CHAPTER 64

THE THEORY AND DESIGN OF BUBBLE BREAKWATERS

by

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ABSTRACT

This paper sets down basic information on the behaviour of bubble breakwaters, drawn from analytical and experimental studies carried out by the author and others in recent years. Design formulae are given for surface velocity and thickness of the horizontal current produced by a bubble curtain, and for the quantity of free air required to suppress waves of known length and height. The effect of an intermittent air supply is examined. It is concluded that the quantity of air required is astronomical and the practical difficulties immense.

1. INTRODUCTION

If a surface current of sufficient strength is propagated in opposition to oncoming waves, their length is reduced and their height increased until instability occurs, and they break over the current in the manner of waves breaking on a beach. This well known action occurs naturally when wind formed waves meet an opposing tidal current in an estuary. One method of artificially producing an opposing surface current is by means of a bubble curtain, which can be obtained by releasing air from a line of jets on the sea bed. As the bubbles rise water is entrained in the form of a vertical current, and this spreads into opposing horizontal currents at the surface.

In recent history this concept was first employed by Brasher[1] of New York to protect civil engineering works in 1907. He patented his design, which consisted basically of a perforated pipe on the sea bed fed by air from shore based compressors, and it was used by the Standard Oil Company in 1915 at El Segundo, California. Other projects seem to have been undertaken, but the results were not promising and interest diminished. Research continued spasmodically, however, and in 1936 Professor Thysse of Deft showed that the surface currents produced by the bubbles were the main mechanism of the system, until then there had been considerable speculation about the precise way a bubble breakwater worked.

During the 1939-1945 war, fundamental research was carried out by Professor White[2] and Sir Geoffrey Taylor[3] in England, because the method was seen to have potential as a transportable breamwater for military purposes. As a result of their work it became possible for the first time to predict the quantity of air required to produce a given surface current, and the speed of current required to kill waves of known length. Taylors theory, however, assumed waves of infinitessimal amplitude and sinusoidal form and did not take account of wave height or the possibility of partial wave damping. This fundamental work and the experiments associated with it showed that for the suppression of storm waves characteristic of N.W.Europe, the quantity of air required per foot run of breakwater would be astronomical.

After the war, inventors and scientists from a number of countries searched for methods of increasing the efficiency of the bubble curtain. It is inappropriate to give a complete survey here, and the reader is directed to a summary by the author[4] published a few years ago. Evans[5] carried out a number of illuminating experiments, and it was clear to him and others that large scale tests were desirable to ascertain whether large current horse-powers could be effectively produced in deep water, and whether a measure of wave damping could be obtained in a full scale installation. These tests were carried out by Bulson[6,7] in the early 1960's and later the effect of an intermittent air supply was investigated[8]

From all these experimental and analytical studies it is possible to build up a design theory for bubble breakwaters. This falls into two sections, the first dealing with the magnitude and distribution of surface currents obtainable from a given air supply, the second with the action of a given surface current against waves of known height and length.

2. THE BUBBLE CURTAIN

Taylor[3], drawing an analogy between the vertical current produced in water by releasing bubbles, and in air by releasing heat, quoted the work of Schmidt[9] in showing that

$$V_m^3 = KgQ, \qquad \ldots\ldots(1)$$

where V_m is the surface velocity of the current, see Fig 1,

K is a constant,

Q is the quantity of air emerging per second from the orifices of the submerged pipe, per foot of pipe.

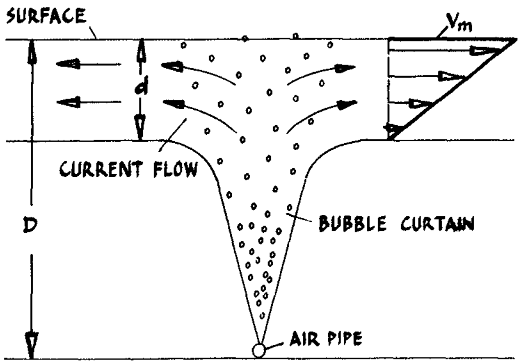
SURFACE
Vm
d
CURRENT FLOW
D
BUBBLE CURTAIN
AIR PIPE

