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LABORATORY EXPERIMENTS

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ACOUSTIC MEASUREMENT OF BED-LOAD LABORATORY EXPERIMENTS

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ABSTRACT

Experiments were carried out to verify some acoustical aspects of impact noise in water for application in the development of a theoretical relationship between the noise generated by river bed pebble collisions and bed-load transport rates. Underwater pebble noise was simulated by rolling ceramic balls on a bed of similar balls in a large laboratory flume. Sound was measured with a stationary hydrophone located in the water above the pebble bed.

Specific information was obtained on the interparticle collision frequency delineating the limit of transition from impact to continuous type of sound, the applicability of theoretical relationship in the determination of total sound pressure levels due to impact sources, the acoustic directivity of pebble collision noise, sound field characteristics surrounding pebble collision sources, the effect of pebble velocity upon the generated sound pressure level and the spectrum characteristics of the pebble collision generated noise.

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INTRODUCTION

General Considerations

It has long been observed that collisions among riverbed pebbles moved by the flow of water can generate sound that is often audible to observers stationed along the shore of a river. Underwater acoustic measurements have also indicated that this noise may be dependent upon the intensity of sediment movement suggesting a new approach for bed-load measurement.

The difficulties in measuring bed-load transport in rivers with available methods are well known. A continuous demand still exists for new and improved instruments and techniques to increase the accuracy and reliability of the observations and to simplify the field procedures of bed-load measurement. An investigation was, therefore, undertaken to explore the acoustic approach for practical measurement of sediment discharges.

The development of an acoustic technique for bed-load measurement can be approached from a number of different directions. These can be distinguished by the parameters chosen to represent the information on the sound produced by the sediments, the methods of measurement employed to obtain the acoustic information, and the techniques of analysis and interpretation of this information.

Throughout this investigation, it was considered that the sound parameter most indicative of the movement of sediments is the acoustic power of the noise produced by the river bed pebble collisions. The acoustic power of a collision source depends to a great degree upon the force of impact which generates it. But the force of impact is a function of the momentum of the moving pebbles, and hence, of their mass and velocity. The rate of sediment transport on the other hand, is also a function of the mass and velocity of the particles, and must, therefore, be related, in some way, to the acoustic power of the noise which the particle collisions make.

The determination of the acoustic power radiated by a source is very difficult. Even when a source produces continuous sound its acoustic power cannot be measured directly but must be estimated from measurements of sound pressure levels (SPL) considering also the acoustics of the environment in which the measurements are made.

No attempts have been made to date to measure the acoustic power of moving riverbed pebbles, mostly because of the presence of a number of complicating factors affecting the observations and analysis of acoustic information in natural rivers. The collision of two pebbles generates sound which exhibits transient characteristics and differs from continuous sound. The interparticle collisions can occur over large areas of the riverbed and simultaneously produce sound at many locations and at different distances from an observation point.

The power generated by the collisions can vary because of natural variations in particle sizes, their mechanical properties and impact velocities. The power transmitted from collision positions to the observation hydrophone may be affected by the directivity characteristics of the pebble. In addition, there may exist in a river high levels of background noise which can mask the sound generated by the bed pebbles.

To provide a model for the assessment of the feasibility of the acoustic concept for bed-load measurement, and to provide guidance for the development of a practical measurement technique, an attempt was made to establish a theoretical relationship between a readily measurable sound parameter and the bed-load discharge. The basis of the model development was the measurement of sound pressure levels at a finite distance from the riverbed with a non-directional hydrophone.

In the development of the model generally accepted acoustic theories were employed. However, because of the uniqueness of the underwater environment and the proximity of the observation hydrophone from the source some assumptions related to the nature of the pebble sound and its behaviour in water, had to be verified experimentally.

The results of the laboratory experiments carried out in support of the theoretical study of the acoustic bed-load measurement approach are presented in this report.

Objectives and Scope

The specific objectives of the experiments were the following:

1. To observe the variation of sound pressure levels with the number of rolling pebbles.
2. To determine the minimum frequency of interparticle collisions for the pebble generated sound to be continuous.
3. To verify the applicability of accepted continuous sound analysis principles for estimating sound pressure levels due to multiple collision sources.
4. To investigate the effect of the velocity of rolling pebbles upon the sound level produced by impact with stationary bed pebbles.
5. To determine the extent and characteristics of the acoustic fields above a bed of sound generating pebbles in water.
6. To obtain information on the acoustic directivity of the sound radiating pebbles.
7. To measure the spectrum of the sound generated by rolling pebbles.

