Proceedings of the Institute of Acoustics

SWCC FOR PREDICTING THE DIFFERENCES BETWEEN SHALLOW AND DEEP WATER EXPLOSIONS.

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1. INTRODUCTION

1.1 General Introduction

Large quantities of explosive are used in underwater civilian applications, especially in the enlarging of harbour draughts. This usually involves the removal of hard bed rock by shallow underwater blasting, often in close proximity to jetties or quay walls. Of obvious importance is the prevention of damage to these structures. The lack of present knowledge concerning damage criteria constrains the blasting company to use small charges thus incurring large financial penalties.

1.2 Current Knowledge

There is much present knowledge on deep-fired underwater explosions mainly in the form of empirical formula as set out by Cole [1] or Slifko [2]. The waveforms from shallow water explosions are very different from deep water explosions. This was recognised by Snay [3] who recorded tht 'high amplitude effects' and cavitation affect the resulting pressure waveform. However, until only recently there has been little research into the quantitative differences between deep and shallow explosive. Chapman [4] produced one of the most significant papers on the subject, which included revised empirical formulae for shallow-fired underwater explosions.

But there is a fundamental lack of analytical knowledge concerning damage criteria for massive structures. Many of the papers written on this subject are of military origin and hence are more concerned with the maximum charge size a structure can survive without being completely destroyed. Blasting companies, however, are more interested in the minimum charge size that a massive structure can survive without any damage occuring. On this subject there are very few papers.

2. THEORY

2.1 Theory of Shallow Water Propagation

In shallow water the pressure time history is created not only from the direct wave but also fom reflections of the signal at the water surface and seabed (see Figure 1). Each ray, subsequent to the direct wave, will be inverted by each reflection at the water surface and attenuated by each reflection at the seabed.

For large ranges, modal analysis may be used. It cannot be used for the shallow water case since the affected structure is usually in the near field of the explosive source. A more appropriate method of modelling this multipath propagation for small ranges is to use ray theory.