FIG. 1

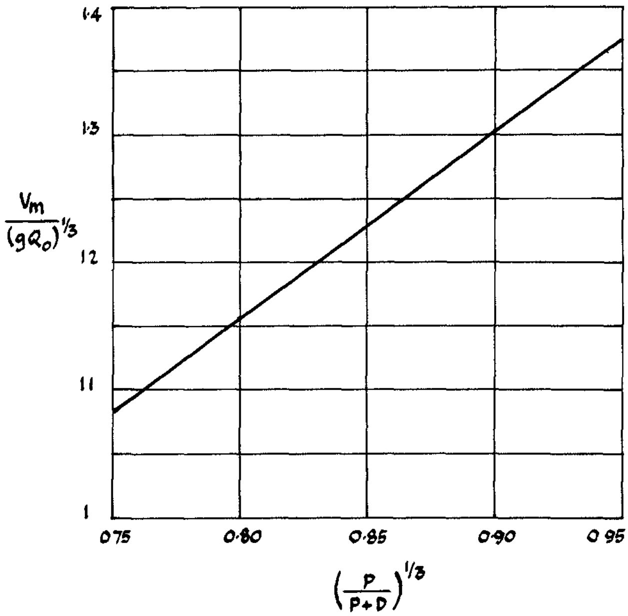
1·4
1·3
1·2
1·1
1
Vm / (gQo)^1/3
0·75
0·80
0·85
0·90
0·95
(P / (P+D))^1/3

FIG 2

The practical engineer is interested in Q_o, the quantity of free air delivered by the compressors per second per foot, and this is linked with Q by a relationship governed by the depth of the manifold (D), and the atmospheric pressure expressed as a head of water (P). Bulson[6] showed that Eq.(1) can be set in the form

$$V_m = 1{\cdot}46 \left(\frac{g Q_o P}{P + D} \right)^{1/3} \quad \text{feet/sec,} \qquad \ldots\ldots(2)$$

where 1·46 is the value of $K^{1/3}$ found by large scale experiment (Fig 2).

The current velocity, V, diminishes approximately linearly with depth, until it equals zero at a depth d below the surface. Bulson gives the following expression for d,

$$d = 0{\cdot}32\, P \log_e \left(\frac{P + D}{P} \right) \text{ feet,} \qquad \ldots\ldots(3)$$

as shown in Fig 3.

When the same quantity of air is passed through a variety of orifice diameters and spacings there is no significant difference in V_m, further, results for a single manifold at depth D are not noticeably different from those when two or more adjacent manifolds are delivering the same total quantity of air.

When D = 34 ft., the vertical velocity at the centre of the curtain when Q_o = 1 ft^3/sec/ft was found to be about three quarters of the horizontal surface velocity V_m. A typical curve of decay in surface current velocity with distance from the centre of the manifold is shown in Fig 4.

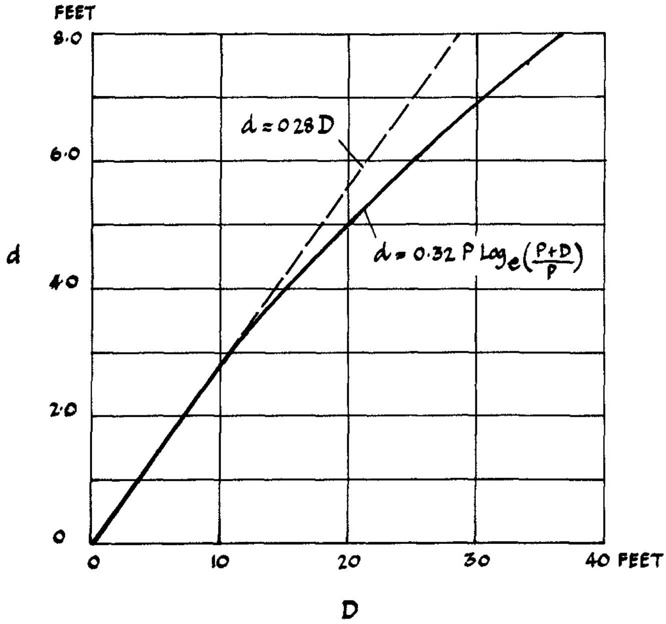
FEET
8.0
6.0
4.0
2.0
0
d
d = 0.28 D
d = 0.32 P Log$_e$(P+D / P)
0
10
20
30
40 FEET
D

