubes used for the test work were of 1-in. diameter and of 1- and 2-ft lengths. The shorter tube had a natural period of 1.14 sec and the longer tube of 1.64 sec. From the curve shown it appears that for wave periods greater than twice the natural period, the magnification factor is very nearly unity.

It was noted that a significant phase shift occurred for values of the natural-period - to - wave-period ratio between 0.6 and 1.0.

The author states that the instrument would likely respond to the short sinusoidal Fourier components of a trochoidal wave; hence, the frequency spectrum present in an ocean wave would likely render the instrument valueless and would nullify an attempt to calibrate the resonance for a series of constant period waves.

13. Johnson, J. W., Fuchs, R. A., and Morison, J. R. The Damping of Submerged Breakwaters. University of California Report No. HE 116-322, April, 1951.

This report presents the results of an experimental investigation and the comparison with theory of the damping action of submerged rectangular breakwaters. A summary of information on the damping action of trapezoidal and triangular breakwaters, reefs of various configurations, and plane barriers is included.

The test variables were the height and width of the barrier, the water depth, and the wave steepness. Both sloping and horizontal beaches were used.

The experimental results shown were as follows:

(a) A barrier with a given height-to-water-depth ratio is more effective in damping steep waves than flat waves.

(b) The wave steepness effect is small when the top of the barrier is at or slightly above the still water level.

(c) Jeffery's theoretical curve is in good agreement with the experimental work for low wave steepness. This theory predicts the most effective barrier width to be $1/4$, $3/4$, $5/4$. . . of the wave length.

(d) The effect of relative depth (water depth to wave length) becomes important when the barrier top is located near the still water level.

(e) On a sloping beach the tests indicate that the most effective damping may occur when the barrier is located about one wave length from the normal break point.

14. Kempf, G. and Hoppe, H. "Die Erzeugung masstäblicher Meereswellen bei Modellversuchen" (The Production of Ocean Waves to Scale in Model Tests). Werft-Reederei-Hafen, No. 10, 1929. (Waterways Experiment Station Translation No. 43-13.)

This paper reports upon the development of a wave-generating machine for ship model test studies. The generating mechanism is a vertical plunger unit actuated by a rotating crank. The method of determining the profile of the plunger is described below.

The cross-sectional area of the wave (Fig. 56) is assumed to be sinusoidal and of not more than 0.4 sq m. This definition gave the limiting curve of Fig. 57. The sectional area of the plunger must obviously be equal to the area of the wave. The maximum immersion depth was selected as 50 cm and the crank radius to connecting rod length was 1:5. Since the motion is sinusoidal, the displacing area must be uniform per centimeter of submergence if the wave displaced is to be immediately propagated at a uniform speed; that is, a rectangle of width (plunger width) = $(0.4 \text{ m}^2 / 50 \text{ cm}) = 0.8 \text{ m}$. Determination of the power requirement was made by Lamb as follows:

$$E = \frac{1}{2} \rho_w g \left(\frac{H}{2} \right)^2 L b \quad (50)$$

and then

$$HP = E \frac{1}{75} \left(\frac{2\pi}{g} L \right)^{-1/2} \quad (51)$$

using an efficiency of 65 per cent. In the above, E is the energy per wave length, H is the wave height, ρ_w is the fluid density, L is the wave length, and b is the channel width.

The symmetry of the wave shape depends upon the uniformity of the crank speed and the cross-sectional shape of the plunger. It is known that the sinusoidal velocity distribution in the case of a crank drive is distorted by the ratio of crank to connecting rod length where the correction factor is $1 \pm (r/\ell) \cos \theta$. Its influence is included in the cross-sectional shape of the plunger so that the displacement within the time unit is sinusoidal. The wave evolved was compared with both a sinusoidal shape and a trochoidal profile. The generated wave was between the two curves but nearer the trochoid. This result is interpreted as meaning that a sinusoidal wave is generated which changes into a trochoid as it progresses downstream. Because of this form change, the actual limiting curve of Fig. 57 exceeds the theoretical limiting curve since a trochoid having the same volume displacement exceeds the height of the sinusoid. The remainder of the grid denotes the limiting curves for other strokes and speeds of generator operation.

An interesting capacity diagram for the machine is given in Fig. 58. The value α is the model scale. By knowing the desired prototype wave length and steepness, the diagram yields the minimum value of the scale ratio α which can be used to model the wave in the wave tank to which the diagram pertains. For example, if a prototype wave of 60-m length and 2-m height is desired, it can be seen that the minimum value of α should be 8.4. Hence, the model wave would be of 7.15-m length and 0.238-m height. From Fig. 57 these values can be seen to correspond roughly to the limiting curve for the machine. In this instance a somewhat larger value of α should be chosen.

15. Killen, J. M. A Capacitive Wave Profile Recorder. University of Minnesota, St. Anthony Falls Hydraulic Laboratory Technical Paper No. 11, Series B, October, 1952.

This paper describes a method whereby wave heights are measured electronically with a recording oscillograph; the deflections correspond to that portion of an insulated wire which is beneath the free surface of the water. This insulated wire acts as a small capacitor whose capacity varies directly with the wetted area of the wire. The system has a linear calibration. Thus, accurate and continuous wave profiles can be recorded. A sensitivity up to 1/2-cm pen deflection per 0.001-ft variation in water level is possible. The recorder will operate with a wide variation in sensing element size and length; consequently, the instrument may be used for a very wide variation in wave height, from a few hundredths of a foot in model studies to many feet in nature.

16. Koelzer, V. A. "Experiments on Waves in Rectangular Channels." Unpublished M. S. thesis, University of Iowa, June, 1939.

A portion of this thesis was devoted to describing the development and calibration of a float type of surface recorder. The principle of operation is shown in Fig. 59. As the float moves up and down, the scribe inks a similar trace on a moving tape. The inertia of the thin pyrolin float gave some error, as did the friction of the pencil scribe. The error due to pivot friction, however, was believed small.

A theory was developed to correct the float measurements; however, the author concluded that the uncorrected curves appeared to be more accurate than the corrected ones. The average error in vertical displacement was 0.049 inches; the average error in time was 0.023 sec. Typical hydrographs show water rises of 2 inches in about 7.8 sec.

17. Larras, J. and Laurent, J. "Experimental Research on Wave Formation, New Method of Generation." Revue Générale de l'Hydraulique, No. 59, p. 251. 1950.

The problem, solved by use of the wave generator described herein, was to generate a pure wave formation and to avoid counter-reflection at the generator of waves already reflected from reflecting barriers.

The apparatus at the French Central Hydraulic Laboratory consists of a hinged plate placed at one end of the channel with downstream pliable elements or curtains suspended vertically from the top of the channel. The motion imparted to the water by the plate gives rise to a movement in the consecutive pliable elements in such a way that they act as a transmitter of movement, the last element behaving in effect as the true generator. The different sections of water, bounded by two consecutive pliable elements, present successive differences in phase.

In order to stifle waves reflected from a downstream obstacle, the different characteristics of the element assembly (i.e., the spacing and the bottom weights of the pliable partitions) must be adjusted for the particular wave being generated.

The device, which has produced waves of 29.5 ft in length, is said to be very economical in construction and to absorb reflected waves completely.

18. Laurent, J. and Devimeux. "Experimental Investigation of Wave Reflection from Steep Obstacles." Reprint from Revue Générale de l'Hydraulique, No. 65, September-October, 1951.

The article consists of two parts: the first is a résumé of the experimental and theoretical work of Schoemaker and Thijsse, and of Miche; the second is a report on experimental studies at the Central Hydraulic Laboratory of France to determine wave reflection coefficients. (Abstracts of the articles reviewed by Laurent and Devimeux are contained herein and mention will be made of the work at Chatou only.)

These studies were concerned with the reflective characteristics of three structural forms, each a discontinuous slope. The types are illustrated by Fig. 33, where the water depth $d = 0.6$ m, and

$$a = -0.4, -0.2, 0, +0.2$$

$$b = 0.6, 0.8, 1.0$$

$$c = 0.6, 0.8, 1.0$$

General conclusions from the studies of Laurent and Devimeux were

(a) That generally the reflectiveness of a slope increased as the steepness of the incident wave decreased.

(b) For discontinuous slopes with the lower part vertical and the upper part sloping, the structure is more reflective as the point of discontinuity approaches the surface.

(c) The effect of the discontinuous vertical beneath the slope becomes unimportant when the point of discontinuity is placed well below the trough of the waves.

19. Martin, Louis-René. "An Account of an Electro-Mechanical Piezometer Installed on a Jetty of the Port of Casablanca." Bulletin of the Permanent International Association of Navigation Congresses, Brussels, No. 28, July, 1939.

A description of a pressure-measuring device is given in this paper. The application of this device is primarily to measure the force of waves upon shore works.

The instrument consists of a cylindrical case housing a spring-loaded plunger which presents a given area to the wave pressure to be recorded.

The plunger moves backward when this pressure exceeds the spring calibration, and in so doing closes an electric circuit which is recorded on suitable equipment. Several of these piezometers, each with a different calibration, may be arrayed over a given area so that a record of changing pressure may be taken. The case is designed for watertightness and ruggedness. Quite accurate results are claimed by the author.

20. Meyer, H. C., Jr. "Wave Generating Apparatus and Its Model Applications." Unpublished M. S. thesis, Louisiana State University, August, 1950.

This thesis describes particularly the features of a generator designed and built at Louisiana State University with primary attention given to the controlling and driving mechanism. Several other generator installations are also reviewed. Several appurtenances necessary to wave study programs were discussed briefly.

Various wave absorbers were installed at the end of the test channel with the following results:

(a) A bed of 1/2- to 1-1/4-in. gravel 3 ft deep and 3.5 ft long at 40° with the bed, reflected badly.

(b) A 4-in. layer of gravel at 19.5° with the bed was "very effective since the layer of water beneath the platform supplied the added absorbability required" (Fig. 60).

(c) Porous concrete slabs at 12° to 15° "have proven very effective."

Discussion is given of a 2-ft wave filter constructed of 1/16-in. thick aluminum sheets with 3-in. spacing between sheets (Fig. 61). The results of these tests are given in Fig. 62. The author indicates, however, that these data were influenced by reflection from downstream. It may likewise be noted that the filter length is only 1/5 of the wave length.

Also mentioned are tests conducted at the Waterways Experiment Station in 1948 on both plain and perforated filters. These tests showed no reduction of wave height through the filter for waves of 6, 10, 14, 18, and 22 inches in height at a period of 8.5 sec. The first filter was of 31 smooth 2- by 1.5-ft plates spaced 3/4 in. apart. The second was of 2- by 1.5-ft perforated plates with 1/4-in. diameter holes on 1/2-in. centers (Fig. 19). The plates were spaced at about 1 inch. Nothing of consequence was reported from these tests.

The wave-generating apparatus discussed is the Beach Erosion Board scoop-type machine. The 18-in. wide and 24-in. deep scoop was a quarter arc of a 24-in. circle with a chord of about 34 in. and a midordinate of 7 inches. For long, low waves of slight steepness, the scoop translated back and forth along the tank. For steeper waves of lesser length the scoop was hinged at its toe and could oscillate through an arc of about 12°.

Considerable discussion is also given to the pneumatic machine of the University of California. This machine has the air dome alternately connected to the inlet and discharge pressure sides of an air blower. Such operation allows shorter period waves to be developed than would be possible under the action of a reduced pressure and gravity acceleration alone.

21. Miche, M. "The Reflecting Power of Maritime Works Exposed to Action of the Swell." Annales des Ponts et Chaussées, May-June, 1951. (Beach Erosion Board Translation.)

A method for determining the wave reflection to be anticipated from sloping maritime structures is discussed in this paper. The author has from previous work [89] presented an expression for the reflection from a perfectly smooth, impermeable, sloping barrier. This is given as

$$\frac{\delta_m}{\delta_o} = \frac{\sqrt{\frac{2\alpha}{\pi}} \frac{\sin^2 \alpha}{\pi}}{\delta_o} = R \quad (52)$$

where δ_o is the incident deep water wave steepness, δ_m is the maximum steepness wave which can be reflected from the barrier (measured in deep water), α is the slope of the beach, and R is a form factor.

The actual coefficient of reflection is equal to the product of the form factor and an intrinsic coefficient ρ , or

$$\frac{H_r}{H_i} = R\rho \quad (53)$$

where H_r is the reflected wave height and H_i is the incident wave height. The coefficient ρ is said to account for the surface roughness and permeability of the barrier. Figures 31 and 32 show the results of applying this

theory. Values of ρ may lie between 1.0 and 0.33. For the case of smooth surfaces, a value of about 0.8 for ρ may be appropriate; and for structures of rubble construction, the value of 0.33 may apply.

22. O'Brien, M. P. and Chaffin, A. D., Jr. "The Effect of Wall Friction on Gravity Waves." Transactions of the American Geophysical Union, Part 1, p. 84. August, 1942.

This paper presents an analysis of the effect of the channel walls and bed in reducing the amplitude of waves propagated within the channel. Its primary purpose was to facilitate the selection of wave channel widths so that the boundary effects would not interfere with the test programs. However, it is felt that good use of this theory may be made in the case of parallel plate-type wave filters.

Use was made in this analysis of Lamb's work which developed the equations for determining the velocities induced in an infinite liquid at rest, by the oscillation of an infinite plate parallel to itself. Knowing this influence of the wall, the authors have determined the velocity distribution in the fluid when the fluid has an oscillatory motion parallel to the plane of the fixed infinite plate. If the motion assigned to the fluid is that due to gravity waves, the expressions for velocity in the fluid become:

$$\begin{aligned}
 u &= \left(\frac{\pi H}{T} \right) \frac{\cosh (2\pi/L)(d-y)}{\sinh (2\pi d/L)} \sin 2\pi(x/L - t/T) \\
 &\quad \left[1 - e^{-\sqrt{\sigma/2\nu} \cdot z} \sin (\sigma t - \sqrt{\sigma/2\nu} \cdot z) \right] \\
 v &= \left(\frac{\pi H}{T} \right) \frac{\sinh (2\pi/L)(d-y)}{\sinh (2\pi d/L)} \cos 2\pi(x/L - t/T) \\
 &\quad \left[1 - e^{-\sqrt{\sigma/2\nu} \cdot z} \cos (\sigma t - \sqrt{\sigma/2\nu} \cdot z) \right]
 \end{aligned} \tag{54}$$

where the origin of coordinates is located at the free surface and in the plane of the vertical rigid boundary. The system is right-handed with the axis of x in the direction of wave propagation, the axis of y vertical, and the axis of z normal to the xy -plane; u is the orbital velocity in the direction of x ; v is the orbital velocity in the direction of y ; H is the wave height; L is the wave length; d is the water depth; T is the wave period; ν is the kinematic viscosity; and σ is $2\pi/T$.

Evaluation of these velocity terms in the dissipation function yields the expression for the dissipation of energy per cycle per unit length of channel as

$$N = \left(\frac{\rho_w}{2}\right) \sqrt{\pi \nu T} \left[\int_0^b (\bar{u}_{y=d})^2 dz + 2 \int_0^d (\bar{u}_z^2 + \bar{w}_z^2) dy \right] \quad (55)$$

$$\text{where } \bar{u}_z = \left(\frac{\pi H}{T}\right) \left[\frac{\cosh(2\pi/L)(d-y)}{\sinh(2\pi d/L)} \right]$$

$$\bar{w}_z = \left(\frac{\pi H}{T}\right) \left[\frac{\sinh(2\pi/L)(d-y)}{\sinh(2\pi d/L)} \right] \quad (56)$$

ρ_w = fluid density.

The average rate of dissipation of energy is N/T , and in a length of channel l

$$P_1 - P_2 = \int_0^l (N/T) dx \quad (57)$$

where P_1 is the entrant power into the region at $x = 0$, and P_2 is the exit power from the region at $x = l$.

Use may be made of this expression in determining the change in wave height by evaluating the integral on the right-hand side. This may be done through step-by-step procedure, or experimental data may be checked by graphical integration of the equation.

23. Ransford, G. D. "Measuring the Amplitude of Low Camber Waves by Optical Images." La Houille Blanche, January-February, 1952.

A somewhat complicated appearing method of determining wave amplitude is described in this work. The process involved is to sight (from a slightly elevated position above the still water level) along the channel length. It may then be noticed that the image of the vertical wall at one side of the channel apparently oscillates snake-fashion at some distance out from the wall. By obtaining a reference distance between trough and crest of the image, the geometry is developed for determining the wave height from this

distance when the position of the observers eyes is known. The process is limited to waves of small steepness for which the author claims good accuracy.

24. Ransford, G. D. "A Method of Measuring Wave Lengths of Model Waves by Synchronization of Visual Signals." La Houille Blanche, September-October, 1951.

This paper describes a device for laboratory use in measuring wave lengths. It consists of two point gates with an intermediate circuit containing a lighting device. One-half of the element lights from contact of the fixed gage with the water surface, and the other half lights from contact of the movable gage with the water surface. When the two signals are synchronized by positioning the movable gage, the distance between probes is that between wave crests.

25. Schoemaker, H. J. and Thijsse, J. Th. "Investigations of the Reflection of Waves." Proceedings of the Third Meeting of the International Association for Hydraulic Structures Research, Grenoble, September, 1949.

This paper presents the results of studies on wave reflection from both continuous and discontinuous slopes. The lower part of the discontinuous slopes studied was vertical and the remainder was sloping. These slopes were studied in an effort to obtain energy dissipation as great as that for continuous slopes, but with a lesser length.

Factors influencing the dissipation of wave energy are listed as:

- (a) Slope of the wall.
- (b) Water depth.
- (c) Wave length.
- (d) Wave amplitude.
- (e) Incidence angle.
- (f) Height of the vertical portion of a discontinuous slope.

For a sinusoidal wave of height H_i , and with the height H_r of the reflected wave, the antinode height becomes $B = H_i + H_r$, and the nodal height $A = H_i - H_r$. Then

$$H_i = \frac{1}{2} (A + B) \quad \text{and} \quad H_r = \frac{1}{2} (B - A) \quad (58)$$

If the wave form is not sinusoidal the foregoing is only an approximation. However, for L/d ratios which are not large, observations indicate that the approximation is good.

Measurements were made only with waves perpendicularly incident to the model structure and having the following characteristics:

$$\begin{aligned} 4 < L/d < 9 \\ 15 < L/H < 20 & \text{ for continuous slopes} \\ L/H = 40 & \text{ for discontinuous slopes} \end{aligned}$$

where $L/H = 1/\text{wave steepness}$, and $d/L = \text{relative depth ratio}$.

It was found that when $t < L/4$ the reflection was nearly total for continuous slopes. The horizontal projection of the slope is designated as t . For values of $t/L = 1/2$, the reflection coefficient becomes of the order of 0.3. No conclusion was drawn from the data concerning the effect of wave steepness.

The experiments conducted upon discontinuous slopes were inconclusive, but certain results were noted. The curves in Fig. 22 for different levels of the point of discontinuity did not coincide, and it was shown that for a slope of fixed horizontal length the reflection was less as the point of transition approached the surface (within the limits of the test data). This suggests that for the length-to-depth ratios used ($L/d = 5.7$), the determining factor was the beach slope.

26. Schwarzacher, W. "A New Method of Measuring the Variations in the Surface Elevations of Liquids." *Physikalische Zeitschrift*, Vol. 44, p. 216, June, 1943. (Waterways Experiment Station Translation No. 44-6, August, 1944.)

Figure 63 was presented by this writer to illustrate a technique for the determination of wave amplitude. Reference to the figure shows that light from the source P is incident upon the mirror at M_1 and reflected to the free surface from that point. The reflective process repeats as shown until the light hits M_2 and thence vertically upward to the surface S . The horizontal motion of light reflection on S is a function of Y .

If the angle 2β as shown in the figure is equal to or greater than $48^\circ 35.5'$, the angle of total reflection at an air-water interface, the author gives the relationship

$$x = f(y, \beta) = 2y \sin 2\beta$$

(59)

$$\text{for } \beta = 30^\circ \quad x = 1.732 y$$

27. Snodgrass, F. E. "Wave Recorders." Proceedings of the First Conference on Coastal Engineering, Council on Wave Research, p. 69. 1951.

This paper presents a summary of ocean wave recording equipment and attempts to evaluate the various advantages, disadvantages, and applicability of each.

The wave gages tested by the Beach Erosion Board, May, 1947, are:

(a) Underwater type

- (1) University of California, Mark III, Shore Wave Recorder.
- (2) Woods Hole shore recording wave meter.
- (3) Inverted echo sounder.

(b) Surface type

- (1) Float-operated recorder.
- (2) Parallel wire gage (large wire).
- (3) Parallel wire gage (small wire).
- (4) Step resistance gage.
- (5) Moving picture camera.

The conclusion of the study was that type (b-4), series and parallel arrangements of the steps, was the most likely for future use.

Both series and parallel step resistance gages are arranged so that the gage current is proportional to the number of contacts beneath the surface. It is noted that for good operation the series type should be limited to fresh water and the parallel type to salt water use.

Various pressure recorders are described: for example, the Mark III recorder of the University of California which is a potentiometer linked to a bellows. It is a differential type and does not record slow variations such as tides. This recorder is said to be heavy and of limited life.