SWCC FOR PREDICTING THE DIFFERENCES BETWEEN SHALLOW AND DEEP WATER EXPLOSIONS

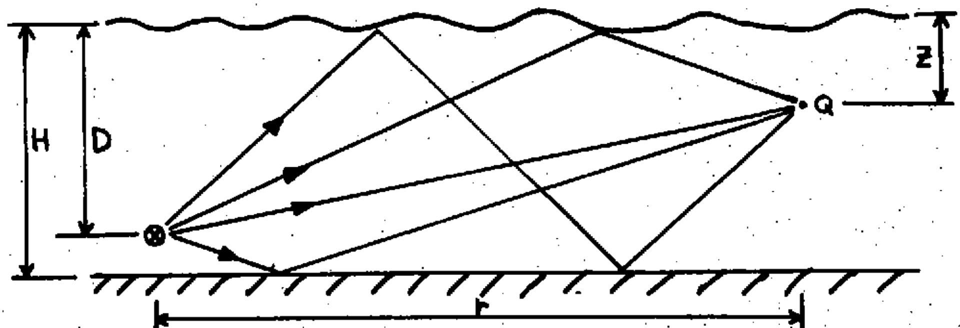


FIG <1>

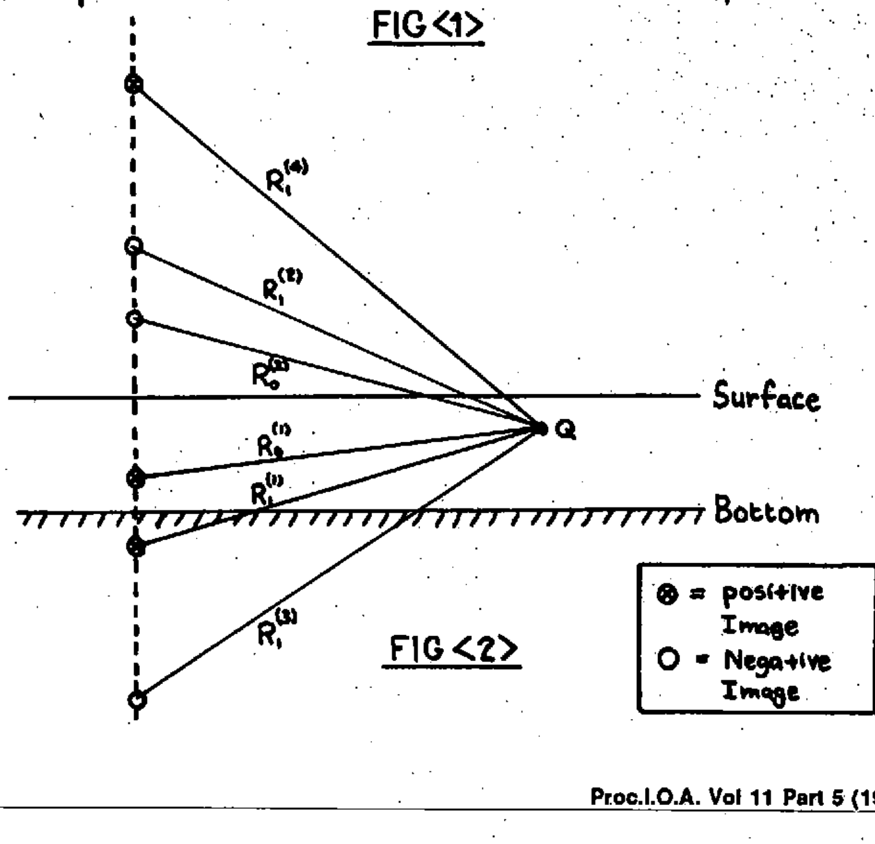


FIG <2>

The pressure waveform recieved at Q, as shown in Figure 2, assuming both surfaces are flat and parallel to each other, may be easily calculated by a simple image-source modle. The effective range of each image can be calculated as

$$R_i^{(1)} = (r^2 + (2iH - D - Z)^2)^{1/2}$$
$$R_i^{(2)} = (r^2 + (2iH - D + Z)^2)^{1/2}$$
$$R_i^{(3)} = (r^2 + (2iH + D - Z)^2)^{1/2}$$
$$R_i^{(4)} = (r^2 + (2iH + D + Z)^2)^{1/2}$$

The range, charge depth, water depth and observer depths r, D, H and Z are shown in Figure 1, and i is any positive integer in the range 0 to $+\infty$.

By allowing for the differences in image ranges and hence the time delays and attenuation with distance, the pressure time history can be constructed. This operation was performed for a range of the geometrical parameters.

2.2 Generation of the Shallow Water Coefficient

Using the pressure waveform calculated by means of the Method of Images the pressure spectrum of the waveform was obtained. The pressure spectrum was estimated by taking the Fast Fourier Transform (FFT) of the pressure wave.

The pressure spectrum is of greater value than the pressure waveform as it displays the waveform as a function of frequency. This allows us to observe how much of the pressure wave is concentrated into the frequency range in which massive structures respond, of say 0-100 Hz, and hence how much the pressure wave is likely to excite the structure.

A more general method of presenting the results is to use the Shallow Water Correction Coefficient (SWCC). The SWCC is the FFT of the total pressure waveform with reflections added in divided by the FFT of the direct pressure waveform. This is effectively a transfer function relating the spectral pressure level in a shallow water explosion to that obtained in deep water. It is of use first since the spectrum for deep water explosions is well established, and second it is independent of the time history of the shock wave generated by the explosion. If the resonant frequency of the affected structure is known, it presents a measure of how much less the structure will be affected by blasting in shallow water, compared to the effect in deep water. This is of use since infromation is available concerning the response of structures in deep water.

3. RESULTS

To plot the results more generally, a set of non-dimensional groups were formed. These groups were:

1. Non-dimensional frequency = $\frac{fh}{c}$
2. Non-dimensional range = $\frac{r}{h}$
3. Non-dimensional observation depth = $\frac{z}{h}$

where r is range; h is depth of water; z is observation point depth; c is speed of sound in water; and f is frequency.

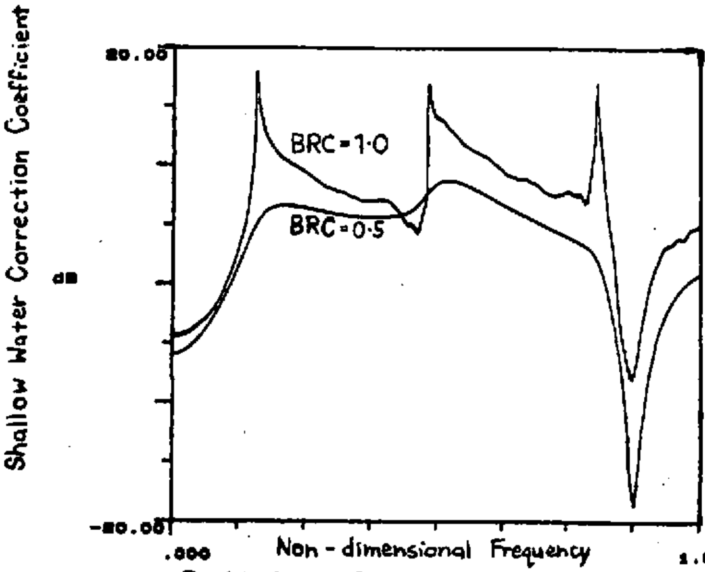
The maximum frequency of interest for massive structures is of the order of 100 Hz. The typical water depth is 20 m. Therefore the maximum non-dimensional frequency of interest is of the order of 1.4. The plots presented are of the SWCC versus non-dimensional frequency, up to non-dimensional frequencies of about 1.5. The resulting plots are shown in Figures 3 to 4. The figures show varying non-dimensional ranges and bottom reflection coefficient (BRC).