FIG. 3

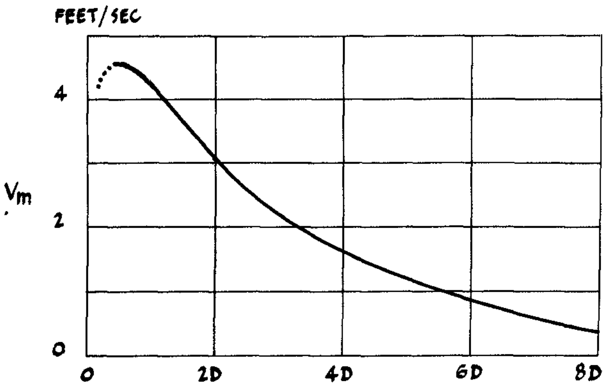
FEET/SEC
4
2
0
Vm
0
2D
4D
6D
8D

FIG. 4

3. COMPLETE WAVE SUPPRESSION

Unna[10], in 1942, discussed the action of a tidal stream on wind formed waves. For deep water waves having a length λ, the velocity of travel, c, is given by

$$c = \left(\frac{\lambda g}{2\pi}\right)^{1/2}, \qquad \ldots\ldots(4)$$

and Unna showed that the critical stream velocity, $\bar{V}$, is equal to $-\frac{c}{4}$. Taylor[3] investigated the general condition when the water cannot be considered deep, and the counter current speed decreases uniformly with depth. The current velocity at the surface to completely suppress the waves, $\bar{V}_m$ was shown to be given by

$$\bar{V}_m = +\frac{1}{\alpha_m}\left[\frac{\lambda g}{2\pi}\right]^{1/2}, \qquad \ldots\ldots(5)$$

where

$$\frac{\alpha_m^2}{Z} = \frac{\lambda}{2\pi d}, \qquad \ldots\ldots(6)$$

$$Z = \frac{dg}{\bar{V}_m^2}, \qquad \ldots(7)$$

and α_m is the minimum value of α, where $\alpha = \frac{g}{\bar{V}_m \sigma}$.

(σ is the speed of the orbital motion in radians/sec).

Taylor gives a curve relating $\frac{\alpha_m^2}{Z}$ and α_m, which is reproduced in Fig 5. In very deep water, $\frac{\lambda}{d} \to 0$, and from Eq.6 $\frac{\alpha_m^2}{Z} \to 0$; then, from Fig 5,

$\alpha_m \to 4$, the value given by Unna.

If the quantity of free air to produce $\bar{V}_m$ is Q_{cr}, by combining Eq.2 and 5 we find that

$$Q_{cr} = \left(\frac{P+D}{Pg}\right)\left(\frac{g\lambda}{2\pi}\right)^{3/2}\left(\frac{1}{1{\cdot}46\,\alpha_m}\right)^3. \qquad \ldots\ldots(8)$$

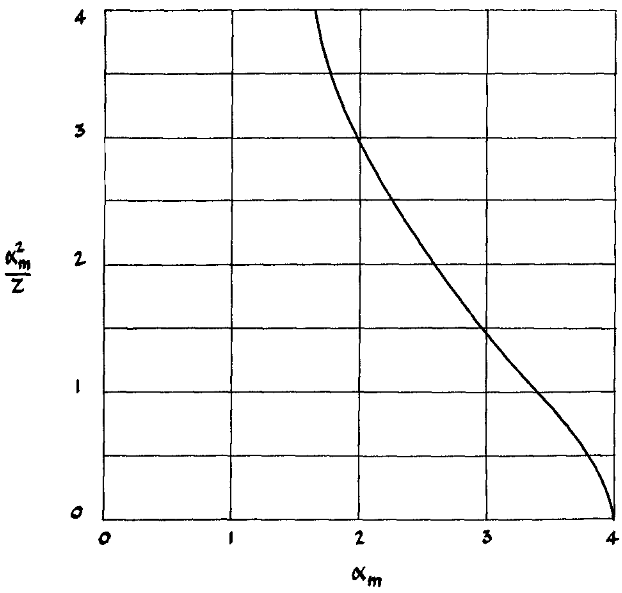

FIG. 5

For a known water depth, D, the current thickness d can be found from Eq.3. For a known wavelength, λ, the value of $\frac{\alpha_m^2}{Z}$ can then be calculated from Eq.6, and Fig 5 used to find α_m. This is substituted into Eq.8 to find the air supply Q_{cr}. The value of Q_{cr} is plotted for a selection of values of D and λ in Fig 6, which graphically illustrates the advantage of setting the air pipe in a depth of water of at least half the wavelength. Q_{cr} rises very steeply when the depth is small.