The University of California Mark V pressure recorder has as its transducer element a 32-junction thermocouple installed in a gas-filled rubber bellows. There are reference junctions to the sea and active junctions to the gas. The recorder does not measure average pressure or tides. The unit

is said to be of limited life and has a calibration which is not independent of period, depth, and short temperature fluctuations.

The Woods Hole shore recording wave meter consists of a coil and magnet device. The coil is attached to a bellows which deflects with changing pressure and thus moves the coil relative to the magnet. Such motion, of course, may be measured and calibrated. This is a differential-type gage and does not record long period disturbances.

28. Valembois, J. "Methods Used at the National Hydraulic Laboratory of Chatou (France) for Measuring and Recording Gravity Waves in Models." National Bureau of Standards Symposium on Gravity Waves, (1951). 1952.

Two methods of determining the characteristic of a wave system are presented herein. One deals with a method particularly well suited for large three-dimensional models. In this, the "starred sky method," a grid of light sources is placed above the model, the image of which is photographed in the mirror formed by the surface of the water. If the surface is motionless, the photo shows a point; if periodically distorted, the trace is a closed curve of some sort, the form and amplitude of which tells of the water movement. For example, in the case of a simple progressive wave, each point describes a line segment, the length of which is proportional to the wave amplitude.

Equations are given along with the methods whereby the slope of the water surface as the wave passes can be determined from the displacement of luminous points. This method seems very useful where wave motion determination is needed over a large area (such as harbor models), particularly when there is need of determining the different wave conditions existing at various points within the area.

The second method described in this paper is that of the "limnograph with a vibrating point." This method permits the recording of rapidly changing surfaces (10 cps) of small amplitude (5 mm maximum) with great accuracy.

The method of operation utilizes a fine platinum needle which forms a circuit through the water to the amplifying and recording equipment. The needle vibrates very rapidly in the vertical (50 cps) to avoid "the effects of surface tension and the entrainment of small drops of water by the needle." Current flow in the circuit is proportional to the immersion of the needle in the water. The registering device integrates the current flow over a cycle of the needle motion. It is claimed that the "stability" of the measurement is assured to at least 1/100 mm.

29. Ware, E. A. "An Electronic Water-Level Measuring Device." Appendix to M. S. thesis by V. A. Koelzer, University of Iowa, 1939. (See Reference [68].)

In conjunction with a mechanical measuring device described in the thesis by Koelzer, the electronic device whose operation is described below was developed and reported on as an appendix to the thesis. This apparatus consisted of a resistance bridge with one resistance concentrated at a point on a rack which penetrated the water surface. When the water level changed, the resistance at the point changed, throwing the bridge out of balance and causing a voltage to appear on an amplifier grid. This operated a Thyrotron which in turn drove the rack in the direction necessary to balance the bridge by changing the depth to which the contact penetrated.

30. Yu, Yi-Yuan. "Breaking the Waves by an Opposing Current." Transactions of the American Geophysical Union, Vol. 33, No. 1, February, 1952.

The work presented by this author describes the effect of deep water progressive waves entering a region of current flow. It was found that for deep water waves propagating from still water upstream against a moving current, complete breaking occurs when the velocity of the opposing current reaches $1/4$ the wave velocity. This was verified by experimental results. Partial breaking took place when the ratio of current velocity to wave velocity was between $1/7$ and $1/4$.

The analytical explanation for this may be arrived at by equating the wave period within the still water region with that in the moving current region. This yields the expression for celerity

$$C = \frac{C_0}{2} \left[1 + \sqrt{1 + \frac{4V}{C_0}} \right] \quad (60)$$

where the zero subscript refers to wave properties in the still water.

This may also be written

$$C_g = \frac{C_0}{4} \left[1 + \sqrt{1 + \frac{4V}{C_0}} \right] + V \quad (61)$$

where V is the stream velocity, and C_g is the group celerity. Hence, if $V = -C_o/4$, $C_g = 0$ and the waves break upon meeting the current since energy cannot be transmitted into the flow region.

If the waves are transmitted into the region of the flowing current without breaking, the ratio

$$\frac{H}{H_o} = \left\{ \frac{2}{[1 + 4V/C_o + \sqrt{1 + (4V/C_o)^2}]} \right\}^{1/2} \quad (62)$$

from conservation of energy. Similarly,

$$\frac{H/L}{H_o/L_o} = \frac{\left[\frac{2}{1 + 4V/C_o + \sqrt{1 + (4V/C_o)^2}} \right]^{1/2}}{\frac{[1 + \sqrt{1 + (4V/C_o)^2}]^2}{4}} \quad (63)$$

and if $H/L = 1/7$ (the maximum theoretical value), then for each value of V/C , the corresponding value of H_o/L_o may be determined. This gives the maximum still water wave steepness which can enter the current zone without breaking.

31. Beach Erosion Board. Reflection of Solitary Waves. Technical Memo No. 11, November, 1949.

This study was made to determine the reflecting characteristics of permeable and impermeable barriers, and of sloping and vertical structures. The study made use of solitary waves to avoid the necessity of distinguishing between the reflected and the incident wave. It is also mentioned that oscillatory waves approach the form of the solitary wave as they move into shallow water.

Four test phases made use of the following structure forms:

- (a) Permeable rock structures with a vertical seaward face. The vertical rear wall was impermeable. Structure composition was changed by varying the size of the rock and the thickness of the structure.

(b) The same as the preceding except that the vertical rear wall was permeable and backed by open water.

(c) A smooth impermeable sloping beach.

(d) A permeable sloping structure backed by open water.

In these studies the viscosity was ignored as a parameter since it was demonstrated that a Reynolds number greater than critical existed when the wave passed into the permeable structure. Figures 23 to 27 graphically portray the results of this study. In general it may be concluded that the permeable sloping barrier appears to be the best energy-dissipating device tested.

32. La Houille Blanche. "Apparatus for Laboratory Wave Measurement," No. 4, pp. 520-522. July-August, 1949.

The equipment described in this report was apparently designed primarily for determining the damping and reflection characteristics of waves inside ports and harbors. The principle involved utilizes a point contact scheme which records on tape.

The vertical plane may be divided into three parts.

(a) Zones untouched by maximum variations.

(b) Zones continually swept by all waves.

(c) Zones in which the frequency of passage of the waves varies between zero and 100 per cent.

The last zones are those in which the recorder is placed. Two groups of points are used: one for crests and one for troughs. A pilot point records all waves passing. A constant vertical distance is maintained between points in a group and each point records the number of waves reaching the elevation of the point in question. The crest group sends impulses on making contact; the trough group registers upon breaking contact. It is reported that greater variations have been observed in crest height elevation than in trough levels.

Figure 64 shows the appearance of the probe head. A relay system is built into the equipment to allow the point to record once only for a single wave crest. That is, a forced dwell of something less than $1/2$ period occurs so that ripples superimposed on the main disturbance do not give second contacts.

33. La Houille Blanche. "The Standardization of Equipment in Hydraulic Laboratories," No. 5, pp. 624-629. September-October, 1949.

The unique servo-mechanism described in this issue of La Houille Blanche is shown diagrammatically in Fig. 65. This equipment is used in France to record the surface profile as a function of time in the following way.

A rubber-tired driver M_1 rotates the drums D_1 and D_2 which swing about pivots. The electromagnets lift D_1 and D_2 away from the driver as directed by the relays. The weight P_2 is heavier than T_2 ; P_1 is lighter than T_1 .

When T_2 comes out of the water, the relay releases E_2 , and M_1 drives T_2 down again. Upon contacting the water, R closes E_2 , releasing the drum M_1 , and weight P_2 lifts T_2 from the surface. The cycle is then repeated. The same process operates in reverse for T_1 . The author states that "the apparatus is very sensitive and accurate, and the detection, by means of an electronic relay, of a point entering or leaving the water is instantaneous"

34. La Houille Blanche. "Description of an Installation for Experimental Studies on the Physics of Waves," No. 6, December, 1952.

This paper describes equipment designed to produce very pure waves, which enable studies of wave characteristics to be accomplished. Since wave filters were to be used, a convergent channel section (0.45 m per 11 m) was constructed to amplify the wave heights after they had passed through the filters. The central section of the convergent section is rectilinear; the two ends form a section of a parabola and a section of a cubic curve with a zero curve at the connecting point.

When studying a relatively impermeable breakwater, for example, the water level behind the model gradually rises, producing an artificial test condition. A large diameter return pipe between this region and the area immediately in front of the wave machine is provided for water level equalization.

Two perforated plate-type wave filters are installed in front of the wave machine and preceding the contracted section of the channel. A cell-like, low-density, homogeneous filter is placed downstream of the contraction and upstream of the test area.

Wave absorbers at the end of the channel are long permeable slopes in front of which several filters are located. The advantage of this unit is said to be that the loss of wave energy is not localized. The absorber profile is curved to allow a very gradual slope near the water surface without an excessive length.

ANNOTATIONS

1. Burgers, J. M. "Über die Erregung von Wellen in einem Kanal durch eine bewegte Querwand." Zeitschrift für Angewandte Mathematik und Mechanik, Vol. 13, p. 67. April, 1933.

First-order potential flow theory is used to describe the action of a movable wall in generating wave motion. An interesting case of a finite gap beneath the oscillating wall is discussed.

2. Dean, W. R. "On the Reflection of Surface Waves by a Submerged Plane Barrier." Proceedings of the Cambridge Philosophical Society, Vol. 41, pp. 231-238. October, 1945.

If the top edge of the vertical barrier is at a depth a below the surface, the coefficient of reflection is found to be about $1/4$ when $a = gT^2/80$. Curves showing variation of reflection and transmission coefficients with the period are presented.

3. Dean, W. R. "On Some Cases of Reflection of Surface Waves by an Inclined Plane Barrier." Proceedings of the Cambridge Philosophical Society, Vol. 42, pp. 24-28. January, 1946.

The case described is for a barrier inclined at an angle $\pi/2s$ to the free surface. Solutions for $s = 1$ (90°) and $s = 2$ (45°) are known. This paper presents the solution and the form of the free surface for the case $s = 3$ (30°).

4. Johnson, J. W. "Scale Effects in Hydraulic Models Involving Wave Motion." Transactions of the American Geophysical Union, Vol. 30, No. 4, pp. 517-525. August, 1949.

A summary is given of various instances where wave theories have been experimentally verified, with a detailed discussion of cases where models built to several scales have allowed an evaluation of hydraulic scale effects.

5. Kennard, E. H. "Generation of Surface Waves by a Moving Partition." Quarterly of Applied Mathematics, Vol. 7, No. 3, p. 303. October, 1949.

This paper extends Havelock's analysis for a moving vertical plate executing harmonic motion to produce surface waves to the case of a finite depth of water.

6. Larras, J. "Methods of Studying Waves." Travaux, Vol. 21, No. 58, pp. 446-450. October, 1937. (Waterways Experiment Station Translation No. 39-32.)

Various methods are described which may be used to determine the height, length, period, and pressures exerted by waves at sea.

7. O'Brien, M. P. and Morison, J. R. "The Forces Exerted by Waves on Objects." Transactions of the American Geophysical Union, Vol. 33, No. 1, February, 1952.

A theory is developed and verified for the forces exerted by surface waves on small spherical objects placed on or near the bottom. Experiments on cylindrical piles have shown that the accelerative forces are of the order of magnitude of the drag forces associated with the orbital velocities.

8. Pierson, J. D. The Penetration of a Fluid Surface by a Wedge. Stevens Institute of Technology, Experimental Towing Tank Report No. 381, July, 1950.

A symmetrical wedge of varying face angle is plunged into a fluid, and analysis indicates a unique surface shape for a given wedge angle. Impact forces and the pressure distribution in the wedge may be computed.

9. Putnam, J. A. and Johnson, J. W. "The Dissipation of Wave Energy by Bottom Friction." Transactions of the American Geophysical Union, Vol. 30, No. 1, pp. 67-74. February, 1949.

A theory is developed for the loss of wave energy as a result of friction by the oscillating motion of waves at the sea bottom, the loss amounting to as much as 30 per cent on very flat beaches for wave periods commonly occurring at sea.

10. Reynolds, K. G. "Investigation of Wave Action on Sea Walls by the Use of Models." Transactions of the American Geophysical Union, 14th Annual Meeting, April, 1933.

Studies included tests of a vertical plunger machine with the front face varied from 66° forward of vertical, to the vertical. An angle of 32° was chosen.

11. Schönfeld, J. C. Propagation of Tides and Similar Waves. Staatsdrukkerijen Uitgeverijbedrijf 's-Gravenhage, Div. 13.2, 1951.

This report describes the theory and application of an inclined manometer in reporting surface level changes for very long waves. Delay, distortion, inertia, free oscillation, and flow in the tube are considered.

12. Schuler, M. "Erzeugung von Oberflächewellen durch schwingende Körper" (Generation of Surface Waves by Oscillating Bodies). Zeitschrift für Angewandte Mathematik und Mechanik, Vol. 16, No. 2, pp. 65-73. April, 1936.

Equations are presented for waves produced by vertically oscillating bodies both at and beneath the water surface. These results are in good agreement with experiment.

13. Schuler, M. "Der Umschlag von Oberflächewellen" (The Displacement of Surface Waves). Zeitschrift für Angewandte Mathematik und Mechanik, Vol. 13, pp. 443-446. December, 1933.

Described is the transition of a progressive wave into a standing wave transverse to the channel axis as the generator frequency is increased.

14. Sines, F. J. "Laboratory Control of Ocean Waves." Engineering News-Record, Vol. 141, p. 96. December 9, 1948.

A description is given of a flexible plate generating device for trochoidal waves of 1-ft maximum height and 10-ft length in a water depth of 5 ft. The paper also mentions a checkerboard arrangement of 6-in. diameter concrete cylinders spaced at 12 to 4 in. apart near the water surface for wave absorption.

15. Thijsse, J. Th. "Growth of Wind Generated Waves and Energy Transfer." National Bureau of Standards Symposium on Gravity Waves (1951). 1952.

This paper discusses waves of 1- to 4-in. amplitude and 1- to 5-ft length, generated by forcing wind at 35 mph over a fetch of the 165-ft test channel.

16. Truscott, S. The Wave Suppressors Used in the NACA Tank. National Advisory Committee for Aeronautics Technical Note 513, December, 1934.

Discussed in this report is the use of a framework covered with fine copper screening and placed horizontally just beneath the water surface to dissipate wave energy incident upon the walls of the towing tank.

17. Valembois, J. "Un manomètre enregistreur de pressions sous-marines pour la détermination des caractéristiques de la houle par la mesure des variations de pression en profondeur." La Houille Blanche, Special No. B, p. 707, 1949.

This article describes a set of recording manometers used in conjunction with a hydraulic "filter" to record average pressure continually, and a differential electric manometer to record the passage of wave heights.

18. Wiegel, R. L. "Experimental Studies of Surface Waves in Shoaling Water." Transactions of the American Geophysical Union, Vol. 31, No. 3, June, 1950.

A series of experiments is reported which compares actual wave dimensions with those given by theory for waves moving over a sloping beach.

19. Bulletin of the Beach Erosion Board, Vol. 1, No. 2, July 1, 1947.

Brief mention is made of a shovel-type wave generator whose bottom edge translates and whose upper edge translates and rotates about the bottom. It produces waves of 11.1-ft length and 0.016 steepness at 2.40-sec period; and 3.0-ft length and 0.055 steepness at 0.82-sec period.

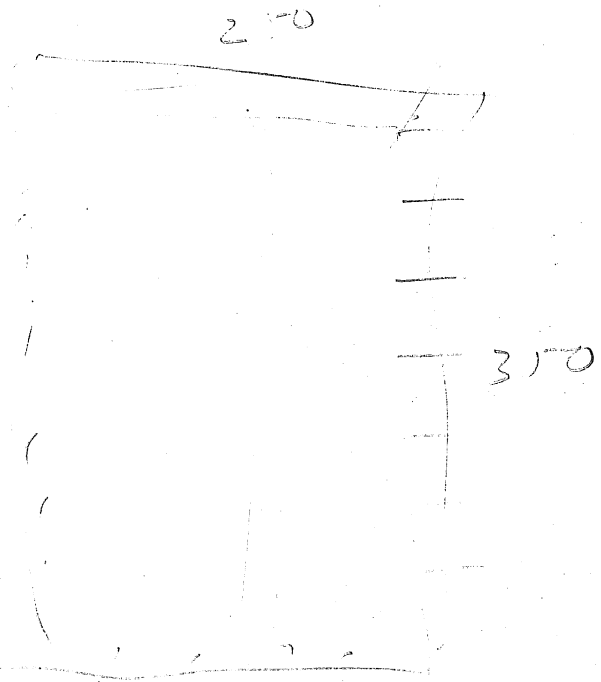
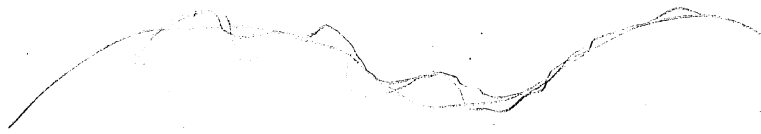
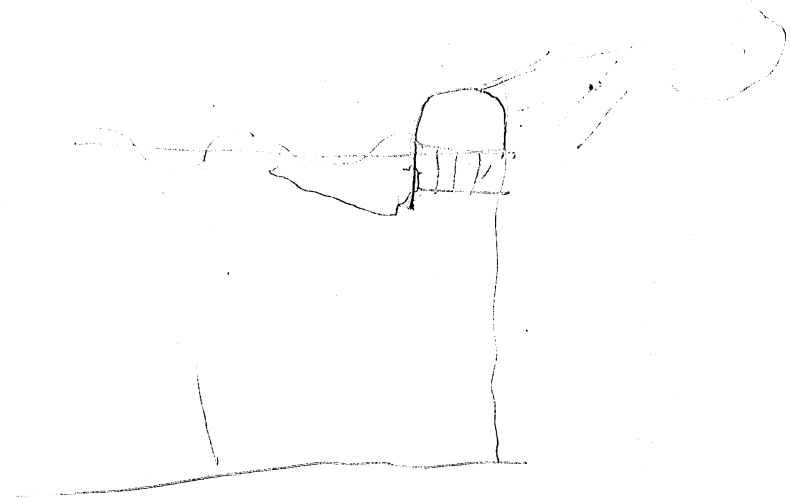
20. U. S. Experimental Model Basin, Washington, D. C. Wave Destruction at a Reflecting Wall. Report No. 296, May, 1931.

Various structural shapes (parabolic shoals, a square trough, cylindrical pipe, pipe and trough, etc.) were tried as suppressors to determine the most efficient means of preventing wave reflection from a wall. The trough arrangement reduced wave amplitude by about 75 per cent; the parabolic shoal removed from the wall was somewhat more efficient.

21. Waterways Experiment Station. Principles of Wave Action--Wave Model Appurtenances. Bulletin, Vol. 4, No. 1, May, 1941.

Discussed are wave height measurement devices and a pressure measuring device which consists of a diaphragm pressure transducer where movement of the diaphragm actuates an armature inside a coil, thus changing the coil reactance. A bridge circuit with a coil at reference reactance is unbalanced by this movement.

APPENDIX B
(Figures 1 - 65)



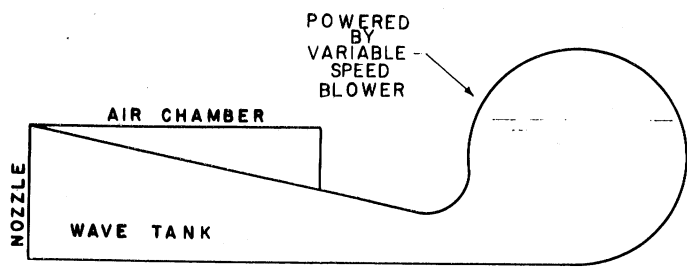
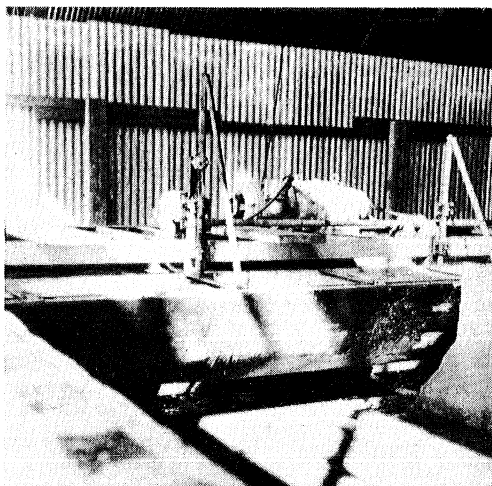
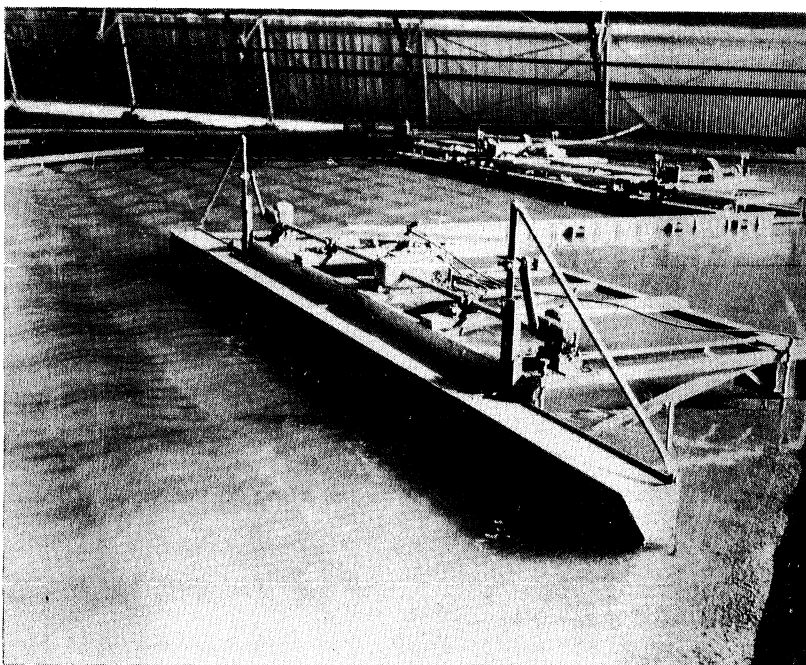


Fig. 1 - Pneumatic-type Machine [86] *



a. Parabolic Shape



b. Wedge Shape

Fig. 2 - Plunger-type Machines [86]

*Numbers in brackets refer to the Bibliography on page 111.