4. DISCUSSION

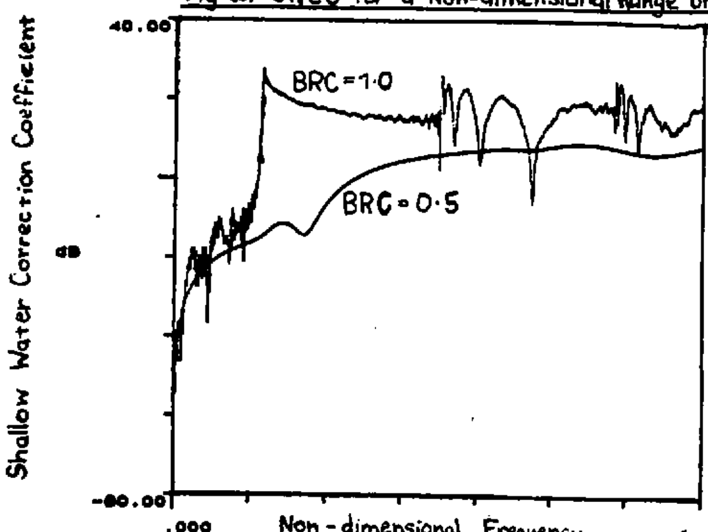
By reference to Figure 3 it is easy to see that at certain non-dimensional frequencies the SWCC becomes large. It is these points which are of interest, as if one of these peaks were to coincide with the resonant frequency of the structure then severe damage of the structure may occur. It is easily established that the peaks shown in the waveform coincide with those predicted by using modal analysis.

Figure 3 presents both a non-typical (BRC = 1.0) and typical (BRC = 0.5).case To have a BRC of 1.0 is in fact only true for rigid bottoms which is never the case in practice. The case of BRC equal to 0.5 is analogous to a typical blasting operation and is a better model of the attenuation that a seabed offers. However, the SWCC is still larger than 0 dB at most points in the waveform, so the pressure due to the total pressure wave is larger than that due to the direct wave. It must be noted though, that massive structures have very low resonance frequencies for which the SWCC is less than 0 dB. Also there are still peaks occurring in the waveform, but these are of a considerably lower level. In the vicinity of these peaks the SWCC is of the order of 5 dB and may be of significance for structures with high reasonant frequencies..

The above points are true of both non-dimensional ranges considered. But for a non-dimensional range of ten the waveform with a BRC of 0.5 (Figure 4) has a much lower SWCC at low non-dimensional frequencies. This is because the direct and reflected wave arrive almost simultaneously at the structure, thus almost totally cancelling one another. The SWCC then rises to approximately the same level as that for the case of one non-dimensional range, at a non-dimensional frequency of about 1.2. So for an increase in non-dimensional range the first maximum of the SWCC will occur at the same non-dimensional frequency.



Fig<3> SWCC for a Non-dimensional Range of One



Fig<4> SWCC for a Non-dimensional Range of Ten.

5. CONCLUSIONS

The following conclusions are drawn.

1. The Shallow Water Correction Coefficient has local maxima greater than zero dB for non-dimensional frequencies above 0.2 Hence. the magnitude of the total shallow water pressure wave is greater than that of the direct waves. In practice strucutres have low fresonance frequencies i.e. non-dimensional frequency of approximately 0.1, at which the SWCC is less than 0 dB. For the case of ten non-dimensional ranes the SWCC is about -40 dB and hence there is no chance of the resonance frequency of the structure being excited.

2. For structures of high resonance frequencies, situated on a rigid bottom (BRC=1.0) there is a real chance the resonance frequency of the structure may coincide with a maxima of the SWCC (at 0.23, 0.75 or 1.26 non-dimensional frequencies). This coincidence could lead to large excitations of the strucutre, and hence damage occuring.

3. With a BRC of 0.5, structures with high resonance frequencies are less vulnerable to excitation as peaks in the SWCC waveform are much broader. However, care should still be taken to avoid coincidence of the resonance frequency and these peaks.

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THE EFFECT OF BUBBLE CURTAINS ON UNDERWATER SHOCKWAVE PROPAGATION

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Large quantities of explosives are detonated underwater in enlarging harbour draughts by removing the hard bed rock which cannot be dredged, and many other civil engineering operations. Usually this blasting occurs in close proximity to structures that may be damaged by the waterborne shockwave e.g. divers, jetties, and quays. Although much is understood about deep water explosions, there is a lack of fundamental information regarding how the shock waves from explosives interact with and damage these structures in shallow water. This limitation of knowledge results in the blasting company having to incur severe financial penalties due to the need either to use small charges or to enforce large exclusion zones both for the divers and the general public, in order to ensure complete safety.