According to Eq.8, Q_{cr} is independent of wave height, but experiments show that when waves are neither truly sinusoidal nor of infinitessimal height the quantity to produce complete damping can exceed Q_{cr}. If we denote this quantity by Q_{max}, Bulson suggests a linear relationship between $\frac{Q_{max}}{Q_{cr}}$ and the wave steepness $\frac{H}{\lambda}$, as shown in Fig 7.

As an example, supppose we wish to investigate the quantity of air required to suppress sea waves 100 ft long, 4 ft. high, in a water depth of 50 ft. Now, from Eq.3,

$$d = 0\cdot32.33 \log_e \frac{83}{33} = 9\cdot63 \text{ ft.} \quad (P = 33 \text{ ft. for sea water})$$

Then,

$$\frac{\alpha_m^2}{Z} = \frac{100}{2\pi\ 9\ 63} = 1\cdot66,$$

and from Fig. 5

$$\alpha_m = 2\cdot82.$$

Substitution in Eq.8 gives

$$Q_{cr} = 13\cdot3 \text{ cusecs per ft.}$$

Also, $\frac{H}{\lambda} = \frac{4}{100} = 0\cdot04$, and from Fig. 7, $\frac{Q_{max}}{Q_{cr}} = 1\cdot4$,

therefore the quantity of free air required, $Q_{max} = 1\cdot4 \times 13\cdot3 = 18\cdot6$ cusecs per ft This represents an air power at the pipe of 64 HP per foot.