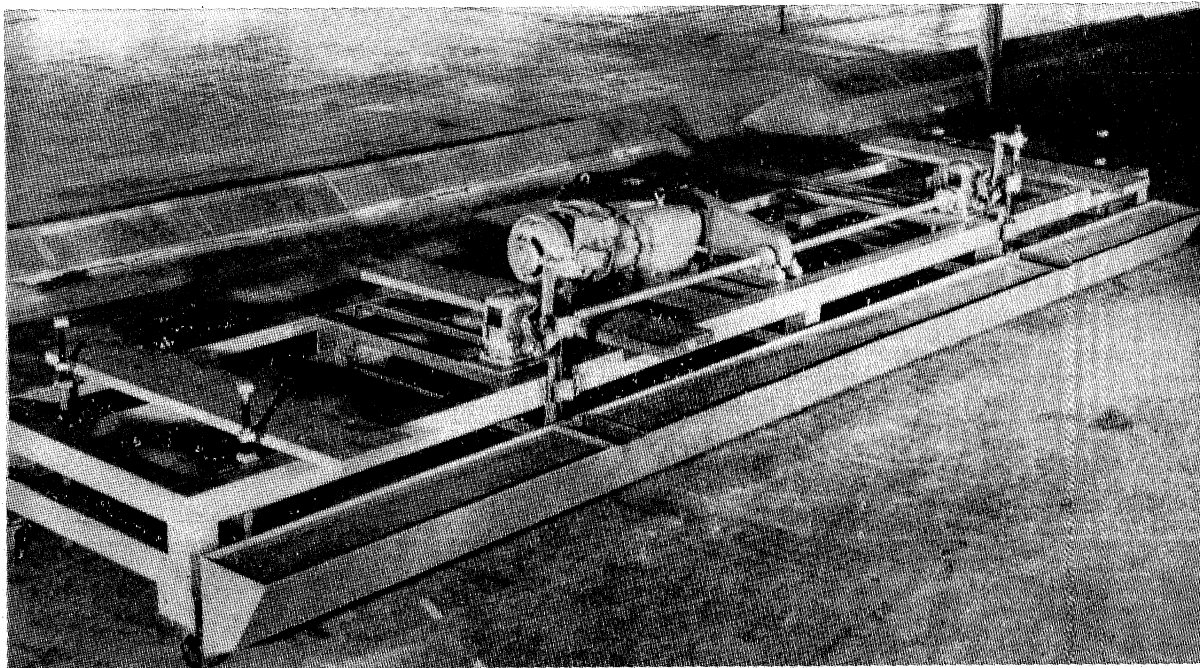
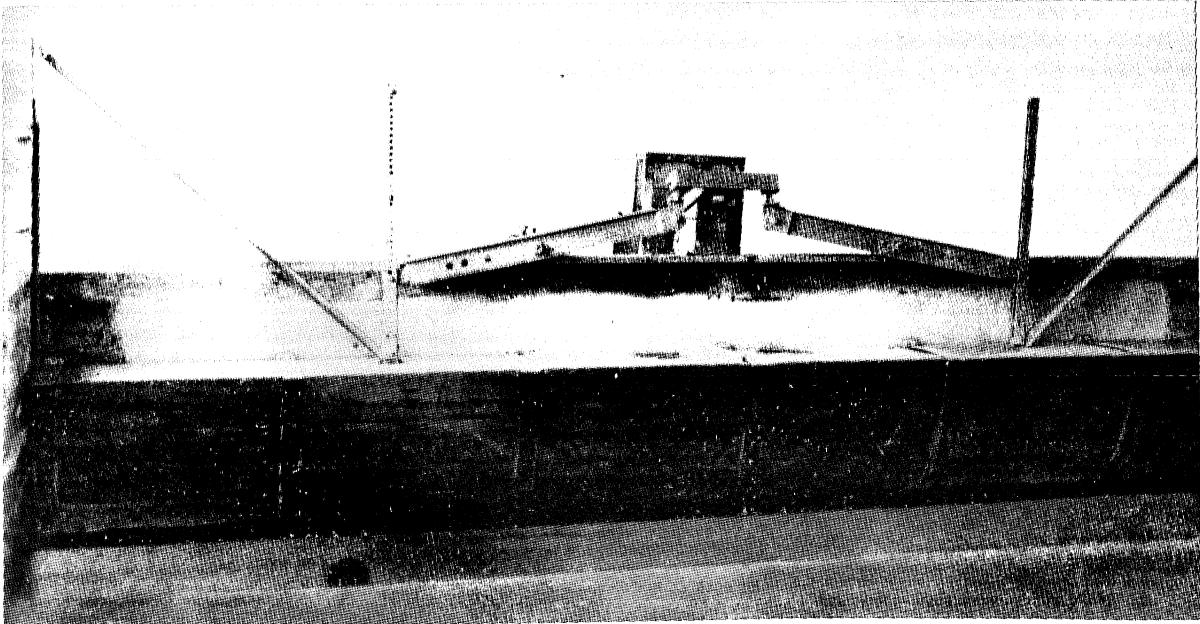


Fig. 3 - Plunger-type Wave Generators [10]

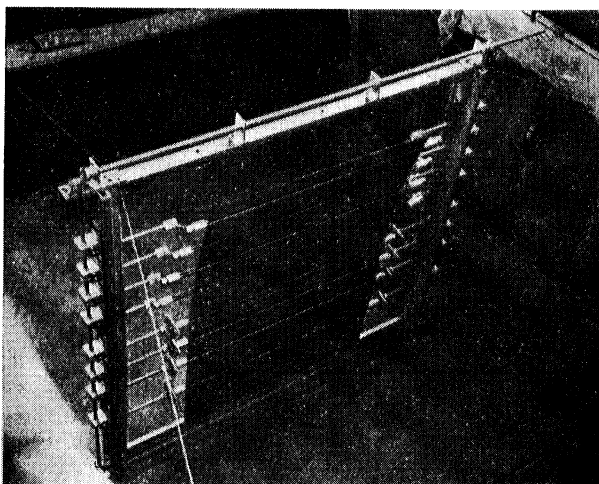


Fig. 4 - Flexible Flap Machine [10]

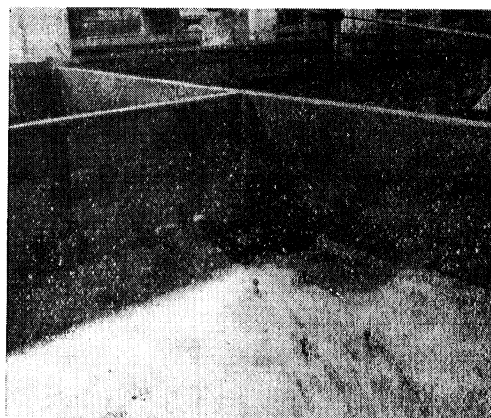
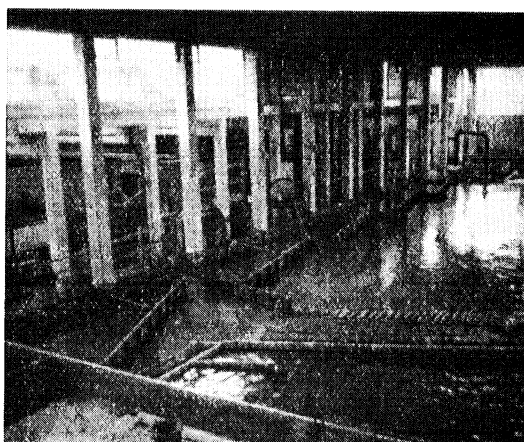


Fig. 5 - Rigid Flap Machines [10]

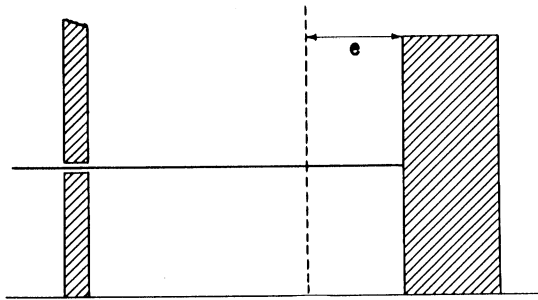


Fig. 6 - Piston-type Machine [10]

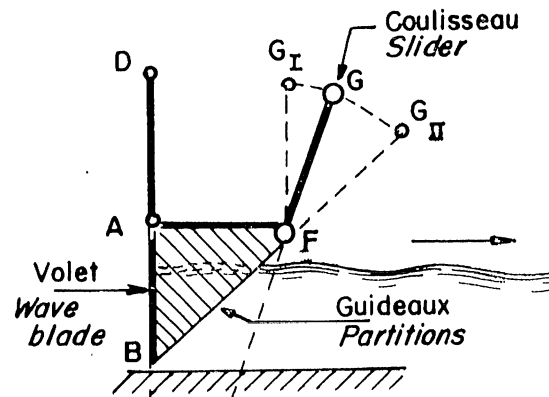


Fig. 7 - Pendulum-type Wave Machine [107]

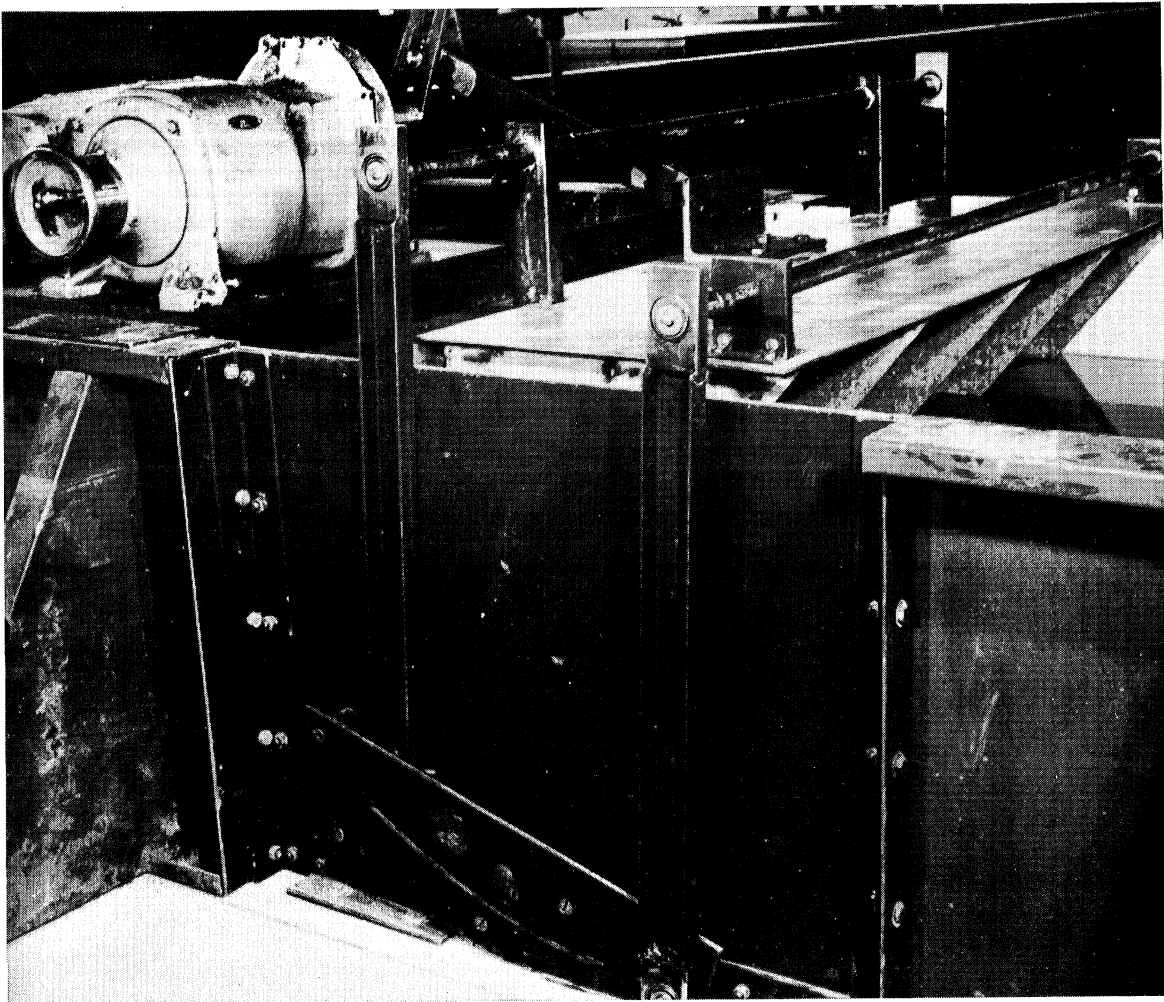


Fig. 8 - Inverse Pendulum Machine [27]

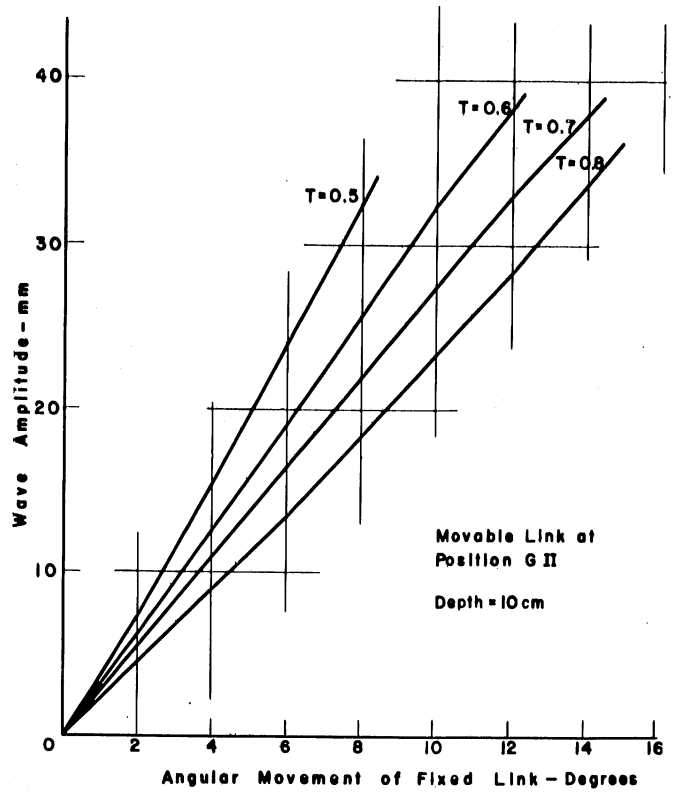
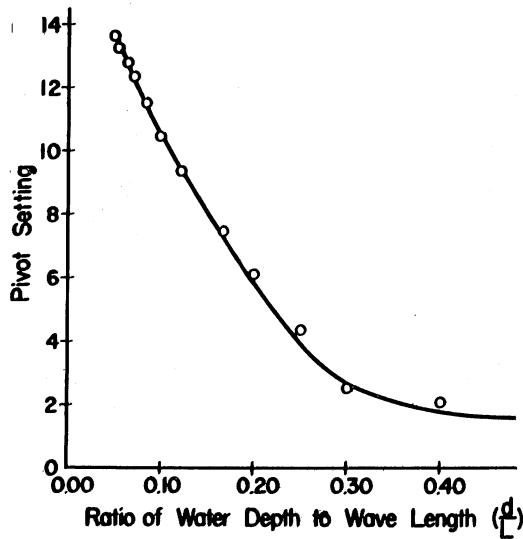


Fig. 9 - Characteristic Diagram for Pendulum Generator [107]

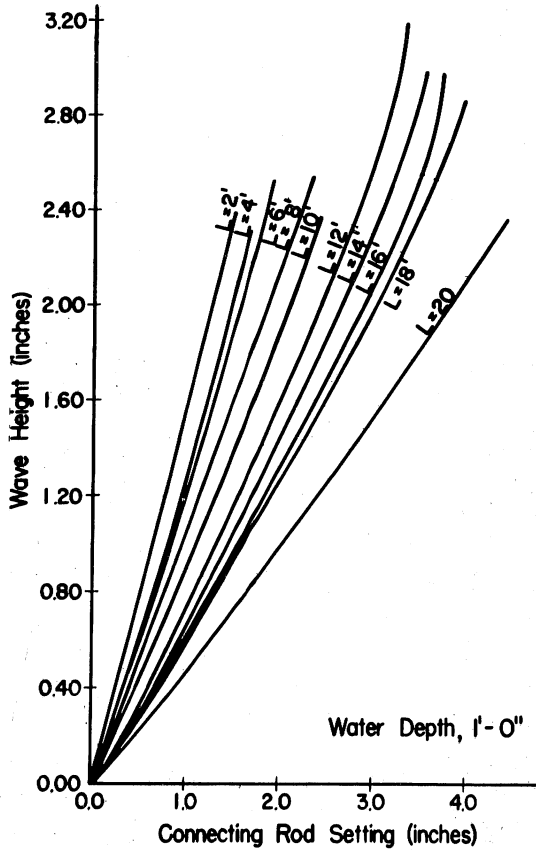


Fig. 10 - Characteristics of the Inverted Pendulum Machine [27]

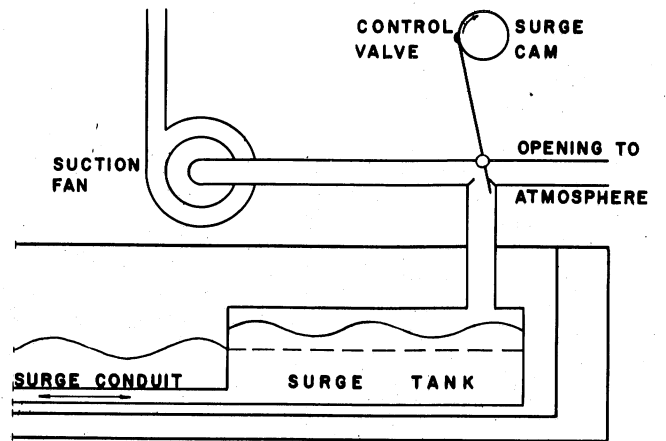


Fig. 11 - Diagram of Surge Machine [86]

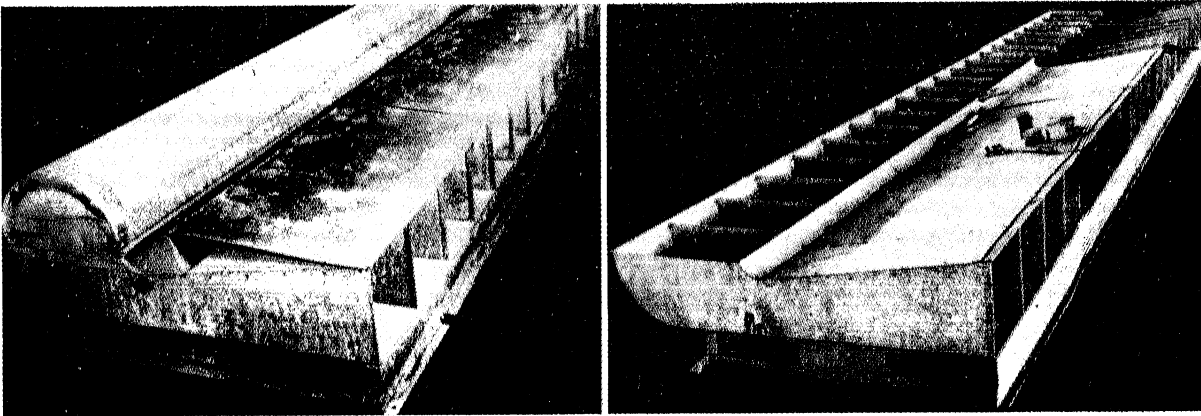


Fig. 12 - Pneumatic Wave Generator [10]