Bubble curtains (that is, streams of bubbles produced at depth in the water from compressed air cylinders) have been used to some effect in reducing the levels of waterborne shock. This investigation aimed to produce an analytical formulation of damage prevention mechanisms using these curtains of bubbles, and test them by experiments using scaled explosions in the laboratory. These results were then compared against measured data.

1. INTRODUCTION

Air bubbles in water increase the compressibility several order of magnitude above that in bubble-free water, thereby greatly reducing the velocity and increasing attenuation of acoustic waves. The effect of air bubbles in water on acoustic wave propagation was studied extensively during World War II as part of an overall effort to apply underwater sound in submarine warfare. Currently air-bubble curtains are used to prevent damage of submerged structures e.g. dams, by shockwaves from explosives, as well as to reduce damage to water-filled tanks in which metals are formed by explosives [1]. Reference [1] gives a detailed description of the previous and present applications of the pronounced attenuating properties of air bubble in water, from the earliest patented use by Fessendon in 1920 [2].

The velocity and attenuation functions depend principally upon frequency, bubble size and fractional volume of air. Below the bubble resonant frequency and in the frequency range of marine energy sources, acoustic wave velocity is essentially independent of frequency and bubble radius, being well below the velocity in bubble-free water.

Shockwaves in bubble-liquid mixtures have been studied by Crespo [3], van Wijngaarden [4], and Campbell and Pitcher [5], amongst others. However, the work has concentrated on describing the shock front mathematically and the variation in sound speed. This investigation is concerned with the prevention of damage to humans and massive submerged structures by using air-bubble curtains.

2 BUBBLE PRODUCTION AND SIZE DETERMINATION

Initially five sintered plastic filters of porosity grades ranging in particle retention size from 10μm-200μm were obtained. Each pipe had dimensions 1.6" outside diameter x 1.305" inside diameter x 8.5" length.

2.1 Determination of Bubble Sizes and Distribution. The aims were:-

(a) to demonstrate the production of bubbles in water using the available porous sintered plastic filters,
(b) to alter the bubble size produced by variation of the grades of the porous media,
(c) to measure the bubble sizes photographically, and
(d) to study the effects of varying air flow rates and the air supply pressure on bubble production.

2.2 Initial Experimentation to Establish the Effectiveness of Sintered Plastic Pipes in Bubble Production. The experiments were conducted in a steel tank of dimensions 1.8mx1.5mx1.2m deep of fresh water. A framework was constructed of 1m lengths of 1/2" stainless steel bar, clamped with boss head clamps, in order to position the equipment accurately. The sintered plastic pipes were placed in turn in the tank at a depth of D = 0.80m. End caps for sealing and joining each pipe in turn to the air supply system were then manufactured, so that air at a low pressure could be blown into one end of the pipe through an adaptor, the other end of the pipe being sealed. The air supply was capable of delivering 30 litres per minute at a maximum pressure of 80 psi. A pressure regulator and a flow meter were used so that the air supply pressure and volume flow rate could be monitored throughout the experiments.

The flow of air through each pipe as well as the pressure was varied and the consequent effects on the production of bubbles noted.

Sintered Plastic Pipe Grade 60 - Particle Retention Size: 10-15 microns.
The air pressure was initially set at 3.5 psi and the air flow rate at 3.75 litres/minute. Upon allowing entry of air to the pipe there was a time delay before the water that had infused into the pipe was ejected. Initially large bubbles were formed near the end of the pipe where the air entered and few elsewhere. On increasing the air flowrate to 4.5 litres/minute a few more bubbles appeared down the length of the pipe. These bubbles were ejected from specific points on the pipe surface and then rose to the water surface in columns, but were still concentrated at both ends. The bubble streams were produced from apparently random points along the whole length of the pipe. However, it was noticed that all bubbles were produced from the top surface of the pipe and that the bubbles were very small i.e 1mm or less in diameter. Increasing the air flowrate just increased the already numerous amount of bubble streams, and when the air flowrate was set to 4.5 litres per minute and the air pressure varied between 2 and 10 psi the number of bubble streams decreased and increased correspondingly.

Further experimentation involving the other grades of filter was undertaken with the consequences of varying the air pressure and flow rate comparative to above.

2.3 Photographic Measurements of Bubble Sizes. The previously described experiments were then repeated using the five grades of sintered plastic filter, the object being to attempt to measure the bubbles produced by photographic means. The five filters were each suspended at a depth

D = 0.8m in the tank in turn and compressed air at a pressure 3.4 psi and a flowrate of 4-10 litres/minute was injected. An underwater video camera and TV monitor were used to record the bubbles.