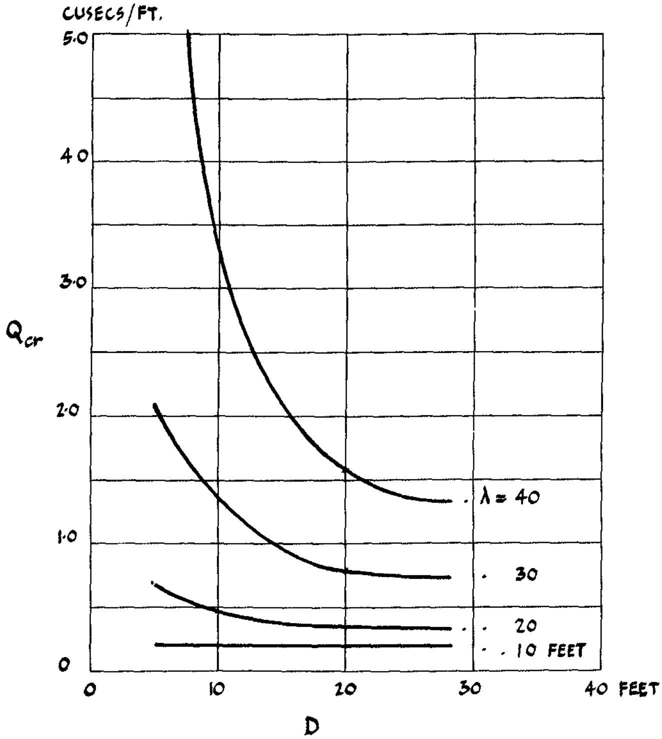

FIG 6

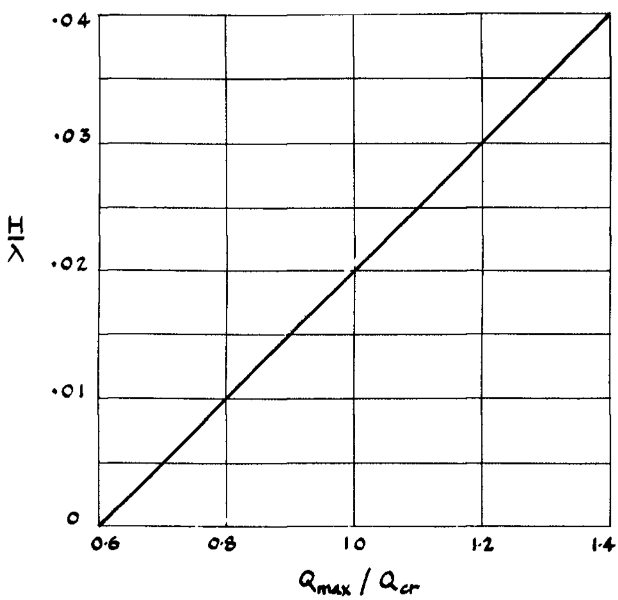

FIG 7

4. PARTIAL WAVE SUPPRESSION

If less than the quantity of air required for complete suppression is supplied, there is some damping of the incident wave. Bulson[7] proposed an empirical relationship between the height of the transmitted wave (h), the height of the incident wave (H), the quantity of air supplied (Q_o), and the quantity to completely kill the waves (Q_{max}), of the form

$$\frac{15}{16}\left(\frac{h}{H}\right)^{\frac{2\lambda}{P}} + \left(\frac{Q_o}{Q_{max}}\right)^2 = 1, \left(\frac{Q_o}{Q_{max}} > 0.25\right). \qquad \ldots\ldots(9)$$

Fig 8 shows a plot of this function for various values of $\frac{2\lambda}{P}$. Note that the amount of damping falls as the wavelength increases, and that for waves greater than 100 ft. in length there is very little reduction in wave height until the quantity of air approaches to within a few per cent of Q_{max}.

5. INTERMITTENT AIR SUPPLY

Bulson[8] showed from model tests that for complete wave suppression an intermittent air pulse offers no advantage over a steady supply; the total quantity of air supplied during a given period must be the same. For partial damping, however, an intermittent supply can be advantageous.

The degree of intermittency is measured by the ratios $\frac{p}{T}$ and n , where

$$\frac{p}{T} = \frac{\text{Time air valve is open}}{\text{wave period}},$$

$$n = \frac{\text{Time air valve is closed}}{\text{Time air valve is open}}, \qquad \ldots(10)$$

and Fig 9 shows the relationship between $\frac{h}{H}$ and n for various value of $\frac{p}{T}$. The graph illustrates that it is best to use as low a value for $\frac{p}{T}$ as possible, when $\frac{h}{H} = 0{\cdot}75$, the intermittent supply with $\frac{p}{T} = 1$ required 50% of the total air of a continuous supply, and the supply $\frac{p}{T} = 2$ required 66%. Fig 10 shows the comparison of total air flows.