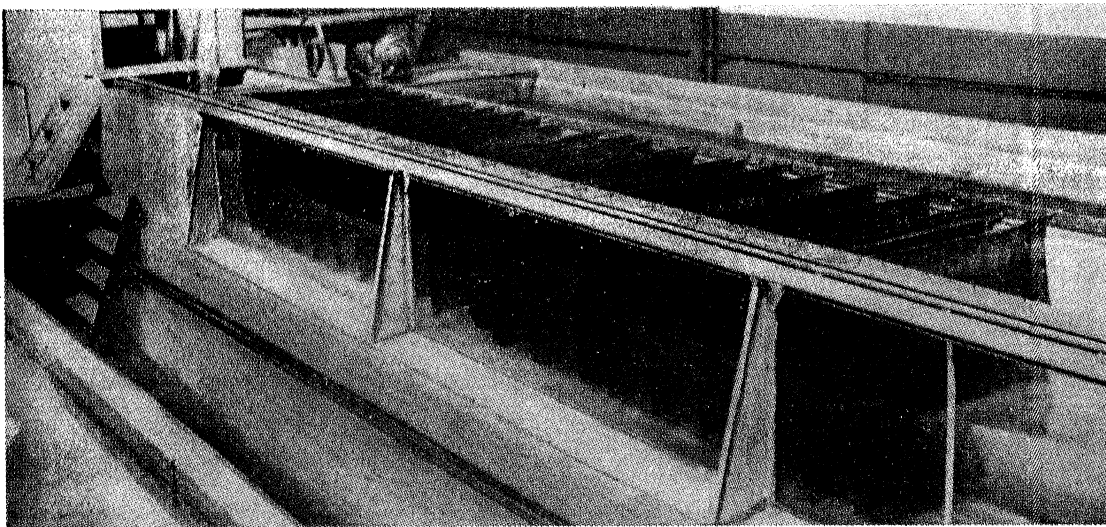


Fig. 13 - Wave Generator with Absorbing Curtains [74]

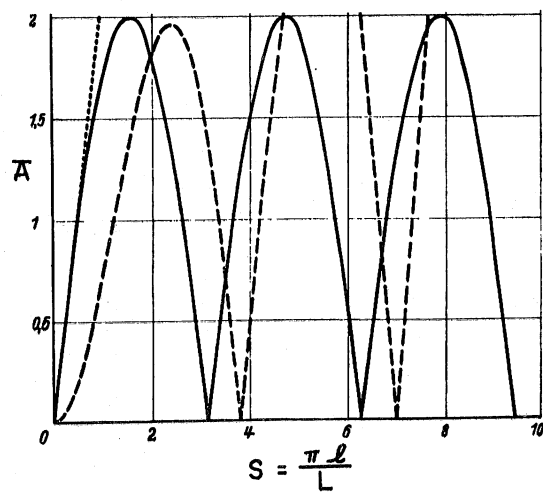


Fig. 14 - Comparison of Plunger Machine Theories [119]

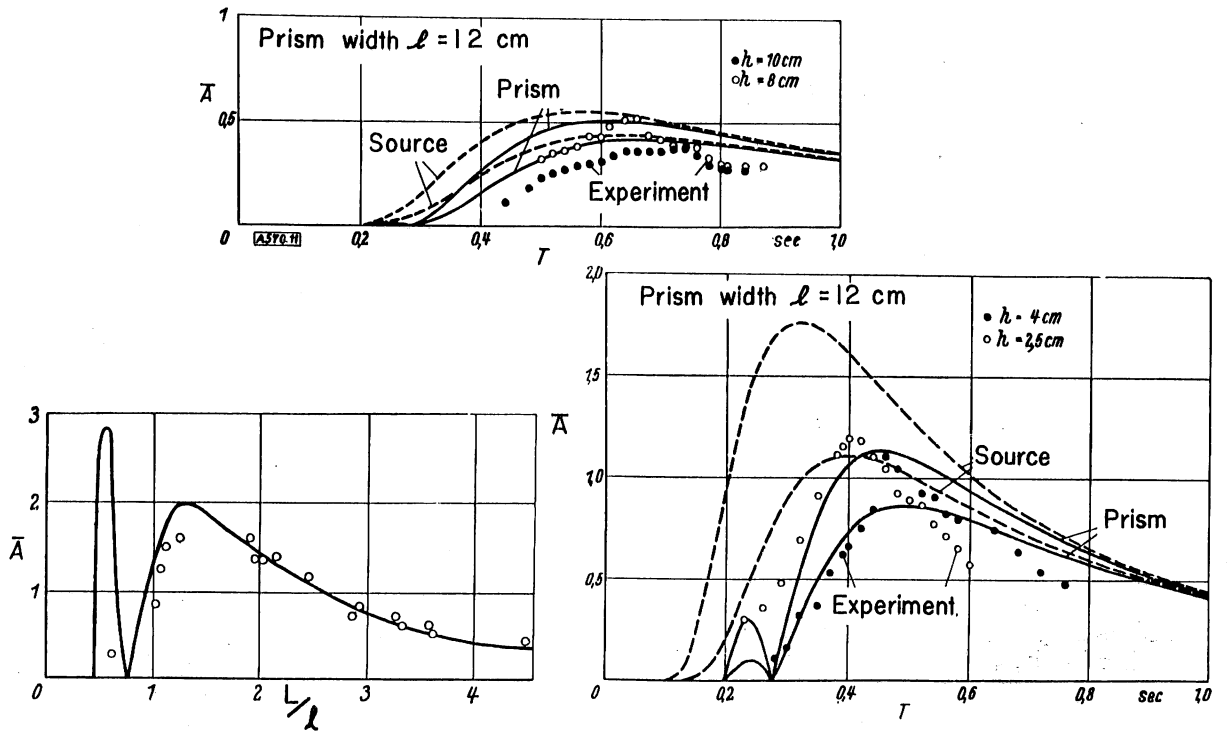


Fig. 15 - Experimental Verification of Plunger Theory [119]

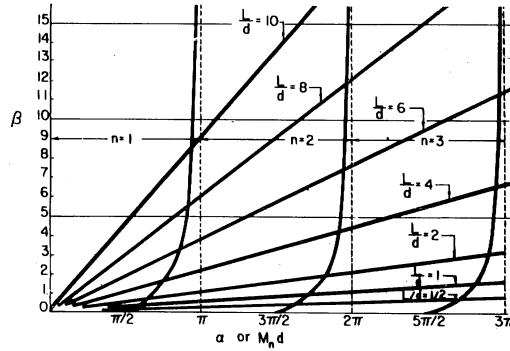


Fig. 16 - Graphical Solution for $m_n d$ [10]

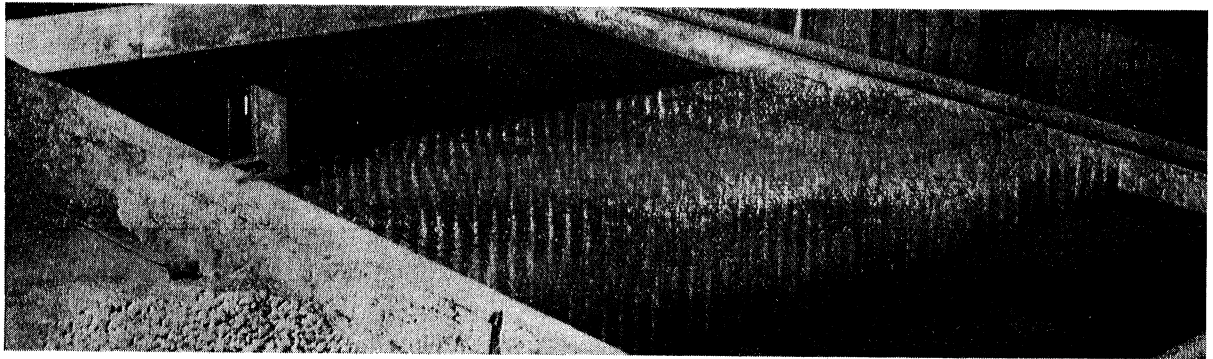


Fig. 17 - Cellular Mesh Filter [10]

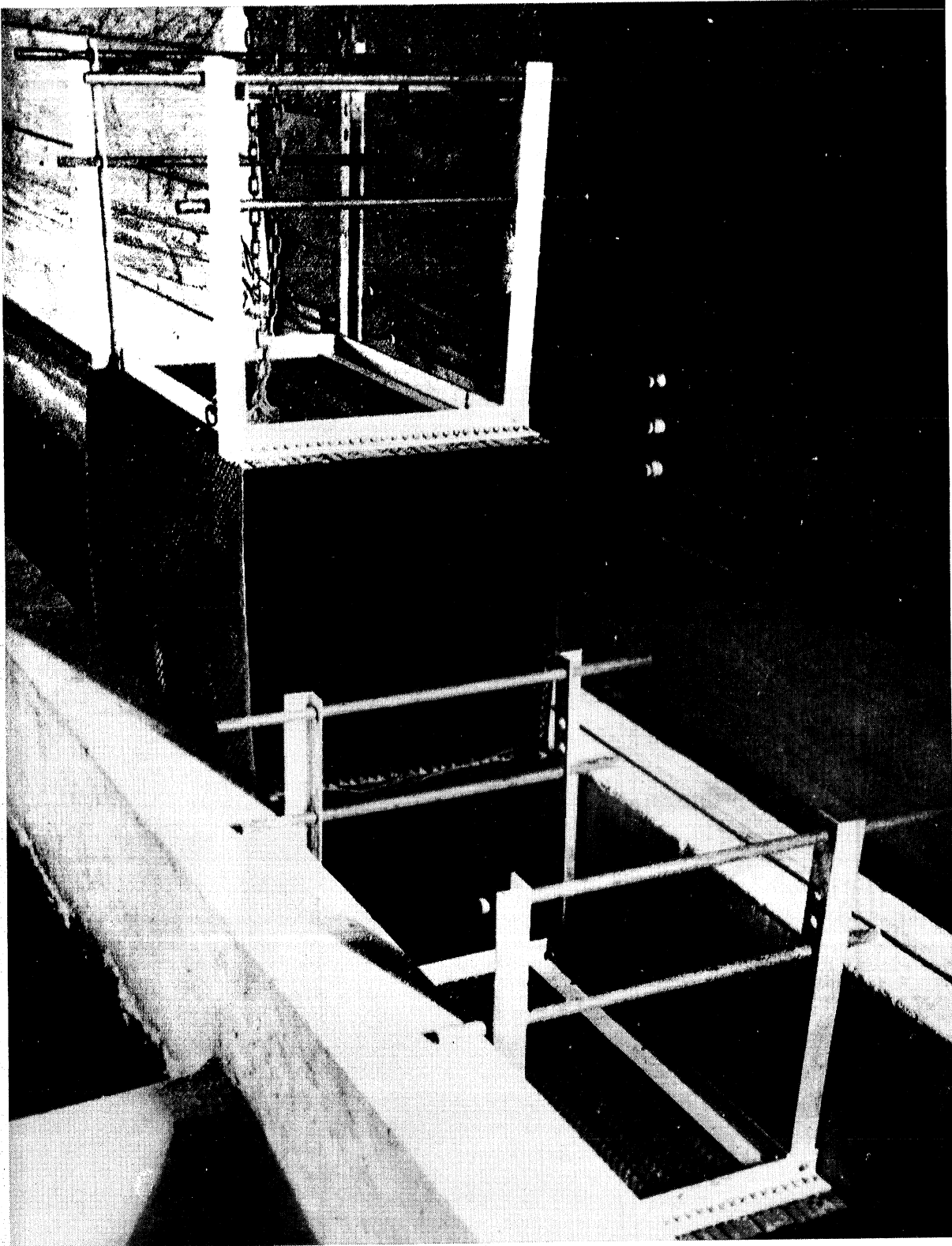


Fig. 18 - Perforated Plate Filter [8]

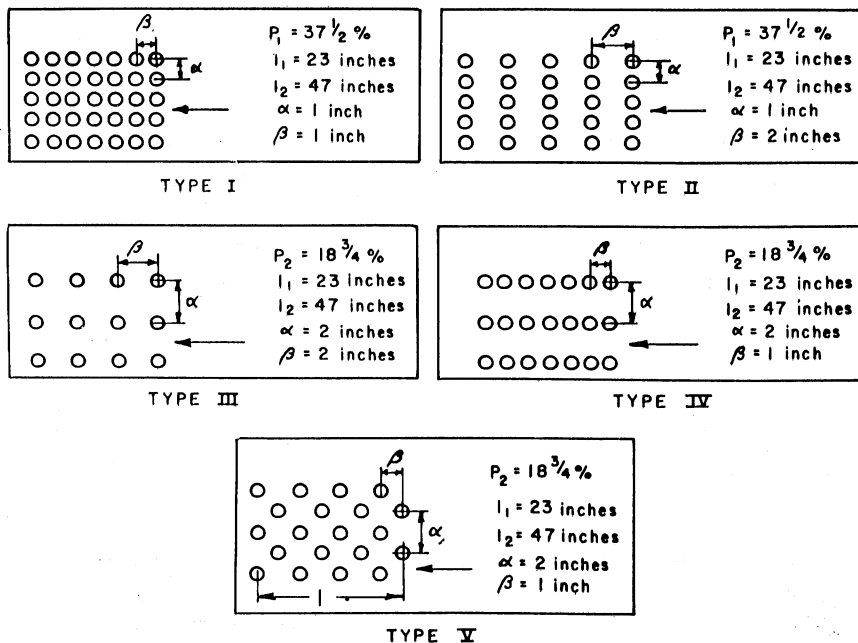
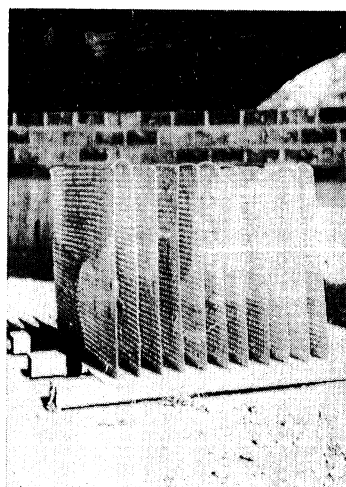


Fig. 19 - Perforated Plate Filter [86]

Fig. 20 - Various Arrays of Circular Cylinders [26]

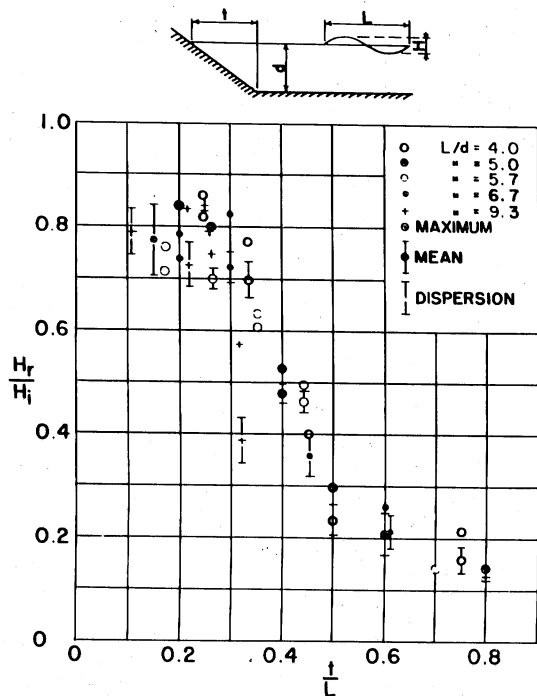


Fig. 21 - Reflection from Slopes [75]

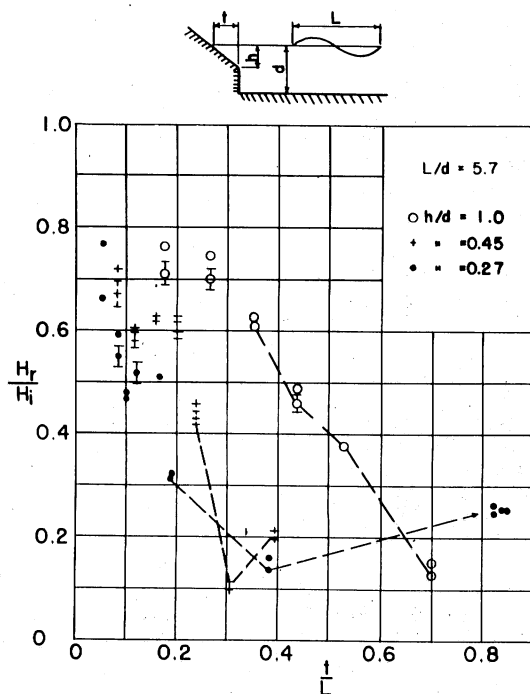


Fig. 22 - Reflection from Discontinuous Slopes [75]

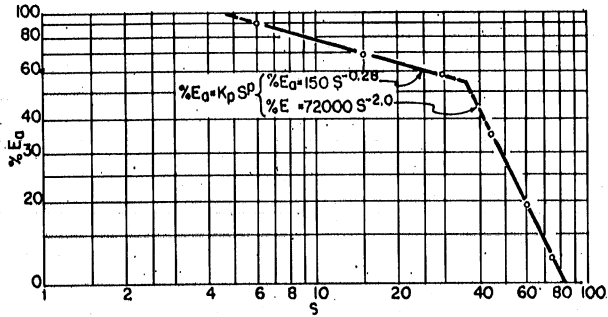


Fig. 23 - Wave Absorption on an Impermeable Beach [144]

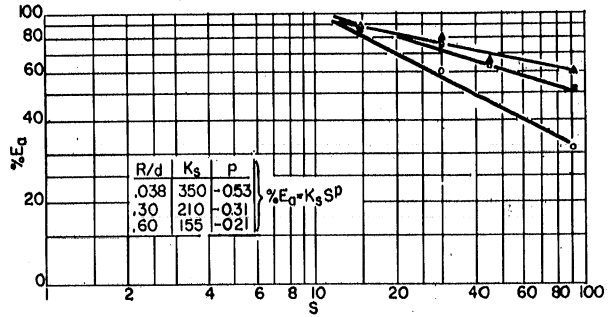


Fig. 24 - Wave Absorption on a Permeable Beach [144]

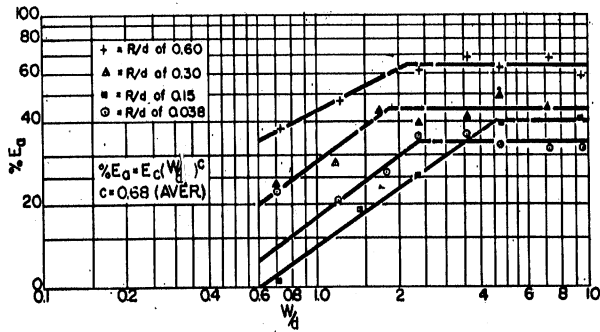


Fig. 25 - Effect of Structure Thickness on Absorption [144]

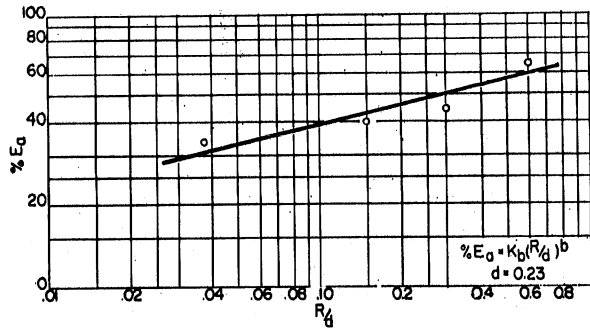


Fig. 26 - Effect of Rock Diameter on Absorption [144]

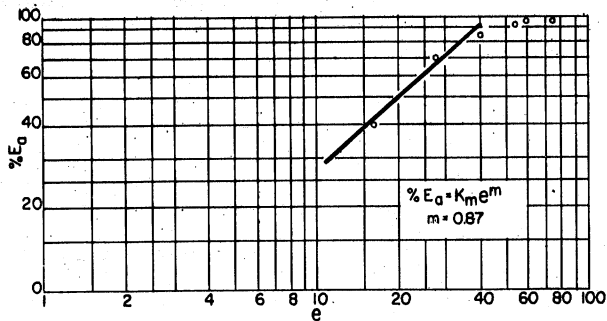


Fig. 27 - Effect of Porosity on Absorption [144]

DEFINITIONS OF SYMBOLS

- R - Median rock diameter
- E_a - Percent incident energy absorbed
- d - Still water depth
- W - Permeable structure thickness
- e - Volume of voids/volume of structure
- S - Slope of seaward face from horizontal