2.3.1 Estimating the Bubble Sizes using a Comparison Method. Initially the underwater camera was positioned so that the bubble sizes would be estimated using a comparison of their diameters with the known diameter of the sintered plastic filter, used as the reference diameter. Unfortunately the resolution of such a picture is inadequate to produce a reliable estimation of bubble size i.e. the outer perimeters of both the individual bubbles and the filter are not distinctly visible. This method is also unreliable due to the depth of view of the camera, as not all the bubbles are necessarily in the same plane normal to the camera. This will cause errors, particularly in estimating the range in bubble sizes produced by each filter as any discrepancies in diameter measurement could be attributed to the bubble being a slightly different distance from the camera. Another major source of error occurs at the ends of each filter as larger and relatively more bubbles are produced at these positions.

2.3.2 Estimating the Bubble Sizes using a Thin Stream of Bubbles. A more accurate method was to partition off a thin stream of bubbles, one bubble wide, with 24 guage aluminium sheeting bent and positioned immediately above the sintered filter. Bending the sheeting meant that the bubbles not actually required were directed away from the camera's field of view. This gave a much clearer representation on the monitor and a piece of graph paper photocopied onto acetate sheet with a white backing was placed immediately behind the bubble stream. By comparing the bubble diameters to the graphical dimensions an estimate of the diameters was possible. In order for this comparison to be made both the bubbles and the graph paper had to be in focus simultaneously.

Another problem encountered was that when the video film was replayed, the bubbles appeared in streaks as their rate of ascent was relatively high. In order to get resolute pictures of individual bubbles a stroboscope was used, set to 1500 flashes per minute to get the best time resolution. It was also found necessary to turn out any other lights in the laboratory to improve definition. Figure 1 shows the experimental set -up used.

2.4 Results of the Bubble Measurement. For each filter an estimate of the range of bubble diameter was made. This is shown on Figure 2 with the curve being drawn through the median value. As each filter only has an estimated range of particle retention size, the mid-value of this range was used for plotting.

Initially the relationship was thought to be parabolic and by plotting on log paper a relationship between the two variables of

particle retention size (µm) = 1000 (observed bubble diameter (mm))$^{8/3}$

was achieved. This is also plotted in Figure 2.

2.5 Conclusions of Bubble Diameter Measurement

1. The method used in 2.3.2 gives the most reliable and accurate measurement of bubble diameter produced by the sintered plastic filters. Method 2.3.2 typically produces an esitmate 0.2-0.3 mm more accurate than 2.3.1.
2. There is a range of observed bubble diameters produced by each filter. This width of range does not seem to be related to the particular particle retention size of the filter, but is typically 0.3-0.5 mm.

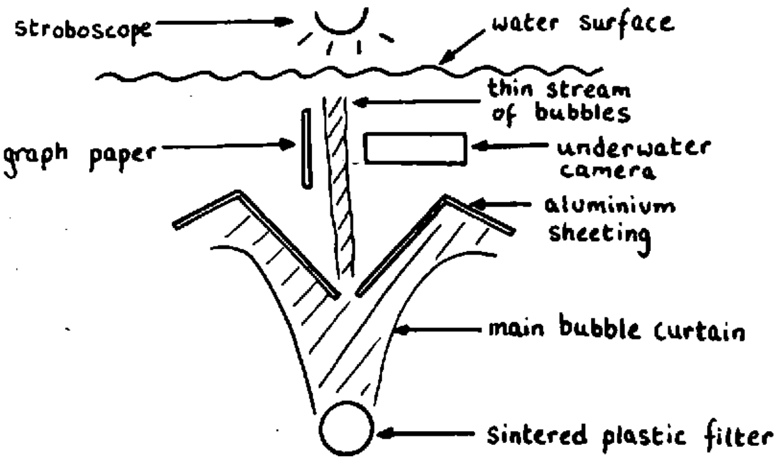
stroboscope
water surface
thin stream of bubbles
graph paper
underwater camera
aluminium sheeting
main bubble curtain
sintered plastic filter