The laboratory work was limited in scope and was carried out in ideal conditions. All experiments were performed in still water and gravel noise was simulated by gravity induced movement of pebbles. No attempt was made to verify the applicability of the laboratory results to natural rivers. However, it was assumed that the acoustic factors which were investigated were relatively independent of the environmental factors, so that the experimental results would be valid in both, the ideal and natural conditions.

THEORETICAL BACKGROUND

Sediment Generated Sound

Although acoustic measurement of bed load transport has been suggested at least 40 years ago, Johnson and Muir (1969) were the first to make quantitative observations of bed load generated sound in a laboratory flume. Their results showed that a relationship between the noise and the sediment discharge existed only in the lower range of sediment transport rates, and that the hydrophone signal became insensitive to additional increases in bed-load discharge as the rates of transport increased.

There may be several reasons for the noise saturation tendency with increasing bed-load discharges. Among these is the possible reduction of acoustic power generated by the inter-particle collisions. At higher velocities, when particle saltation occurs, the trajectory of the particle paths becomes elongated and their angles of collision with the stationary bed are decreased reducing the change of particle momentum upon collision. Because momentum changes determine the force of collision, the impact generated acoustic power is also reduced.

The occurrence of saltation of the moving particles can also decrease the number of interparticle collisions. In the limit, when all moving sediments are suspended by the flow and collisions with the stationary bed do not occur, no sound is generated at all.

A re-examination of the experimental results presented by Johnson and Muir (1969) indicated that the loss of acoustic sensitivity with increasing sediment discharge rates may also be due to the multiple sound source effect. Although the acoustic data reported by the authors were given in terms of electrical output of their measurement system and not in the accepted acoustic units, it was determined from their results that the average microphone output increased by a constant for each doubling of the measured rate of bed-load transport. If doubling of the transport rate is assumed to double the number of sound sources, the observation agrees with theoretical results obtained when the number of sound sources is doubled. As shown by Beranek (1971), if more than one source contributes to the total sound at a point, the total rms pressure p for continuous sound tones of different frequencies is given by

$$p = \sqrt{p_1^2 + p_2^2 + p_3^2 + \ldots + p_n^2} \qquad (1)$$

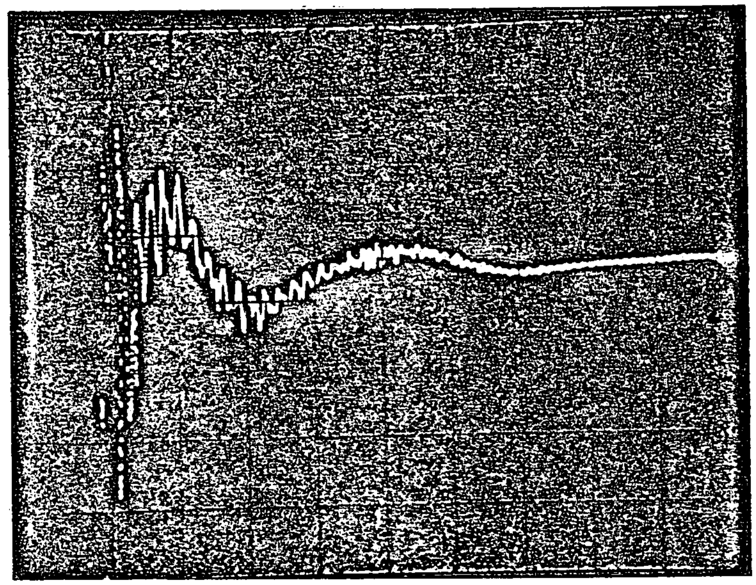
where p_1, p_2, and p_n are the rms magnitudes of the pressures contributed by the individual sources. When all sources produce equal p_i at a point, the relationship can also be be expressed

$$SPL = SPL_1 + 10 \log n \qquad (2)$$

where SPL represents the sound pressure level in decibels (dB) due to n sources when each source contributes a sound pressure level of SPL_1. Equation (2) indicates that as the number of sources increases, the increment in SPL due to addition of each new source decreases, and that doubling of the number of sources increases the SPL by a constant 3 dB regardless of the initial number of sources.