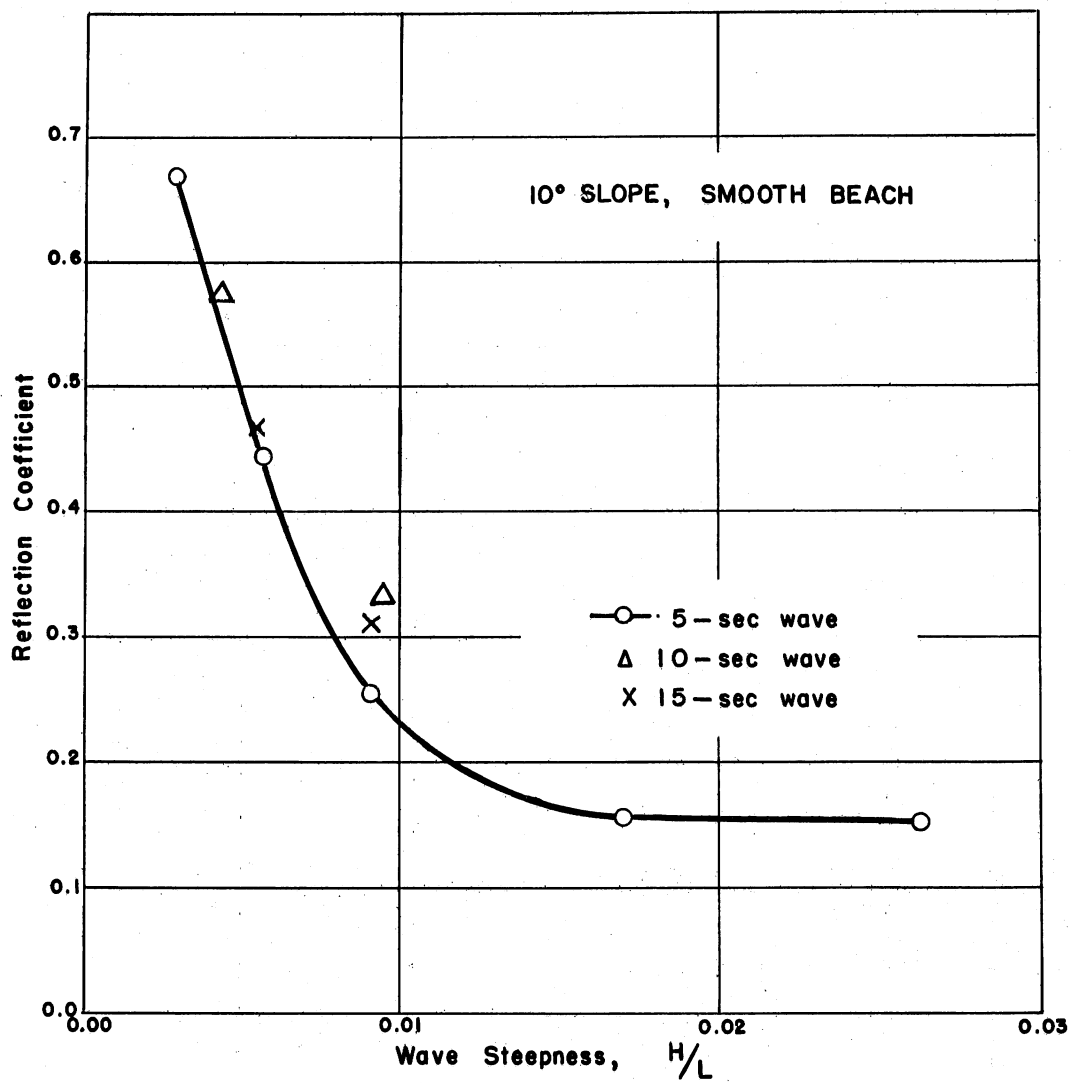


Fig. 28 - Wave Reflection as a Function of Steepness [48]

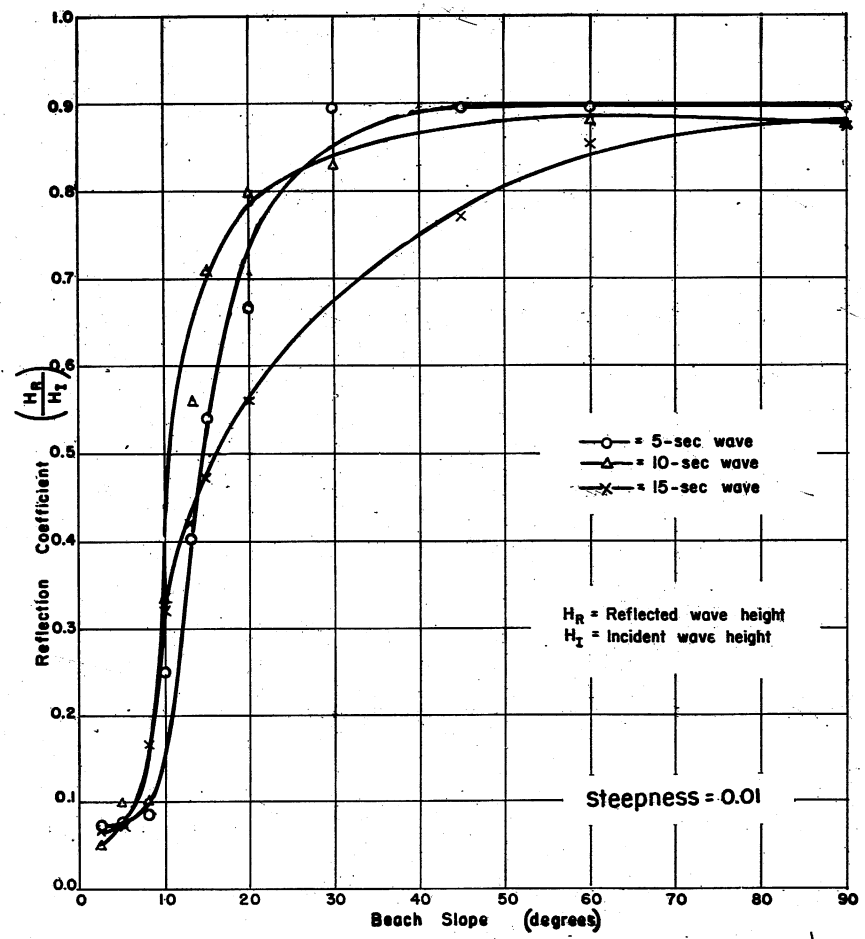


Fig. 29 - Wave Reflection as a Function of Slope [48]

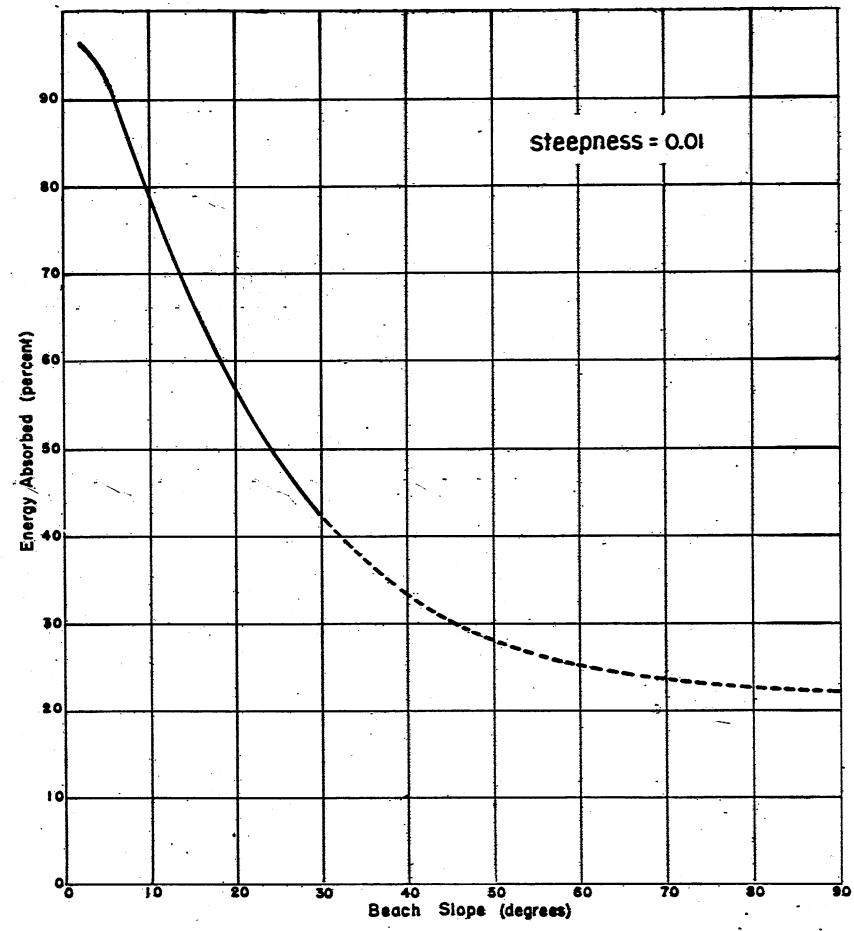


Fig. 30 - Energy Absorption as a Function of Slope [48]

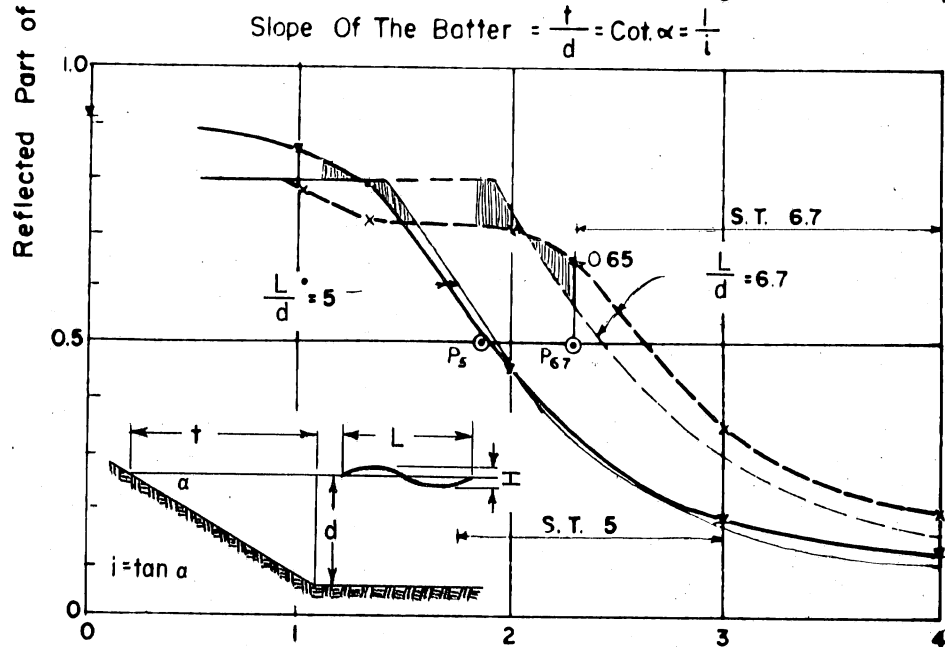
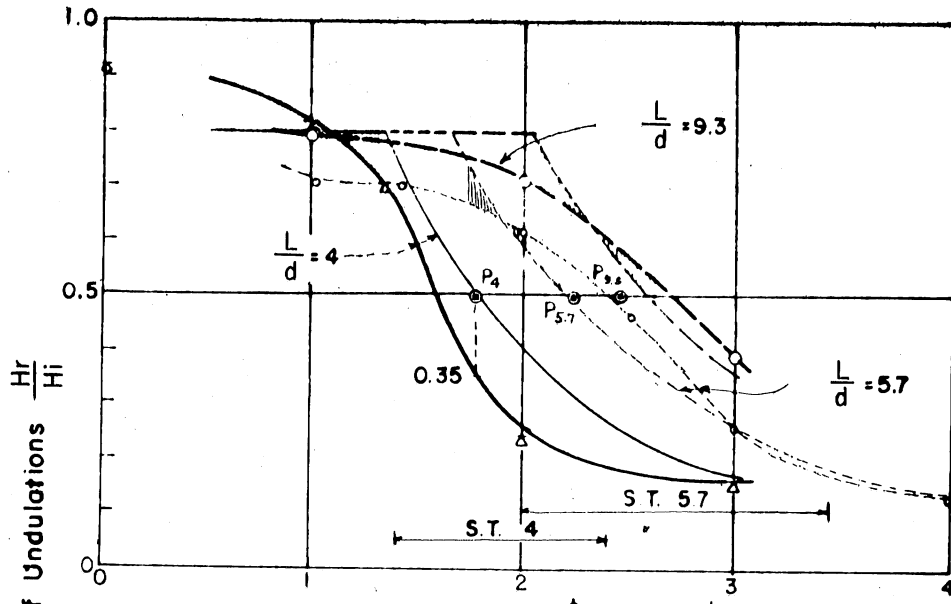


Fig. 31 - Wave Reflection from Continuous Slopes [88]

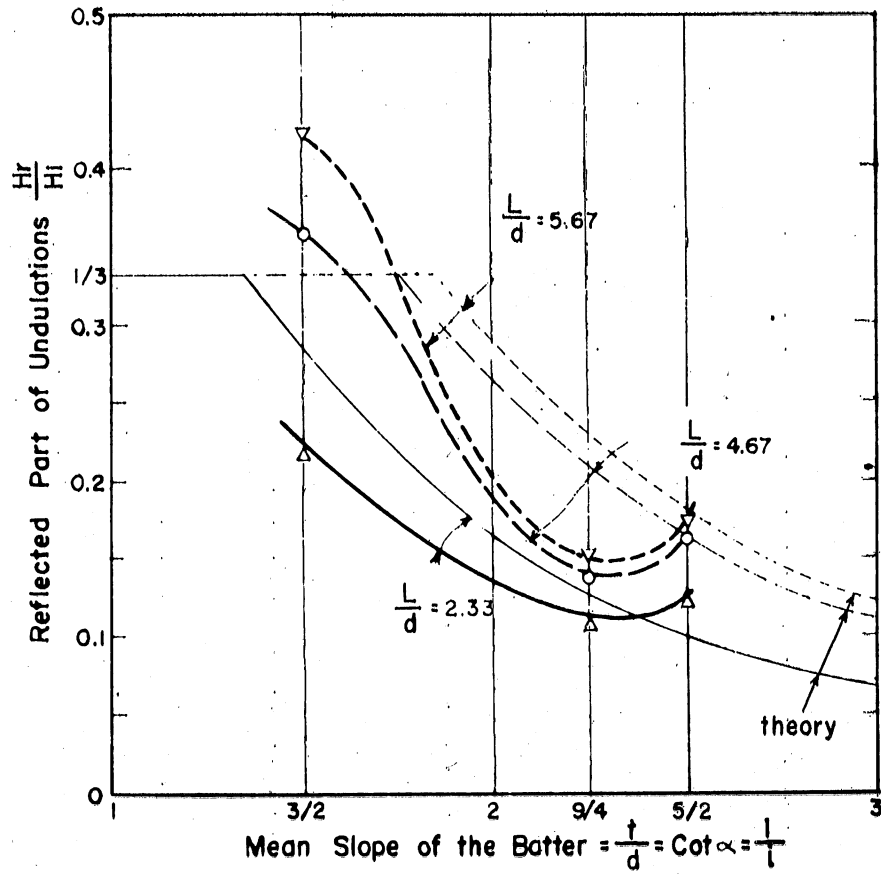


Fig. 32 - Wave Reflection from Rock Seawalls [88]

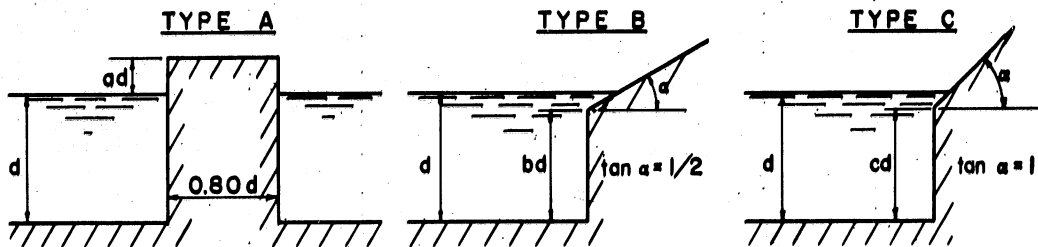


Fig. 33 - Slope Types Tested [75]

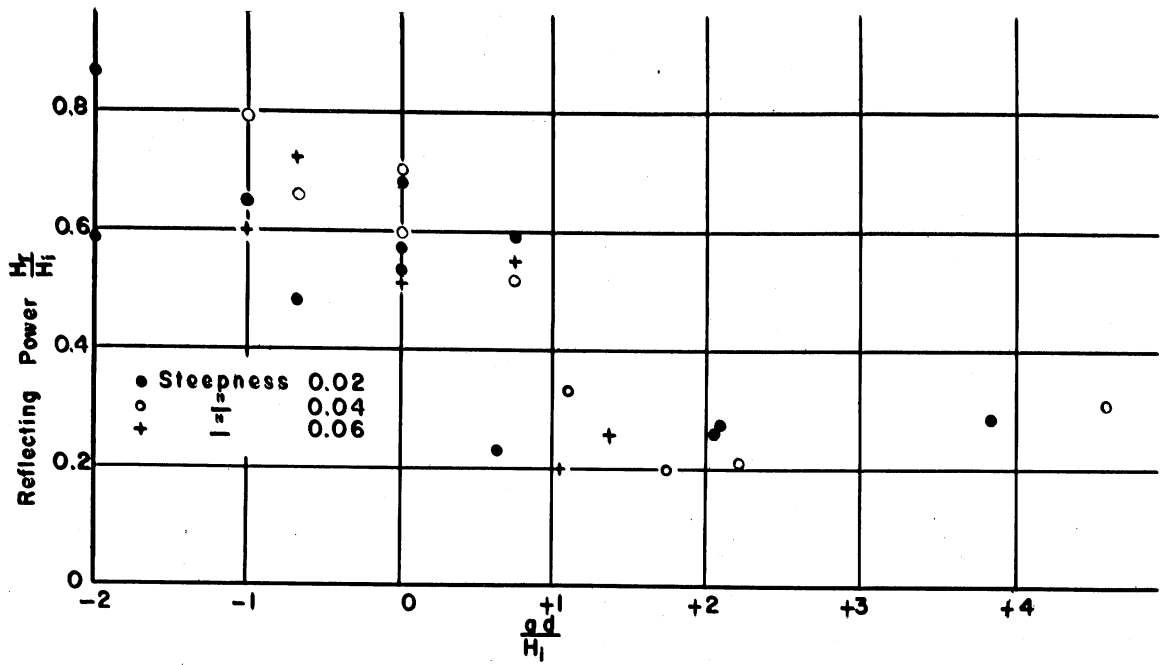


Fig. 34 - Wave Reflection from Type-A Barrier [75]

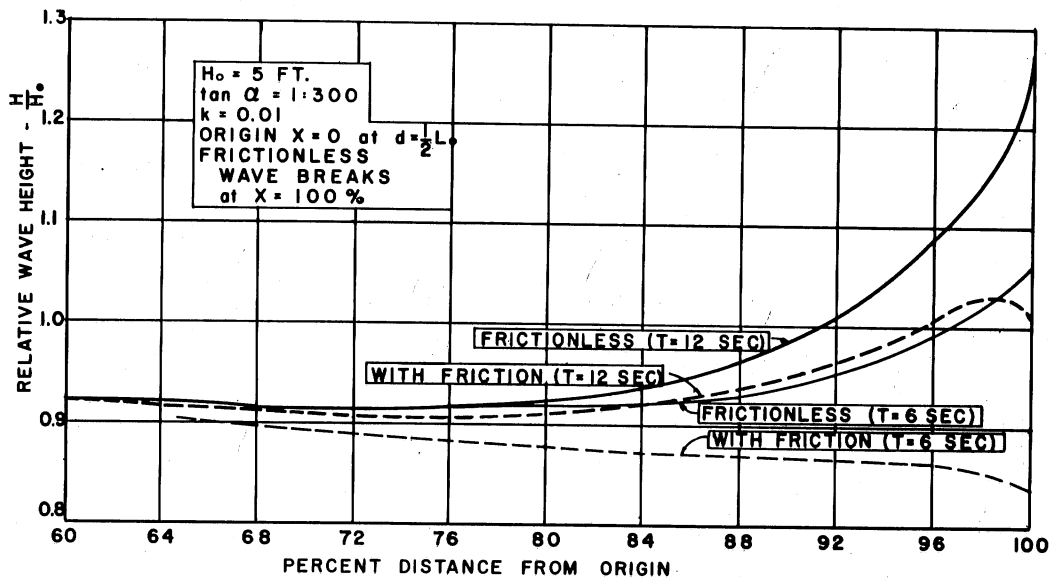
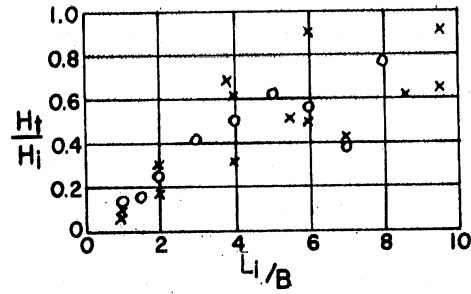
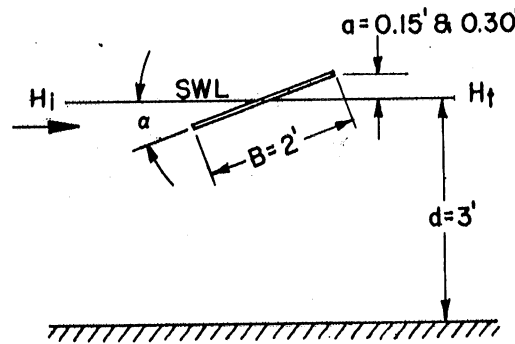