figure 1

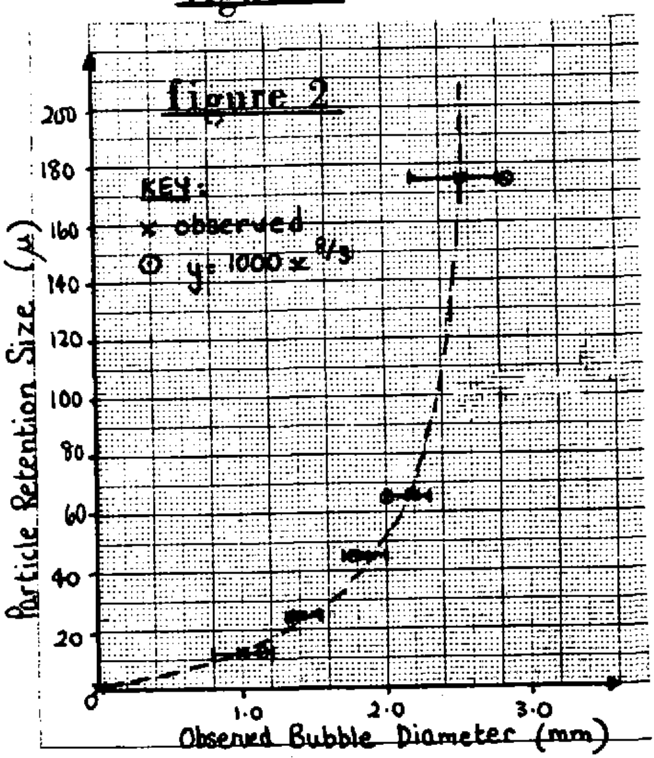
figure 2
KEY:
× observed
⊙ y = 1000 x^(8/3)
Particle Retention Size (μ)
200
180
160
140
120
100
80
60
40
20
0
1·0
2·0
3·0
Observed Bubble Diameter (mm)

3. The bubble diameter seems to tend towards a finite value with increased particle retention size. There may be a parabolic relationship.

particle retention size (μm) = 1000 (observed bubble diameter (mm))$^{8/3}$

3. TRANSMISSION LOSS DUE TO A BUBBLE CURTAIN

As previously explained, the speed of sound in an air-water mixture is greatly reduced when the air bubbles are all much smaller than the resonant size of the particular sound frequency under investigation. Above this the effect of the suspended air content is negligible. This investigation is aimed at reducing the particular frequency components of the shockwave which would damage massive structures and cause injury to divers.

3.1 Existing Acceptable Levels of Blast Waves. It has long been established that the air-containing organs are the most susceptible to damage - the ear, respiratory system and the intestines/abdomen. Lung damage is often cited as the predominant injury, although the ear drum has been shown to rupture at around 35 kPa [6]. Bowen et al [7] showed the percentage mortality from lung damage as a function of peak pressure and shockwave duration for air blast. This suggests no injury below a peak pressure of 70 kPa, but above this impulse is the damage controlling criteria. Jönsson [8], extrapolating work from rabbits, quotes a fundamental natural frequency for the human chest at 20-60 Hz. Existing BSI acceptable levels are a peak pressure $P_o < 1.7 \times 10^5$ Pa and an impulse $I < 15$ Pa.s. Wheezing from the lungs has been seen to occur where $P_o \approx 4 \times 10^5$ Pa, $I = 20$ Pa.s [9].

For safety of large structures at sea relatively low frequencies of up to ~ 100 Hz are important. As explosion shockwaves contain substantial energy at low frequency it is obvious that one way of reducing damage would be to lessen the energy content of these particular frequencies.

3.2 Transmission Loss Theory - 'Three Media' Problem. This investigation was at 1/50th scale. This meant that instead of looking at frequencies from 20-100 Hz, those of 1 kHz-6 kHz were examined. Reference [10] gives the equation for the transmission loss in a three media situation with the first media the same as the third, i.e. in this case water - an air and water mixture - water, as

$$10\log_{10}\left(\frac{1}{1 + 1/4\left(\frac{r_2}{r_1} - \frac{r_1}{r_2}\right)^2 \sin^2 k_2 L}\right) \quad \text{dB} \qquad (1)$$

where r_1 = characteristic impedance of medium 1 i.e. water
r_2 = characteristic impedance of medium 2 i.e. air and water mixture
k_2 = wavenumber of the frequency in question
L = width of the bubble curtain.

In order to produce bubbles of a suitable size to absorb the shockwave energy form 1 kHz-5 kHz, filters producing bubbles of resonant frequency >> 6 kHz were needed.

3.3 Experimentation. This was carried out in a large tank of dimension 8mx8mx5m deep of fresh water. Figure 3 shows the apparatus used. The bubble curtain was produced by using ten of the