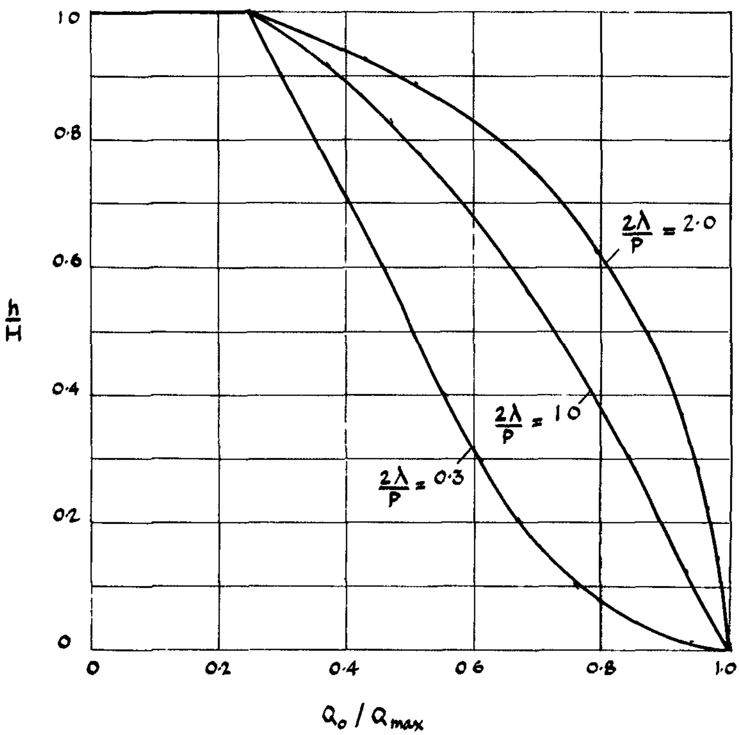

FIG 8

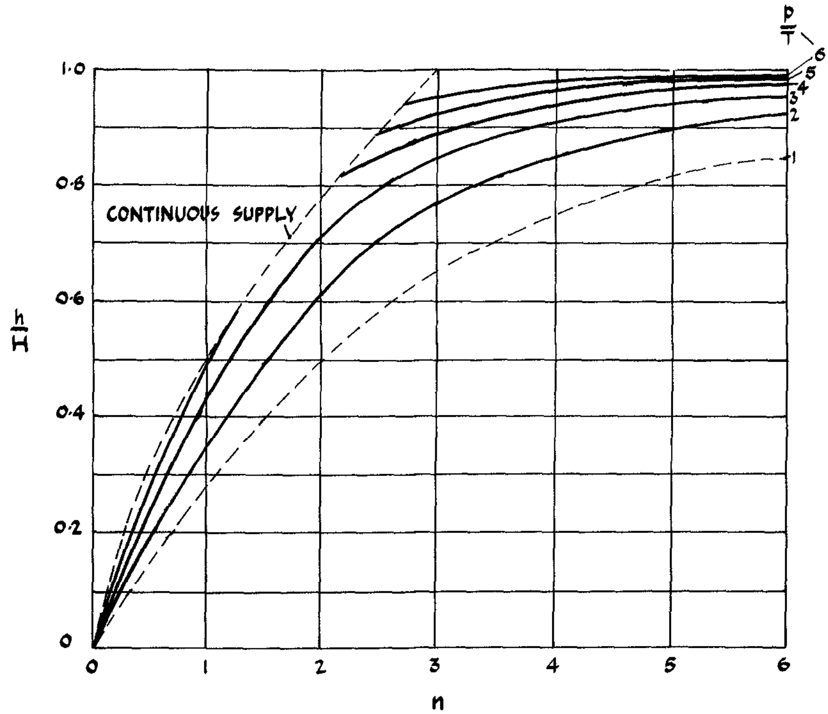

FIG. 9

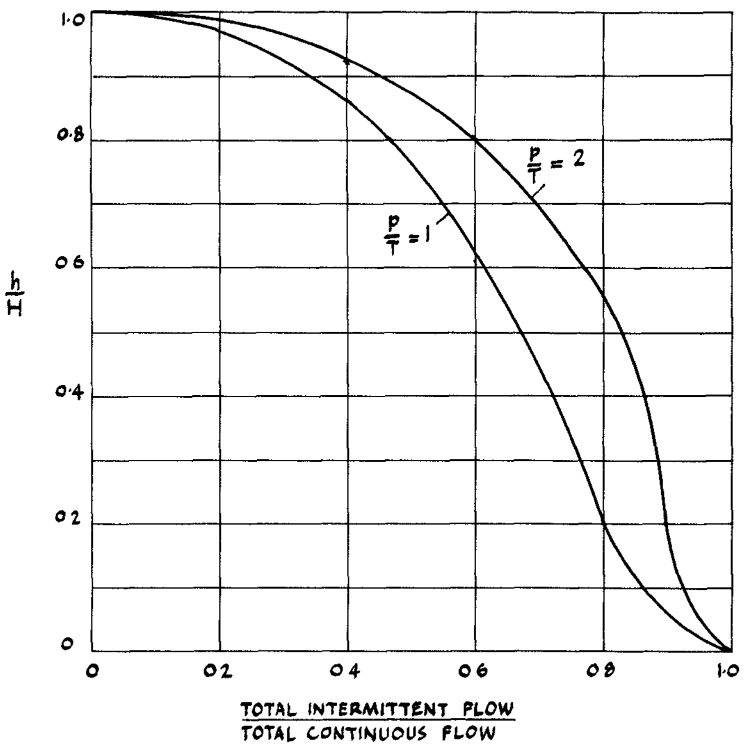
1·0
0·8
0·6
0·4
0·2
0
h/H
0
0·2
0·4
0·6
0·8
1·0
p/T = 2
p/T = 1
TOTAL INTERMITTENT FLOW / TOTAL CONTINUOUS FLOW