Fig. 35 - Effect of Bottom Friction on Wave Height [106]

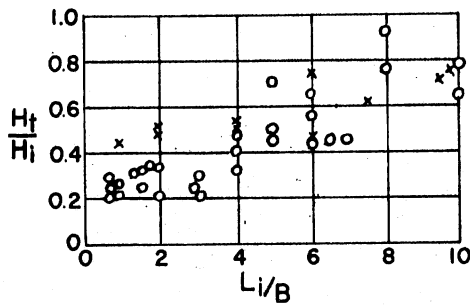
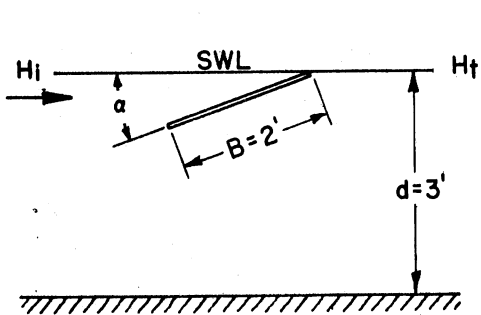


$\frac{a}{H_i} = 0.25 \text{ to } 1.5$

o -- $\sin \alpha = 0.15$

x -- $\sin \alpha = 0.30$

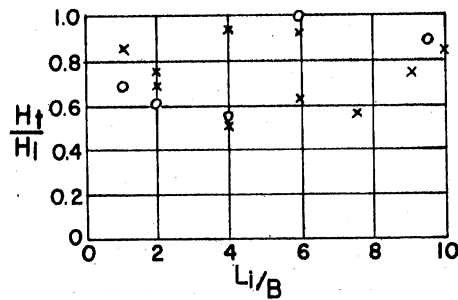
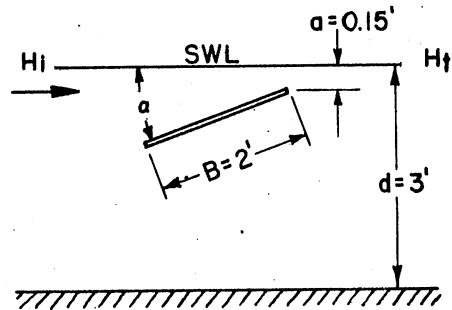
a



o -- $\sin \alpha = 0.15$

x -- $\sin \alpha = 0.30$

b



$\frac{a}{H_i} = 0.25 \text{ to } 1.5$

o -- $\sin \alpha = 0.15$

x -- $\sin \alpha = 0.30$

c

Fig. 36 - Transmission Coefficients for Submerged Inclined Barriers [46]

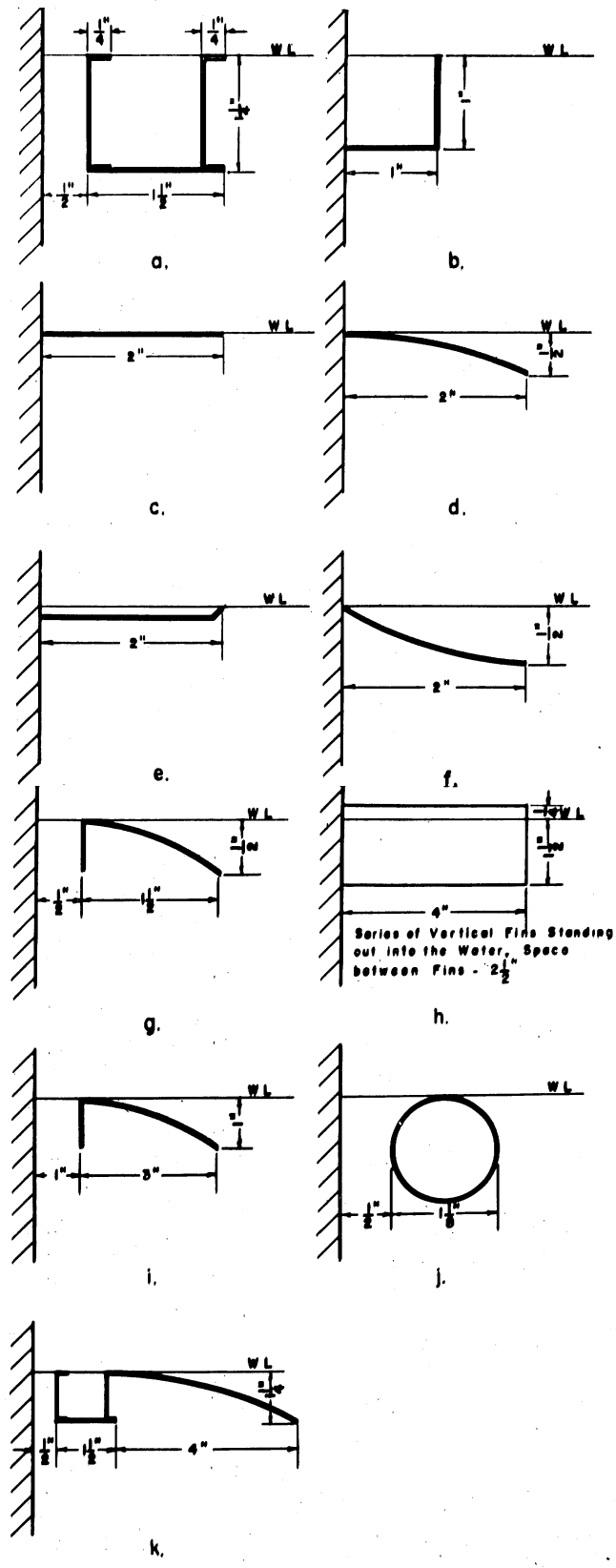
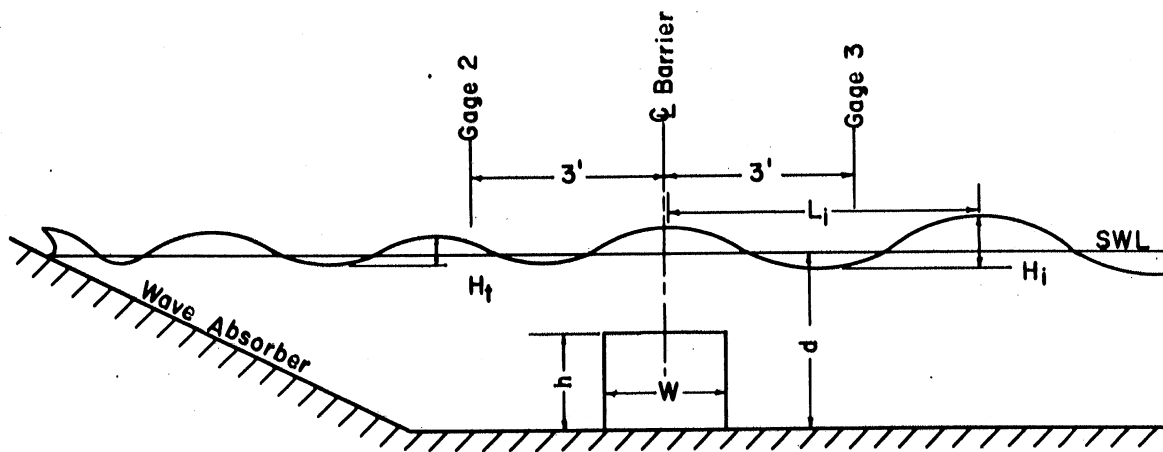
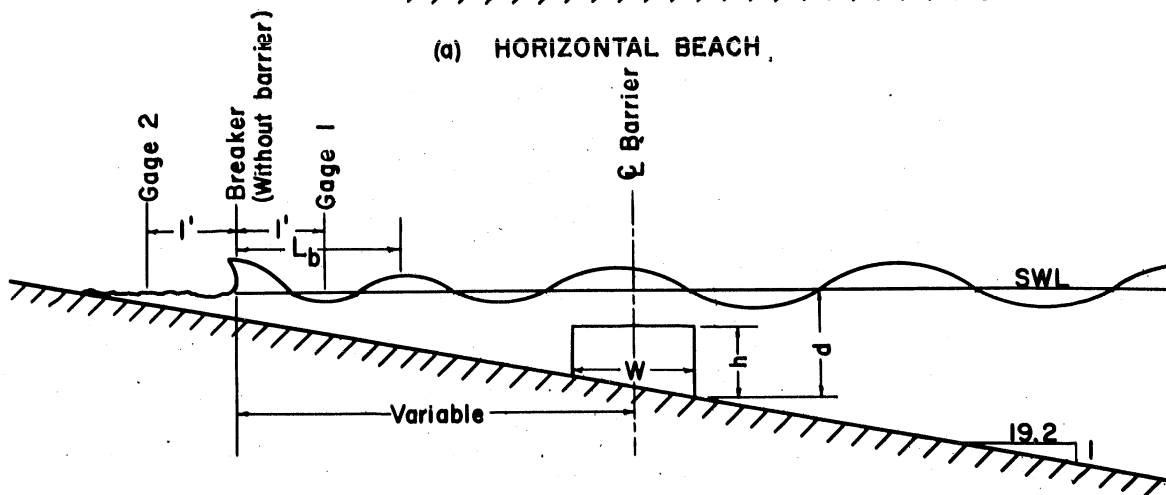


Fig. 37 - Wave Absorbers Tested at the Experimental Model Basin [160]



(a) HORIZONTAL BEACH



(b) SLOPING BEACH

Fig. 38 - Experimental Test Set-up for Submerged Barriers [63]

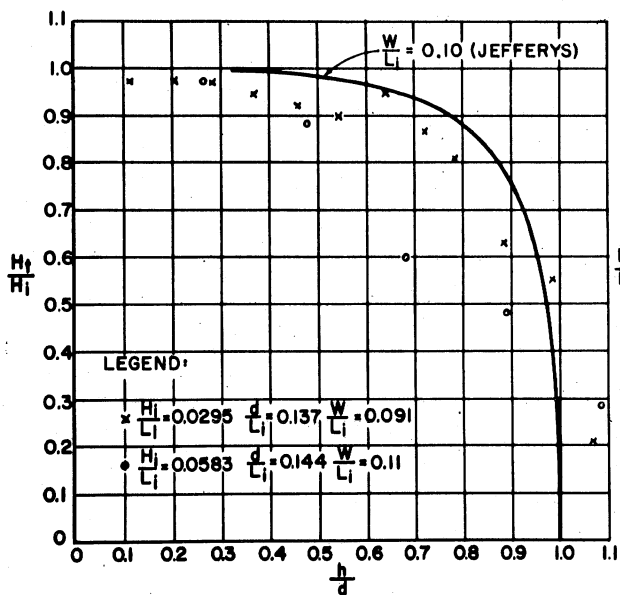


Fig. 39 - Effect of Wave Steepness on Wave Transmission over an Underwater Barrier [63]

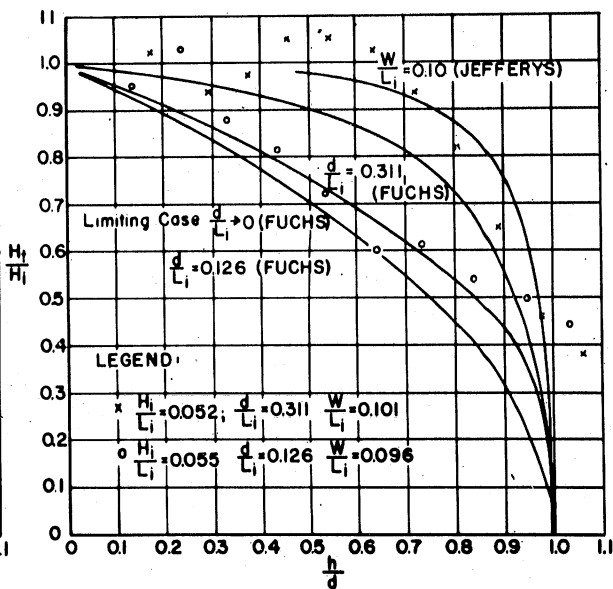


Fig. 40 - Effect of Relative Depth on Wave Transmission over an Underwater Barrier [63]

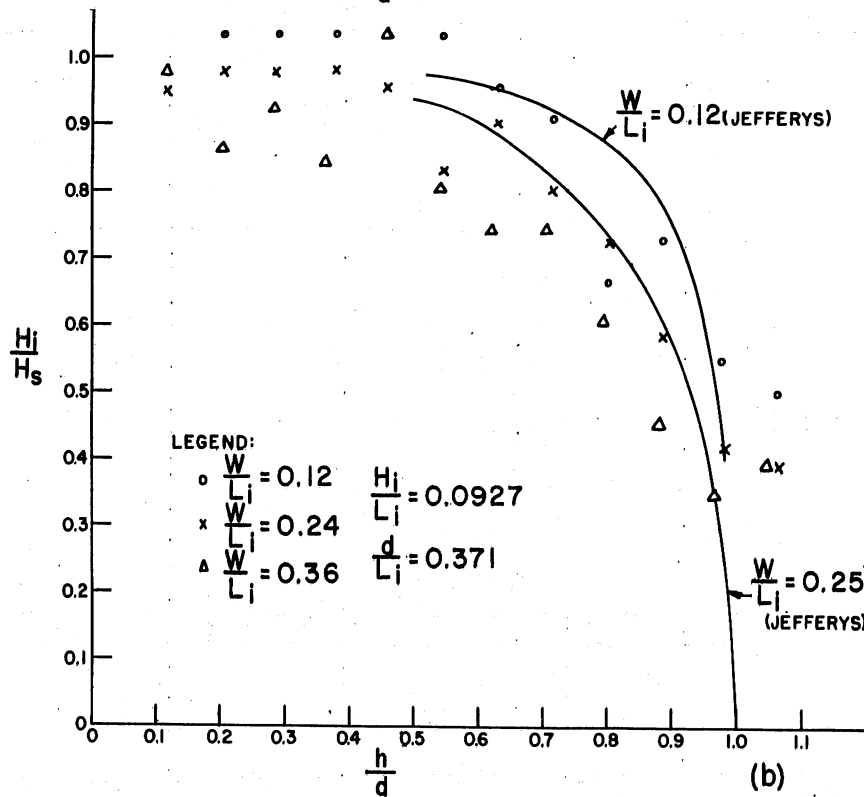
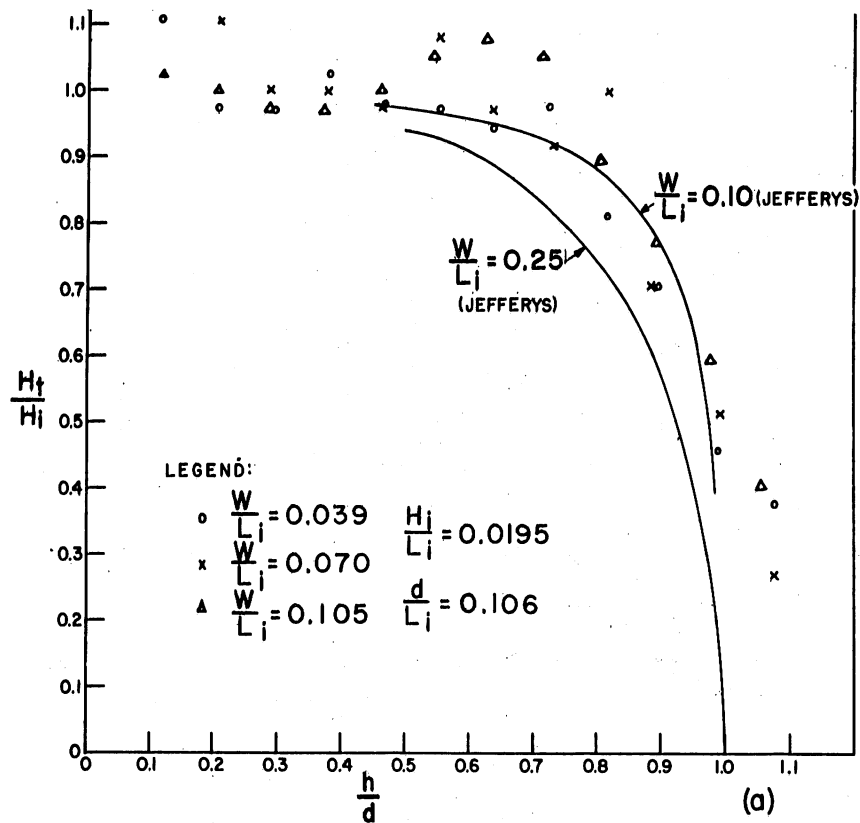


Fig. 41 - Effect of Relative Width of a Structure on Wave Transmission over an Underwater Barrier [63]

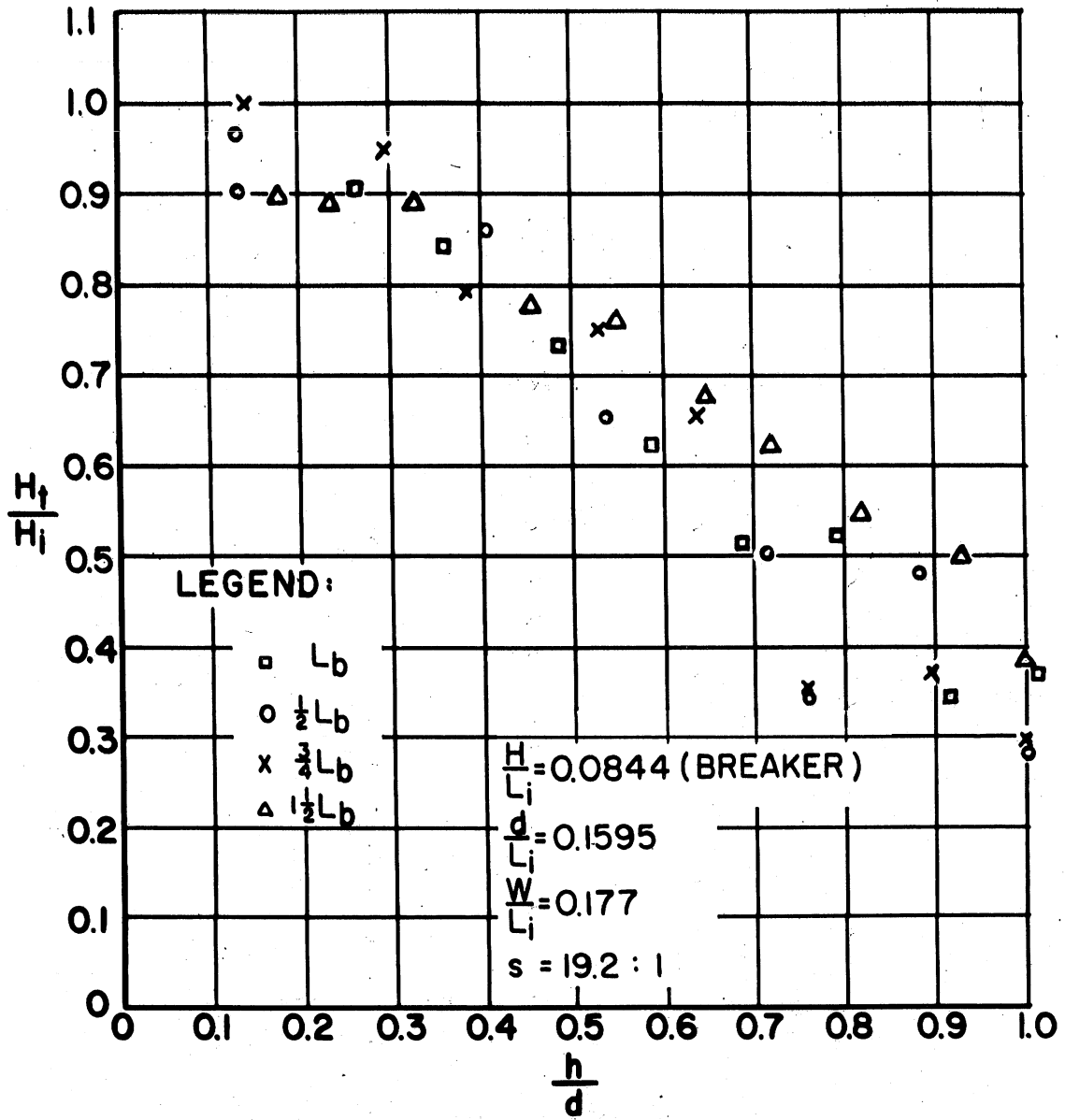


Fig. 42 - Effect of Barrier Position on Wave Transmission over an Underwater Barrier [63]