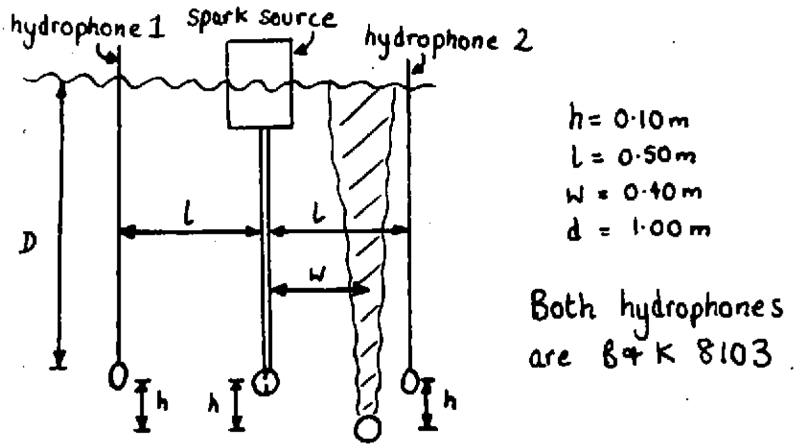
hydrophone 1
Spark source
hydrophone 2
D
l
l
w
h
h
h
h = 0·10 m
l = 0·50 m
w = 0·40 m
d = 1·00 m
Both hydrophones are B&K 8103

figure 3

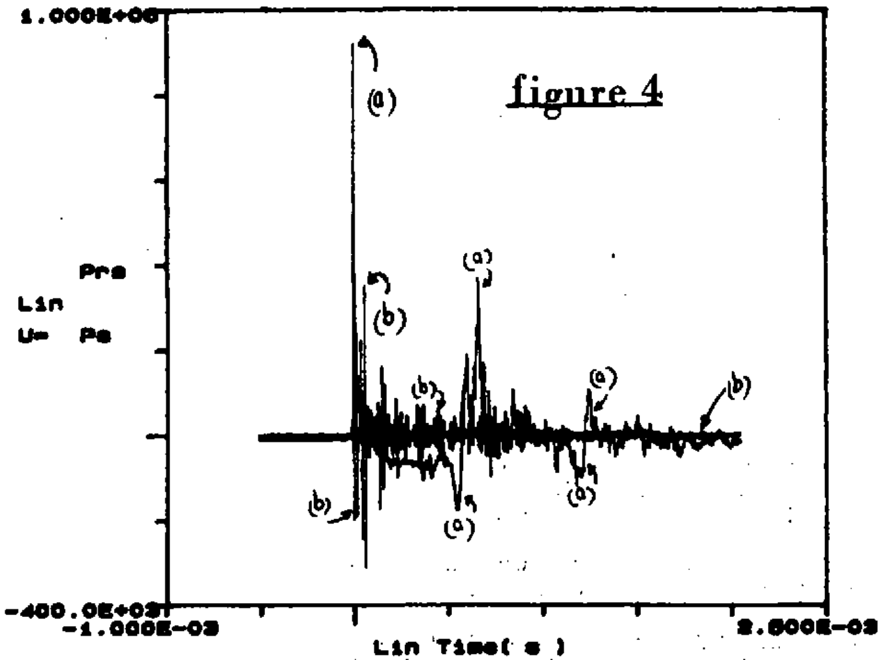
figure 4
1.000E+00
-400.0E+03
-1.000E-03
2.500E-03
Pre
Lin
U= Pa
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(a)
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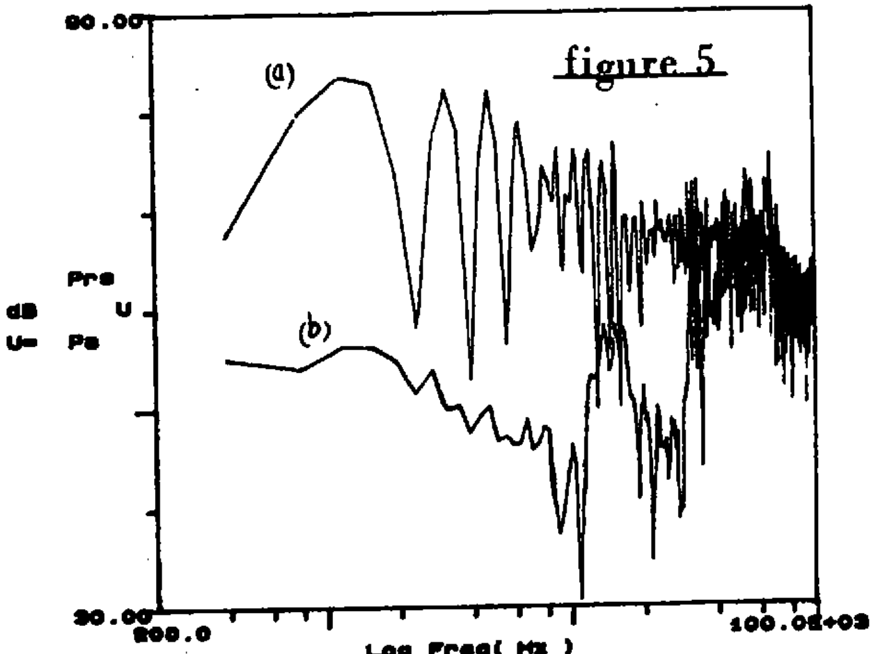
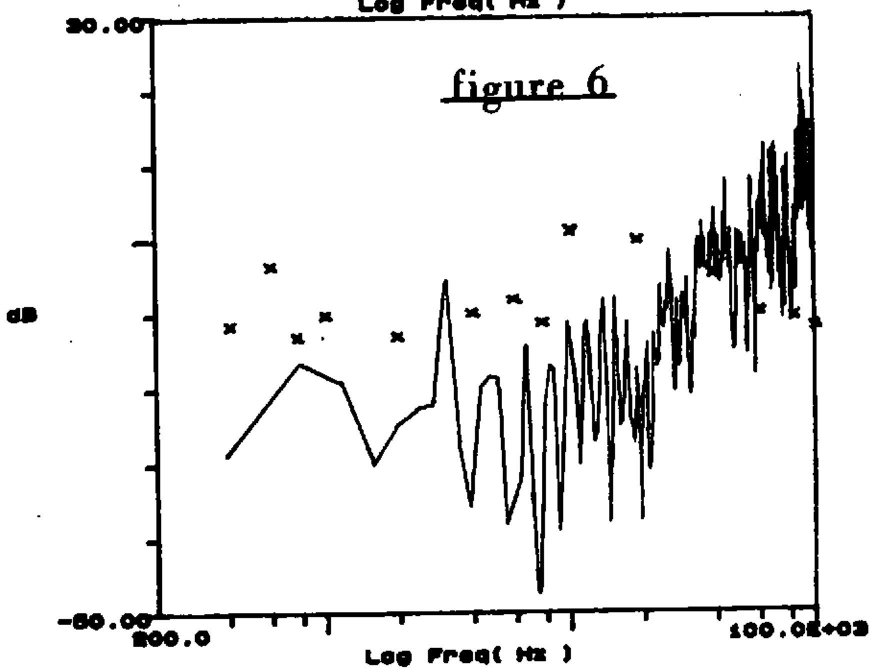