FIG 10

6. TYPICAL DESIGN CALCULATION

Suppose we wish to examine the feasibility of using a bubble breakwater in deep water to reduce a range of incident wave heights to a transmitted height of 3 feet. Three feet is assumed to be the maximum height that unloading and berthing operations can take place within the breakwater. By 'deep water' we mean that the air pipe on the sea bed is at least $\frac{\lambda}{2}$ below the surface. Then, taking an incident wave height of 10 feet for the first calculation, and atmospheric pressure, P , as 33 feet of sea water, Eq.9 gives

$$\frac{15}{16}\left(\frac{3}{10}\right)^{\frac{2\lambda}{33}} + \left(\frac{Q_o}{Q_{max}}\right)^2 = 1 . \qquad \text{.....(11)}$$

If a wave steepness ratio of 0·03 is assumed, $\lambda = \frac{10}{0 \cdot 03} \simeq 340$ feet, and substituting this value in Eq.11 gives

$$\frac{Q_o}{Q_{max}} \simeq 1 . \qquad \text{.....(12)}$$

As indicated earlier, at these long wavelengths the quantity of air for partial suppression is virtually equal to the quantity for complete suppression, Q_{max}.

The next step is to calculate Q_{cr} from Eq.8, and use this value to find Q_{max} from Fig 7. This part of the calculation follows closely the method given in section 3. From Eq.3,

$$d = 0 \cdot 32.33 \log_e . \frac{170 + 33}{33} = 19 \cdot 2 \text{ ft.}$$

Then,

$$\frac{\alpha_m^2}{Z} = \frac{340}{2\pi \times 25 \cdot 7} = 2 \cdot 82,$$

and from Fig.5 $\alpha_m = 2 \cdot 1$.

Substituting in Eq.8 gives $Q_{cr} =$ 476 cusecs per ft.

Also, $\frac{H}{\lambda} = \frac{10}{340} = 0 \cdot 03$, and from Fig. 7 $\frac{Q_{max}}{Q_{cr}} = 1 \cdot 2$, so that the air quantity for complete suppression, $Q_{max} =$ 571 cusecs per ft.

Then, from Eq.12,

$$Q_o = 34{,}260 \text{ c.f.m per foot of breakwater.}$$

The quantity of air required is seen to be vary large. If the breakwater is operating against the same incident waves, but in only 50 feet of water, the quantity is almost doubled. For this condition Eq.3 gives

$$d = 0{\cdot}32.33 \, \log_e \frac{50 \times 33}{33} = 9{\cdot}63 \text{ ft.,}$$

and $$\frac{\alpha_m^2}{Z} = \frac{340}{2\pi \times 9{\cdot}63} = 5{\cdot}62.$$

From Fig.5 $\alpha_m \triangleq 1{\cdot}3$, and substituting in Eq.8 gives

$$Q_{cr} = 830 \text{ cusecs per ft.}$$

$\frac{H}{\lambda} = 0{\cdot}03$, as before, and from Fig.7 $\frac{Q_{max}}{Q_{cr}} = 1{\cdot}2$,
so that the air required for complete suppression, $Q_{max} = 996$ cusecs per ft., and, from Eq.12,

$$Q_o = 59{,}700 \text{ c.f.m. per foot.}$$

Similar calculations for continuous and intermittent supply produce the curves shown in Fig 11 , which apply to an air pipe set in 50 feet of water.

7. PRACTICAL CONSIDERATIONS

a. Wave height outside breakwater

When the breakwater is operating successfully there is a marked build-up in the height of the incident waves just before they break over the counter current. Judging by the results of trials with 30 ft. wavelengths, an increase in wave height of up to 4 times could be expected, combined with a length decrease of 30%. This means that for an incident wave train 10 ft in height, wave heights immediately off-shore of the breakwater might be 40 ft, and wave lengths reduced, for example, from 340 ft to 240 ft. These figures check with the accepted steepness ratio for unstable waves of 0·14 (since $\frac{40}{240} = 0{\cdot}16$).