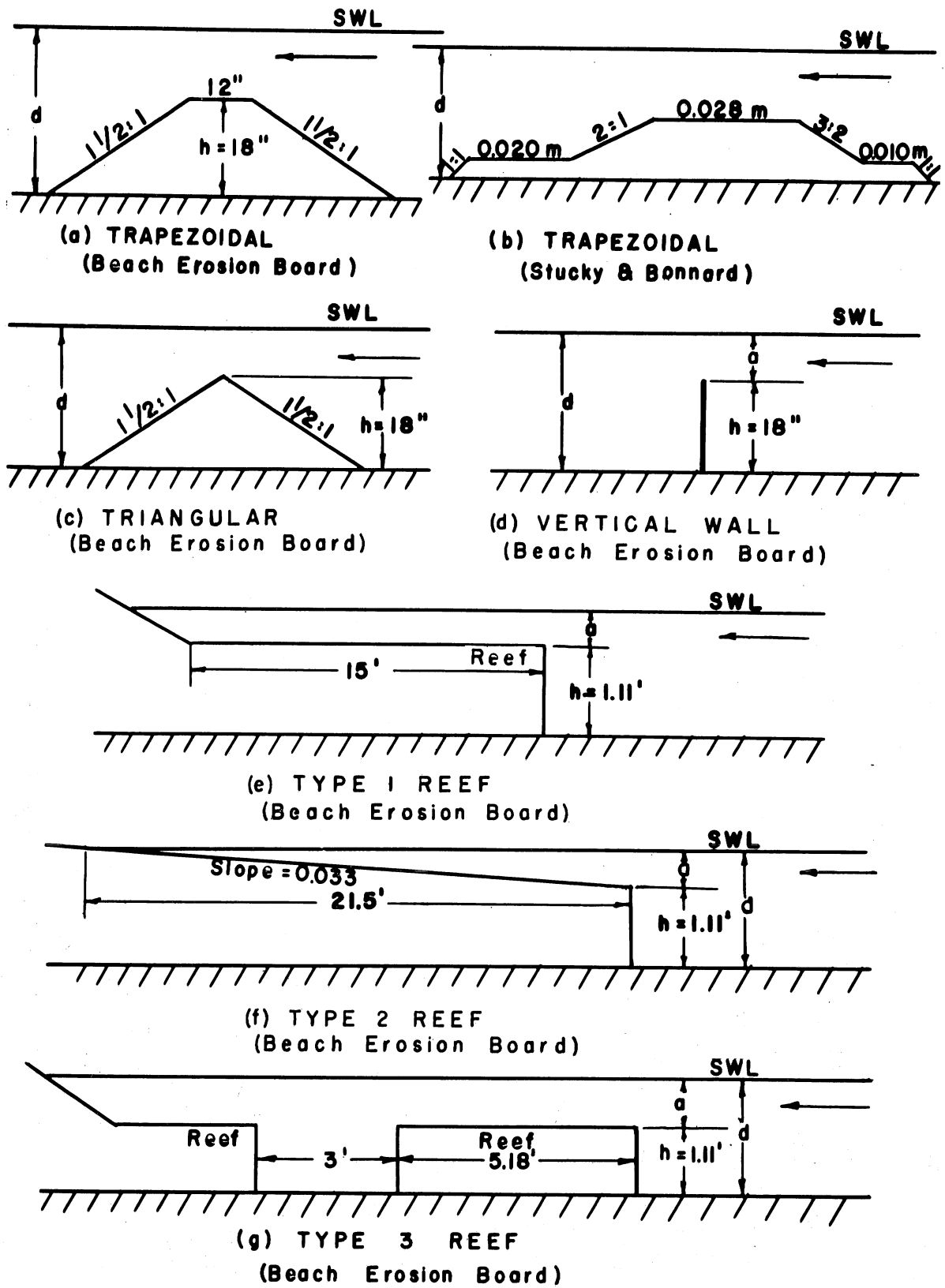


Fig. 43 - Types of Underwater Barriers Studied [63]

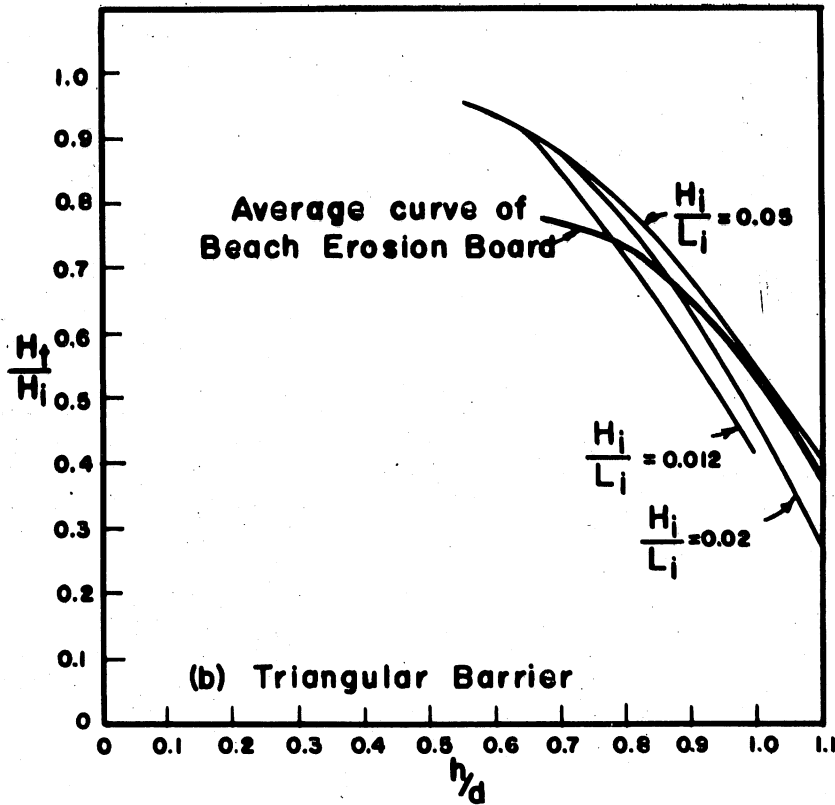
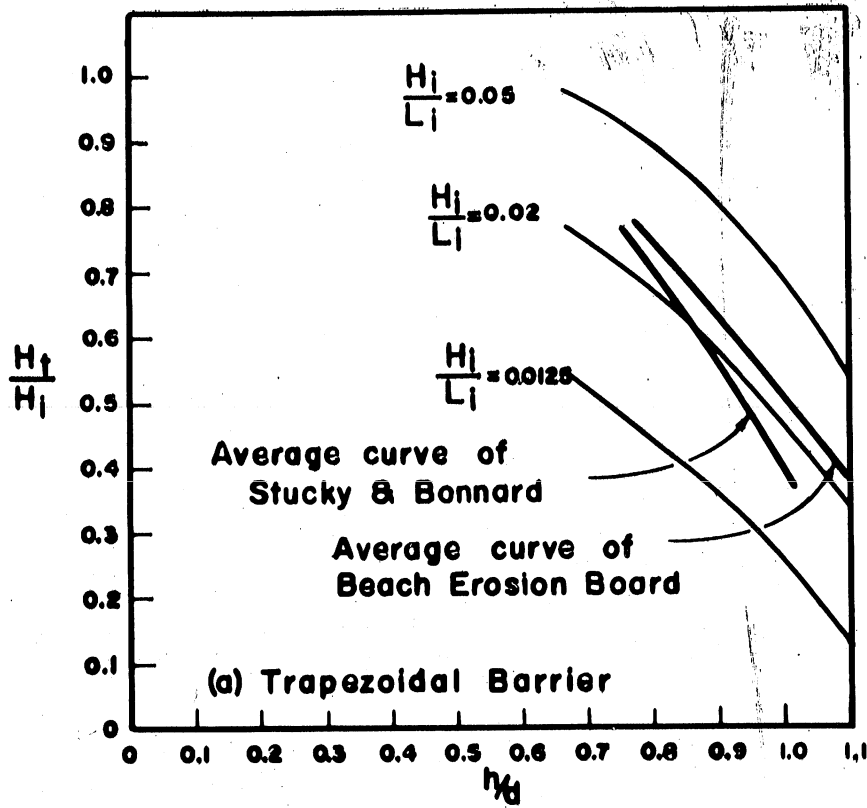


Fig. 44 - Transmission Coefficients for Trapezoidal and Triangular Barriers [63]

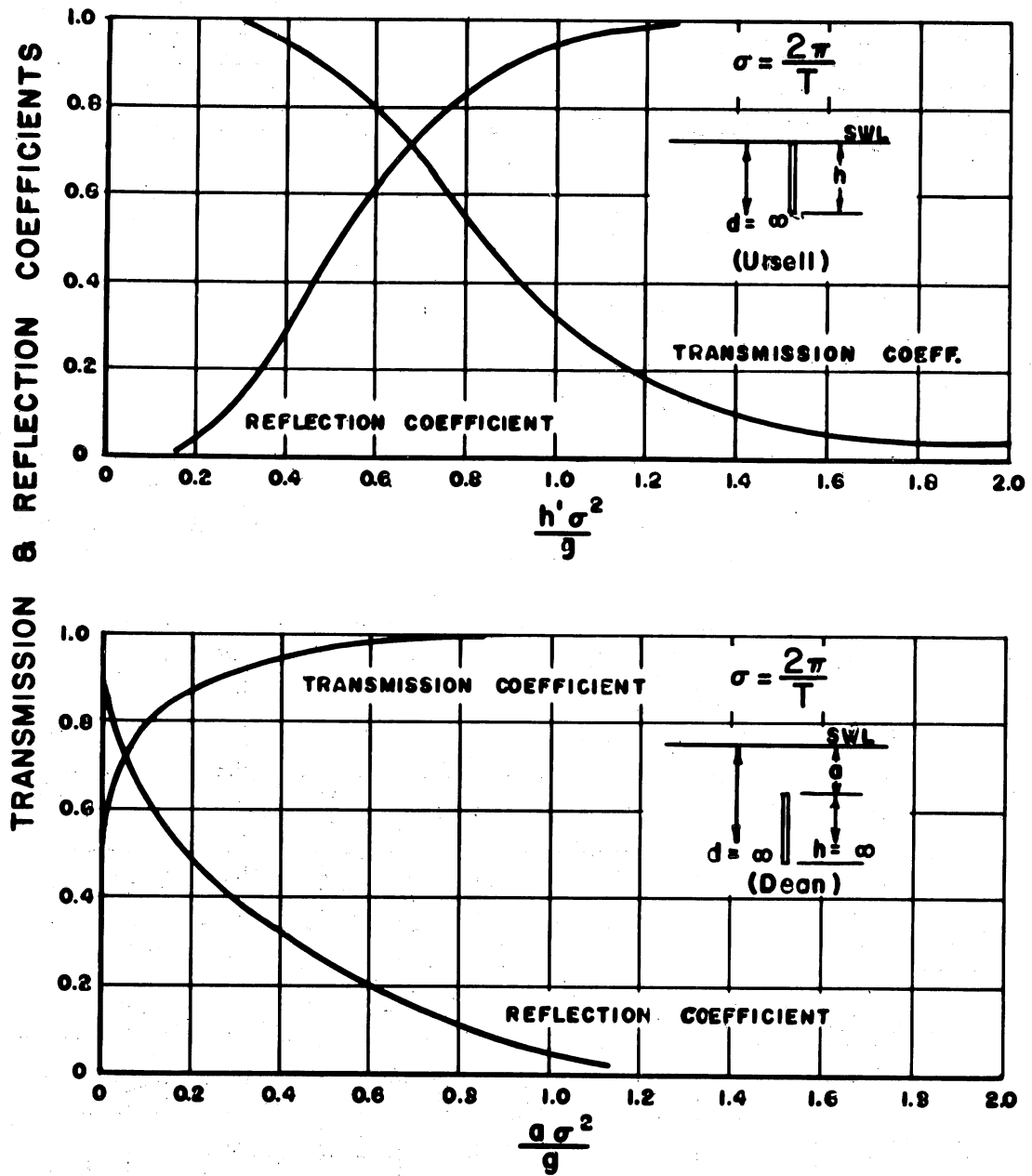


Fig. 45 - Theoretical Reflection and Transmission Coefficients Obtained by Dean and Ursell for Wave Action at Fixed Vertical Barriers [63]

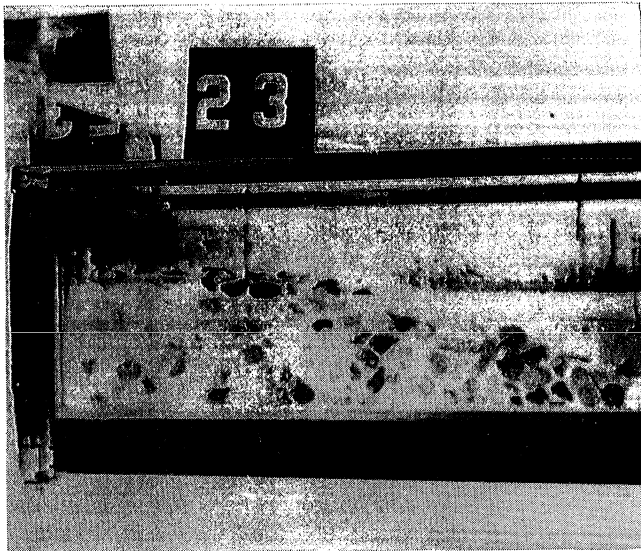


Fig. 46 - Stone Crib Absorber [3]

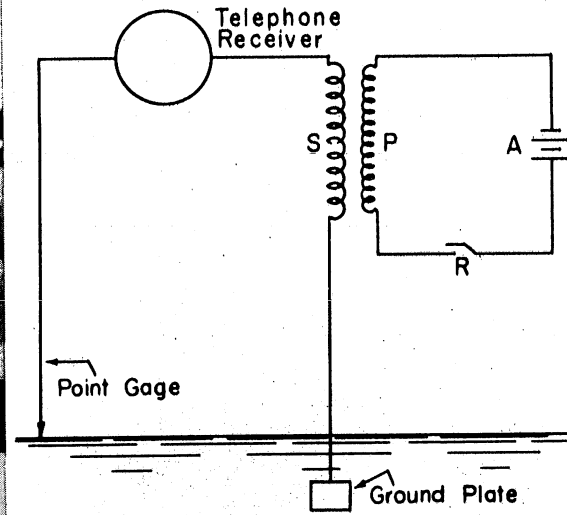


Fig. 47 - Surface Level Indicator [14]

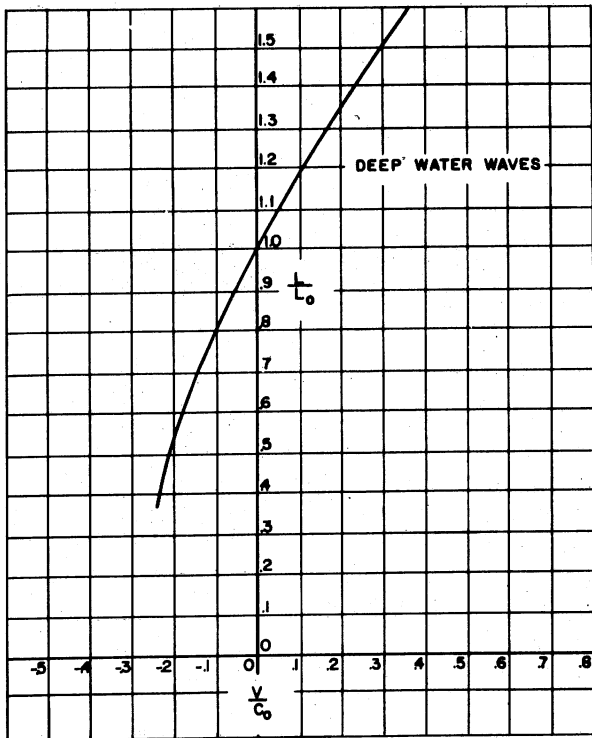


Fig. 48 - Change in Wave Length by a Uniform Current [22]

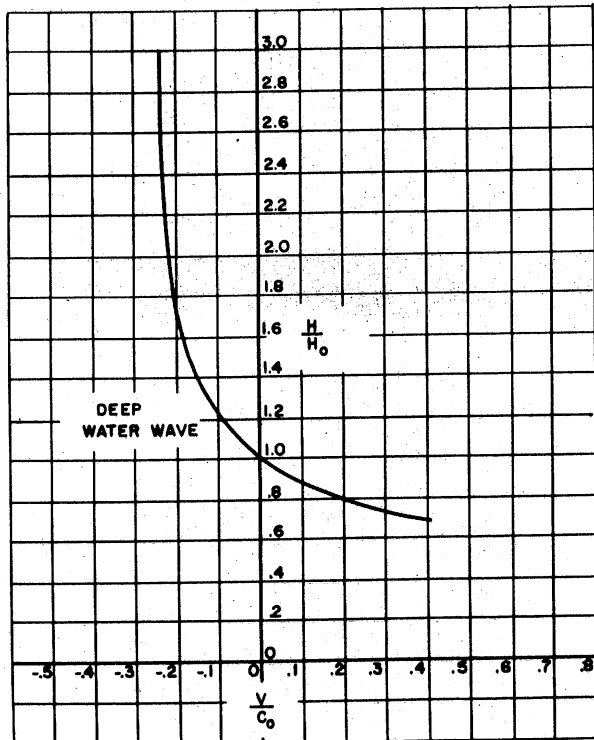


Fig. 49 - Change in Wave Height by a Uniform Current [22]

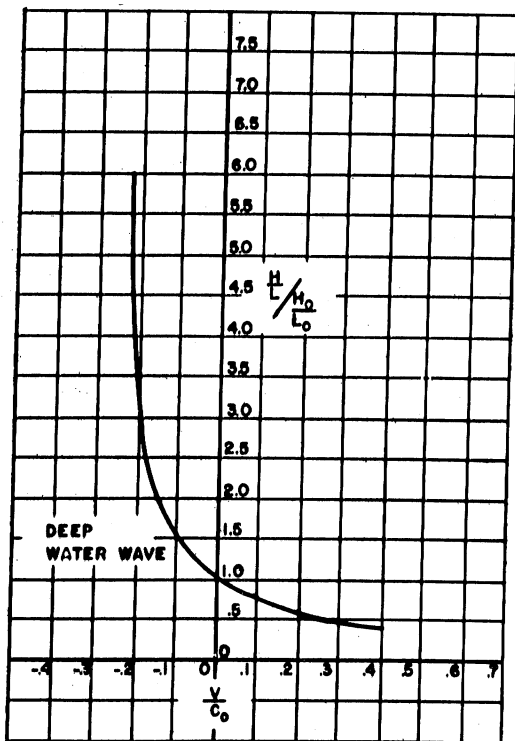


Fig. 50 - Wave Steepness in a Uniform Current [22]

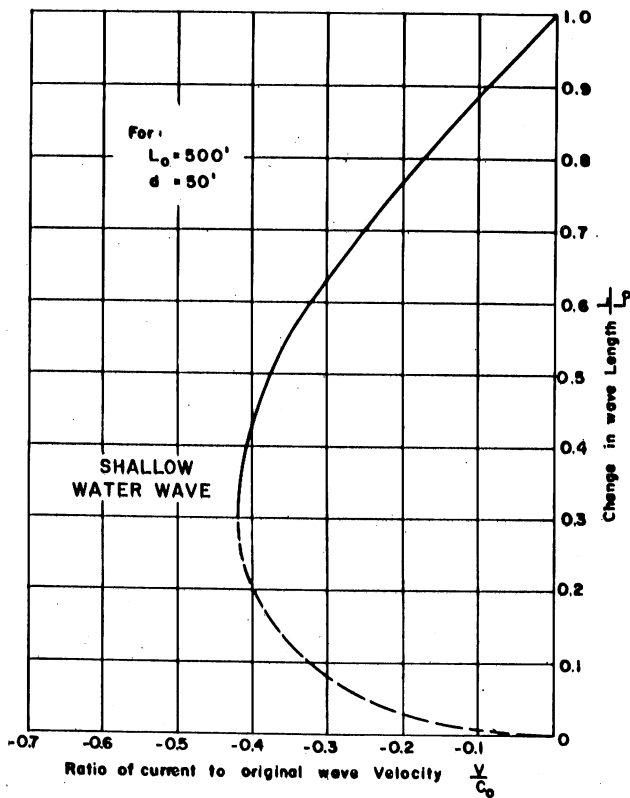


Fig. 51 - Relationships for Wave Refraction by a Uniform Current [22]