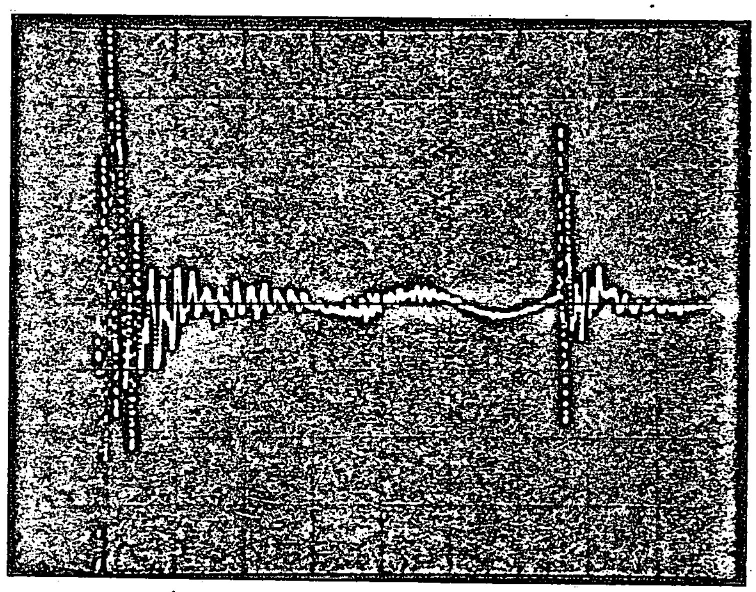
The sound generated by the collisions of two gravel pebbles, as illustrated in Figure 1, possesses highly transient characteristics. It can influence the acoustic determination of bed-load because the measurement and analysis of impulsive sounds differs from those for continuous sound.

In the measurement of bed-load, each pebble collision constitutes a pulse source, and the frequency of collisions or the number of sources is one of the parameters related to the sediment discharge. If the pebble generated sound were continuous, it should be possible, in principle and under certain conditions, to determine the frequency of collisions from theoretical considerations. However, this may not be possible throughout the full range of collision frequency values. As indicated by Beranek (1971) impulsively generated sound in air exhibits quasi-steady characteristics and may be considered as continuous only if the frequency of impulses exceeds 10 Hz. In water, this limiting frequency value has not been determined.



→| |← 5 ms

Single collision



→| |← 5 ms

Two collisions

Figure 1 Collision Sound Transients

Sound Fields and Source Directivity

The existing methods to determine acoustic power of an individual sound source are of two categories and depend upon the sound field at the location of SPL observations. The sound fields vary with distance from the source and are affected by the nature of the enclosure around the source.

Generally, three distinct acoustic fields, illustrated in Figure 2, are associated with a sound source. In the near field, which is immediately adjacent to the source, the SPL exhibits large variations because fluid particle velocities have tangential components relative to the direction of the pressure wave travel. In the free field part of the far field the SPL decreases by 6 dB for each doubling of the range from the source. In the reverberant field, sound waves which are reflected from the boundaries of an enclosure are superimposed upon the incident waves from the source, and the SPL again exhibits large variations.

The role of the sound fields in the measurement of bed-load noise is twofold. First, only the incident sound waves, arriving directly from the sources to the observation point in the flow, can be considered in the theoretical determination of the total SPL due to the individual pebble collisions. This requires that no contributions originate from the reflected waves, and, therefore, is possible only if