90.00
30.00
Pre
dB U
U= Pa
(a)
(b)
figure 5
200.0
100.0E+03
Log Freq(Hz)


30.00
-50.00
dB
figure 6
200.0
100.0E+03
Log Freq(Hz)

previously used sintered filters connected in one row. A spark source was used with hydrophone 1 being a reference while hydrophone 2 recorded the shockwave after it passed through the bubble curtain. Figure 4 shows (a) the waveform recorded by hydrophone 1 i.e. the shockwave generated by the spark source, and (b) the resulting waveform after the shockwave had passed through the bubble curtain. The bubble curtain was produced by an air flowrate of 50 L/min at a pressure 25 psi and was 2m x 0.12m wide at thaehydrophone depth.

Figure 5 shows (a) the FFT of the shockwave recorded by hydrophone 1 and (b) the FFT recorded by hydrophone 2. By dividing (b) by (a) we can get the insertion loss due to the bubble curtain, see Figure 6. Figure 6 also shows the loss predicted by equation 1. Frequencies up to about 40 kHz are attenuated, with 5-37 dB reduction for frequencies between 1 kHz-6 kHz. The experimental results show far more of a loss than those predicted by equation 1, by as much as 25 dB in some cases. At high freqencies i.e. ~40 kHz and above the mixture behaves more as a homogeneous medium of water and th e bubbles have no effect on the sound propagation.

3.4 Conclusions.

1. Air bubbles can significantly reduce the pressure from a waterborne shockwave at frequencies damaging to divers and massive structures i.e. between 20 and 100 Hz, by up to 37 dB.

2. Experimental results shown an insertion loss due to the presence of a bubble curtain up to 25 dB more than predicted with the 'three media' method.

3. In the freqency range below the resonant size of the bubbles i.e. < 6520 Hz in these experiments, the attenuation increases with increasing frequency, decreasing bubble radius, and increasing fractional air volume.

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AUDITORY HAZARD TO DIVERS FROM UNDERWATER EXPLOSIONS

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The sea is a noisy environment, but only recently has the need to introduce hearing guidelines for underwater blasting been recognised. In many places, divers and swimmers are exposed to explosive sources, such as compressed air-guns, which are used for seismic explorations, and explosive stud guns. The initial aim of this project has been to investigate hearing underwater to carrying out audiometric tests in air and water. Knowledge of the resulting threshold shift can then be used, together with data from research into the auditory hazard from air-borne blasts, to estimate the hearing damage caused by underwater explosives.

Very little is known about the mechanisms of hearing underwater, and no experimental studies have been carried out to assess the effects of underwater blasting on divers heating. By investigating the auditory hazard from underwater explosions a set of guidelines for hearing conservation including safe stand off distances, can be established.