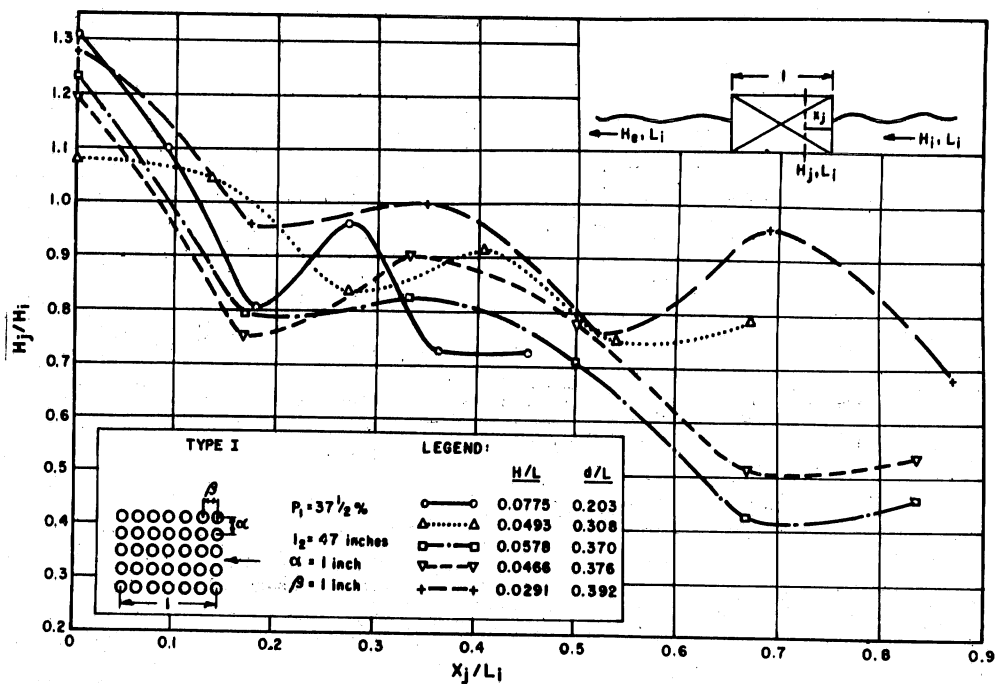


Fig. 52 - Transmission Coefficients within the Structure [26]

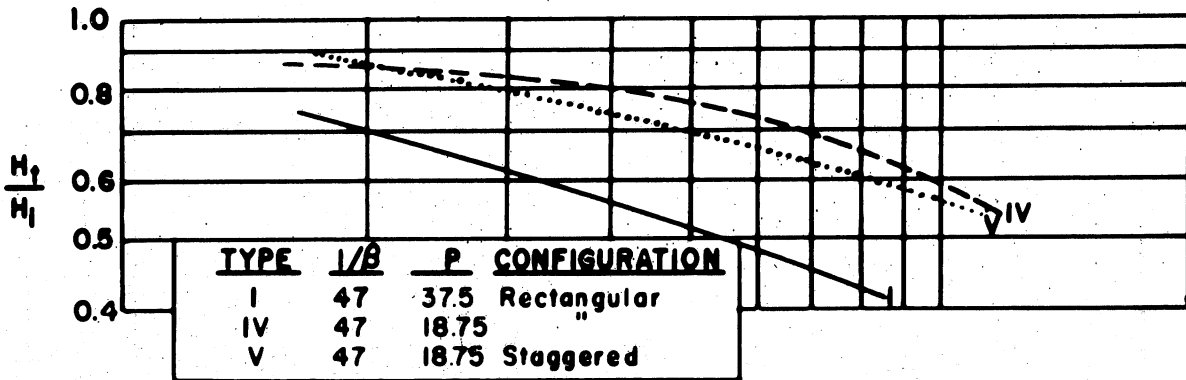
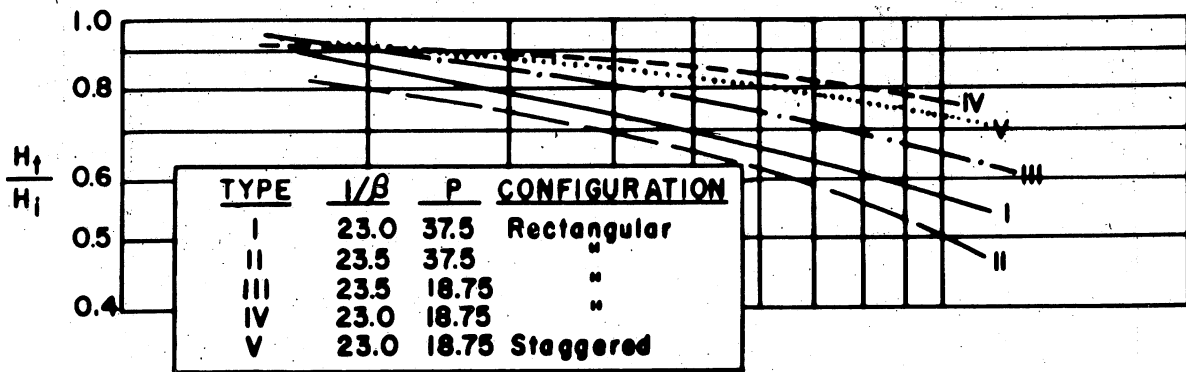
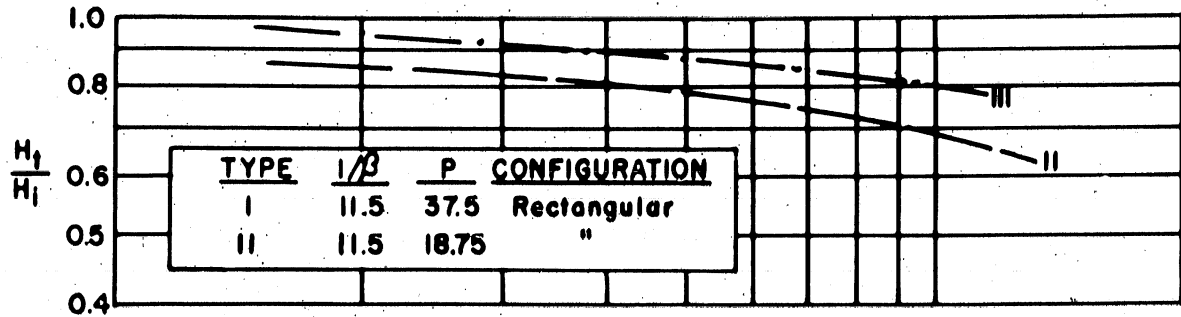


Fig. 53 - Effect of Incident Wave Steepness on Wave Transmission [25]

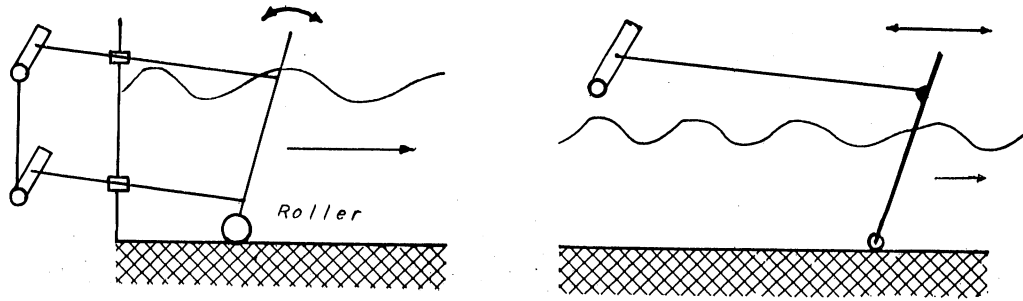


Fig. 54 - Hinged Plate and Roller Hinged Plate Wave Machines [27]

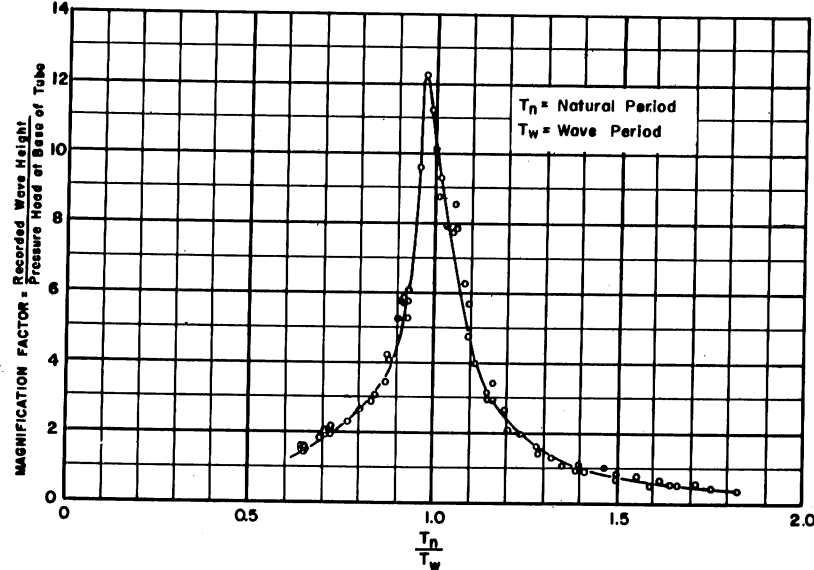


Fig. 55 - Magnification Factor for a 1-in. Tube [55]

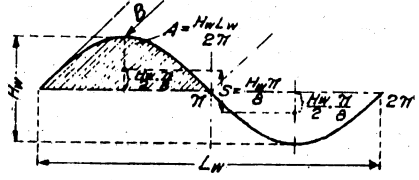


Fig. 56 - Definition Sketch [65]

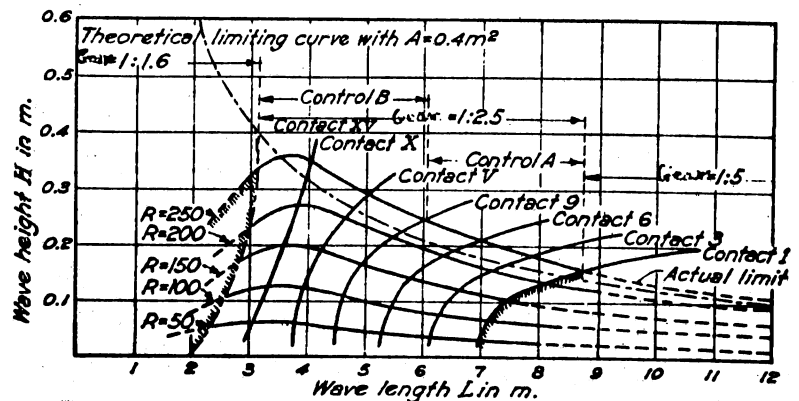


Fig. 57 - Wave Machine Adjustment [65]

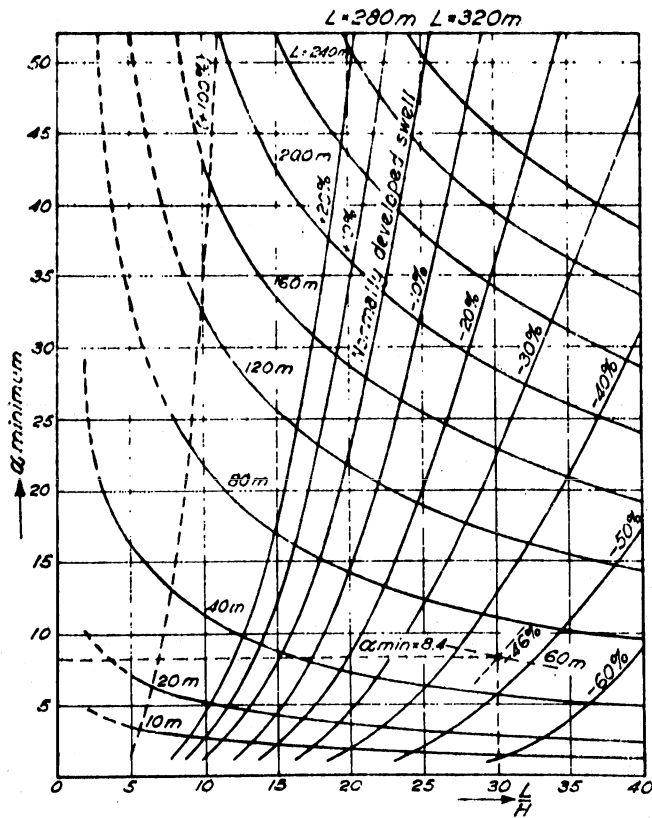


Fig. 58 - Wave Machine Capacity [65]

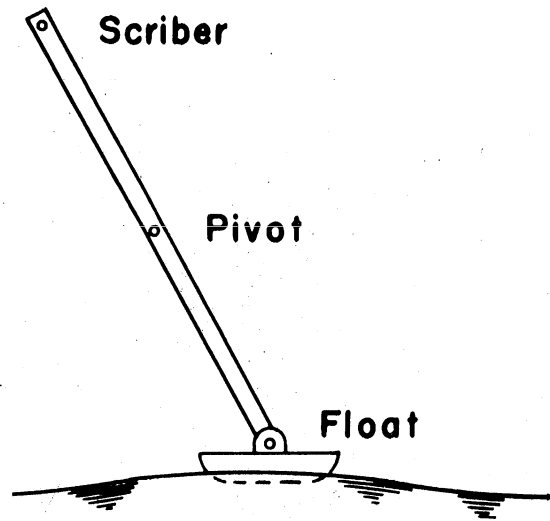


Fig. 59 - Float-type Scriber [68]

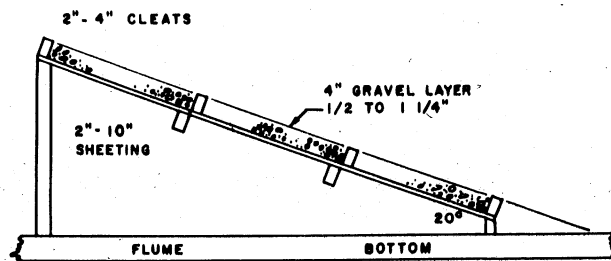
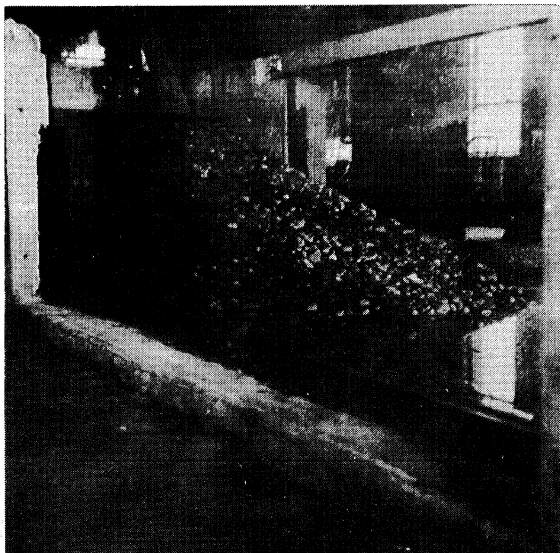


Fig. 60 - Gravel Wave Absorber [86]

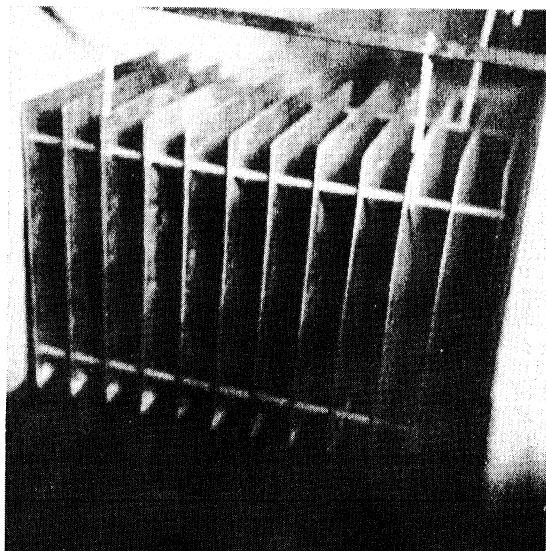


Fig. 61 - Plate-type Wave Filter [86]

FILTER MEASUREMENTS
(A-1)

Depth of Water	Wave Height	
	Out Filter	In Filter
1.25	0.115	0.111
1.29	.130	.125
1.38	.148	.142
1.42	.161	.152
1.47	.180	.169
1.50	.179	.176
1.52	.185	.190
1.55	.188	.195
1.58	.196	.193
1.60	.181	.219
1.62	.190	.211
1.64	.184	.228
1.68	.191	.243
1.70	.204	.224
1.73	.214	.228
1.76	.212	.229
1.78	.216	.249
1.82	.212	.365
1.86	.214	.360
1.90	.225	.235
1.93	.231	.264
1.98	.246	.260
2.00	.209	.278

Period of wave - 1 second.

Fig. 62 - Wave Filter Data [86]

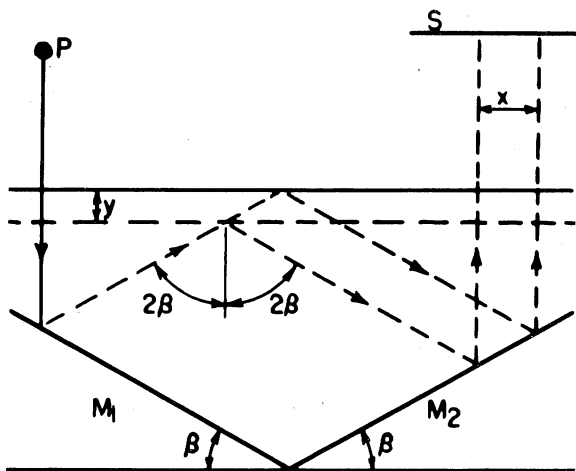


Fig. 63 - Technique for Measuring Surface Elevation [121]

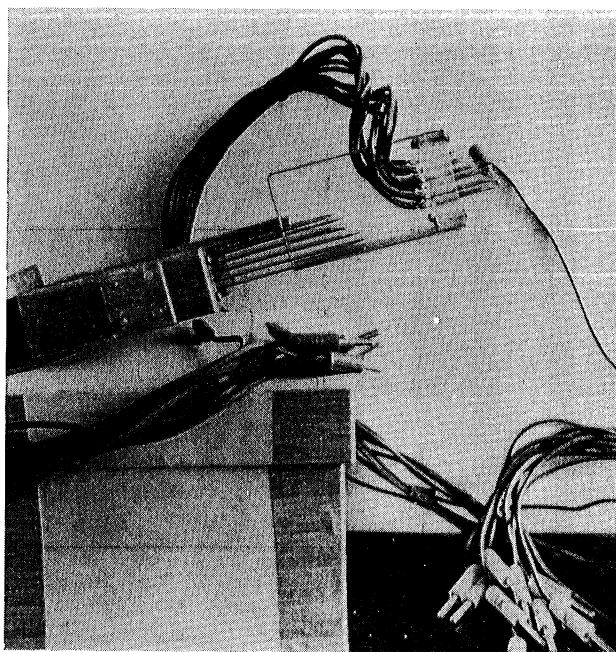

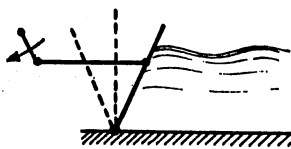
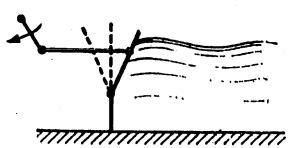
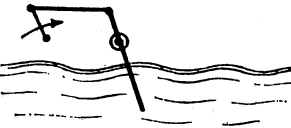
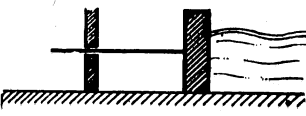
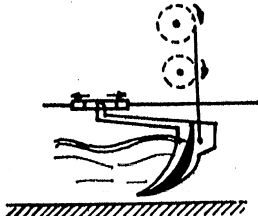
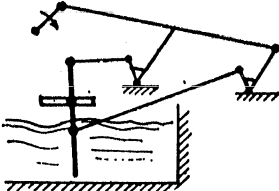

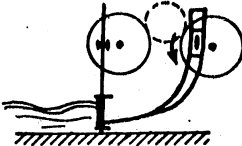
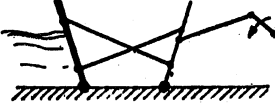
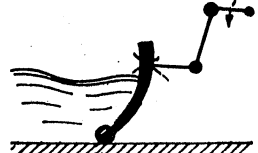
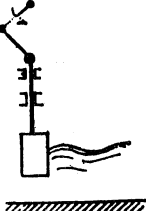
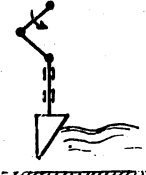



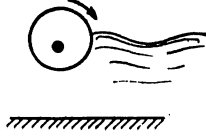
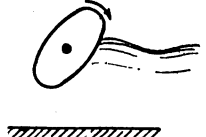
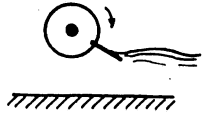

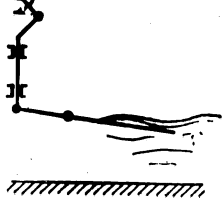

Fig. 64 - Recorder Probe Head [155]

A P P E N D I X C

SYNOPTIC TABLE OF VARIOUS WAVE GENERATORS

Type of Wave Generator		Diagram of Principle	Amplitude
Flexible flap			
Rigid flap with single articulation	Articulation at channel bed		Calculable
	Articulation above channel bed		
	Articulation above free surface		Not calculable by Biésel's theory
Piston			Calculable

Type of Wave Generator	Diagram of Principle	Amplitude	
<p>Rigid flap with double articulation</p>	<p>Suspended flaps</p>		<p>Calculable if the paddle is plane</p>
			
			
			
	<p>Flaps in contact with bed by means of rollers or slides</p>		
			
<p>Plunger</p>		<p>Generally not calculable by Biésel's theory</p>	
			

Type of Wave Generator	Diagram of Principle	Amplitude	
	Serpent		Calculable
Various Devices	Eccentric roller		Not calculable by Biésel's theory
	Elliptical cylinder		
	Cylinder with paddles		
	Paddle wheel		
	Surface paddle		
	Pneumatic device		

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