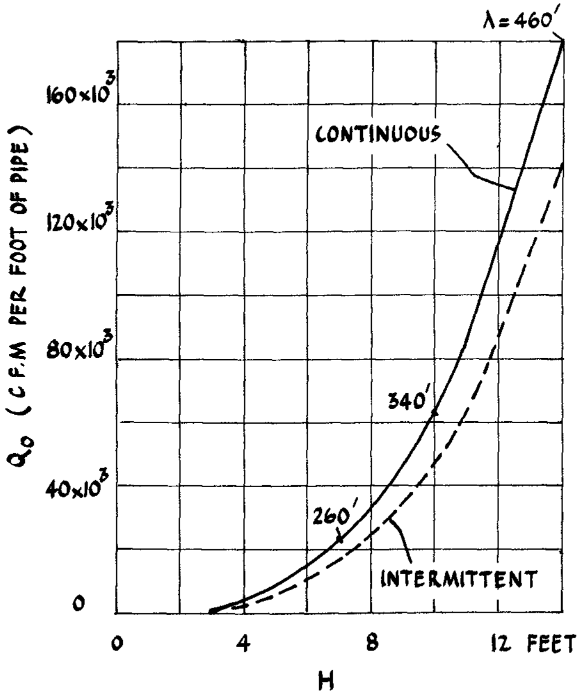
λ = 460′
160×10³
120×10³
80×10³
40×10³
0
Q₀ (C.F.M PER FOOT OF PIPE)
CONTINUOUS
340′
260′
INTERMITTENT
0
4
8
12 FEET
H

FIG 11

In these conditions it would be difficult for a small vessel to approach the breakwater from the seaward quarter. It would be necessary to sail around and approach from leeward. Similarly, a lighter or small craft leaving the breakwater could not sail out across the bubble curtain without considerable hazard.

b Surface currents within the breakwater

There would be a considerable conflux of surface currents within the breakwater. In the range of breakwater designs considered in section 7, these currents would be at least 12 knots, and might cause difficulty in mooring and controlling small craft.

c. Air supply

It was demonstrated above that to reduce waves 10 feet high, 340 feet long to a height of 3 feet requires a continuous air supply of 34,260 c.f.m. per foot of breakwater. This is under ideal conditions when the depth of water is 170 feet (In 50 ft. of water a supply of 59,700 c.f.m per foot is needed). At best then, the output of 57 large commercial compressors is required for every foot of breakwater, alternatively there are very large engine driven centrifugal compressors available commercially with a capacity of 30-40,000 c.f.m., but these weigh over 20 tons and consume 215 gallons per hour of fuel. On this basis a 500 yard long breakwater would cost about £100,000 per day in fuel and involve a capital expenditure for air supply of £20m.

d. Intermittent supply

An intermittent supply can save air, but the engineering problems in providing one could be difficult to solve. Interrupting the supply from the compressors seems a less likely solution than directing the air along lengths of pipe alternately by means of a valve system. Care would be needed to ensure that the air feed lines to these valves were clear of the hull of any vessel within the breakwater.

8. CONCLUSION

The experimental and theoretical studies during the past 25 years have made it possible for a reasonably accurate estimate to be made of the air quantity required to operate a bubble breakwater. The quantity is astronomical and costly to supply. The practical difficulties of operating a full scale system are immense. It is doubtful whether any novel ideas of bubble formation and size can produce economies, and high cost is bound to be the basic feature of any apparatus of this type which is designed to combat the energy of the sea.

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Notation

c velocity of travel of waves
d thickness of current
h height of transmitted wave
k coefficient in formula for current velocity
n ratio of time air valve is closed to time it is open
p time air valve is open
v_m surface velocity of current
$\bar{v}$ critical stream velocity
$\bar{v}_m$ surface current velocity to completely suppress waves

D depth of manifold below surface
H height of incident wave
P atmospheric pressure expressed as head of water
Q quantity of air emerging from orifices, per foot of pipe
Q_o quantity of free air delivered by compressors, per foot of pipe
Q_{cr} quantity of free air to produce $\bar{v}_m$, per foot of pipe
Q_{max} quantity of free air to completely suppress waves of finite height, per foot of pipe
Q_I quantity of free air supplied intermittently per foot of pipe
T wave period
Z $dg/\bar{v}_m^2$.

α $g/\bar{v}_m\sigma$
α_m minimum value of α
λ wavelength
σ speed of orbital motion in radians/sec