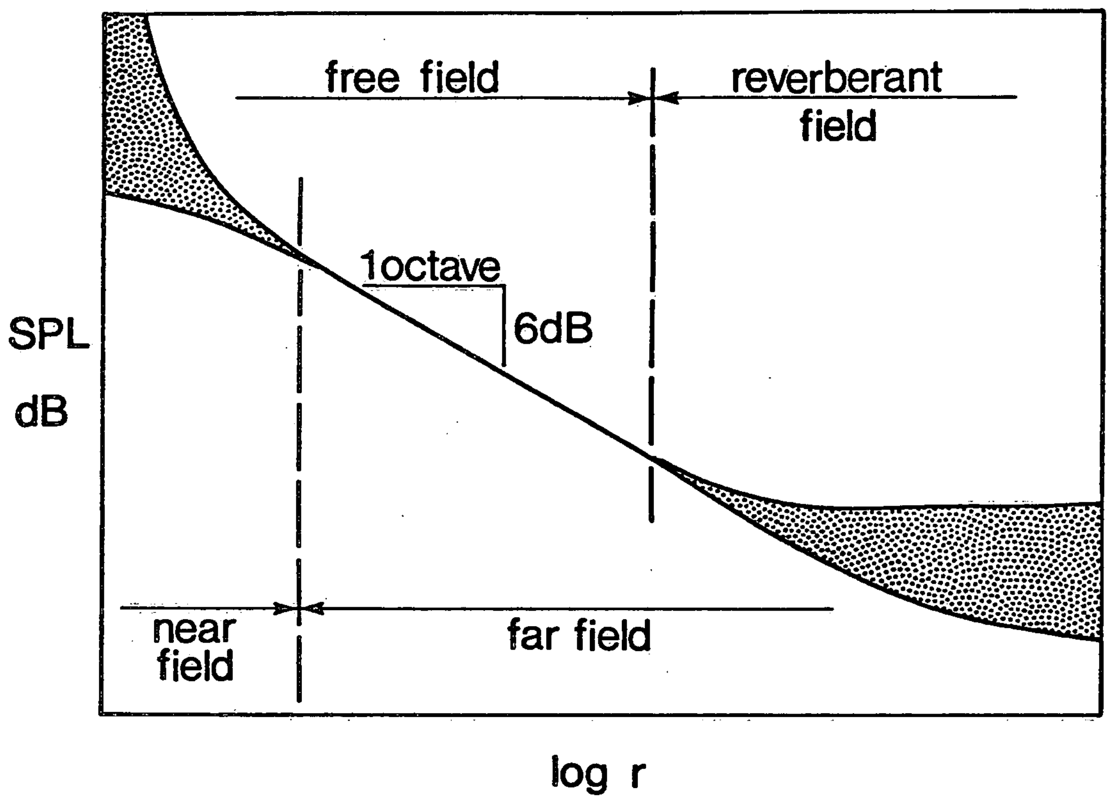


Figure 2. Acoustic Fields in an Enclosure (From Broch, 1971)

the observation point is in the far field part of the free field. Secondly, identification of near-bed sound sources and, hence, of the pebble noise should be possible, because of wide divergence, by SPL observations at different distances from the bed .

The extent of the different sound fields in rivers is not known. For example, it is not known if the reverberant field due to the pebble noise, is affected by the proximity of the free surface which provides an excellent reflective boundary.

The acoustic directivity of a source, describes the spatial distribution of the energy radiated by the source and can greatly affect the measurement of the acoustic power which a sound source generates. A directive source emits the acoustic energy into one or more specific directions. To determine the acoustic power of such a source, observations of SPL are required at a number of positions in the surrounding space. A non-directive source, on the other hand, radiates the acoustic energy uniformly into the space which surrounds it and, the power of the source can be determined from a single observation of SPL at a known distance from the source.

In principle, the directivities of individual river bed pebbles will influence the observed SPL at any position in the flow. However, it is most likely that their directivities will be random in which case their individual effects would be impossible to assess. In the development of the theoretical model of bed-load transport, therefore it was considered that particle directivity would not be important if it could be shown that either the individual particles are non-directive and radiate the acoustic energy hemispherically above the bed, or that the random directivities of individual pebbles, because of their numbers, are statistically averaged and produce an equivalent uniform directivity.

Background Noise

The background noise, present in the river water, is a key factor in determining the feasibility of the acoustic bed-load measurement technique, because it has the potential to mask the pebble generated noise.

The effects of background noise in the measurement of pebble generated noise in rivers are illustrated in Figure 3. Range r represents the distance of the observation point from the river bed when the total depth of flow is d. Background noise level variations are represented by curves B_1 and B_2 and curve S, taken from Figure 2, is the level of sound generated by the source-pebble collisions. Curves B_1 and S intersect at r_1 and the background noise masks the source sound when the range exceeds r_1. Curves B_2 and S intersect at r_2 and show that the observation range in the free field is limited by the reverberation field at r and not the background noise. Obviously, measurement of SPL due to river bed pebbles is possible only in the ranges

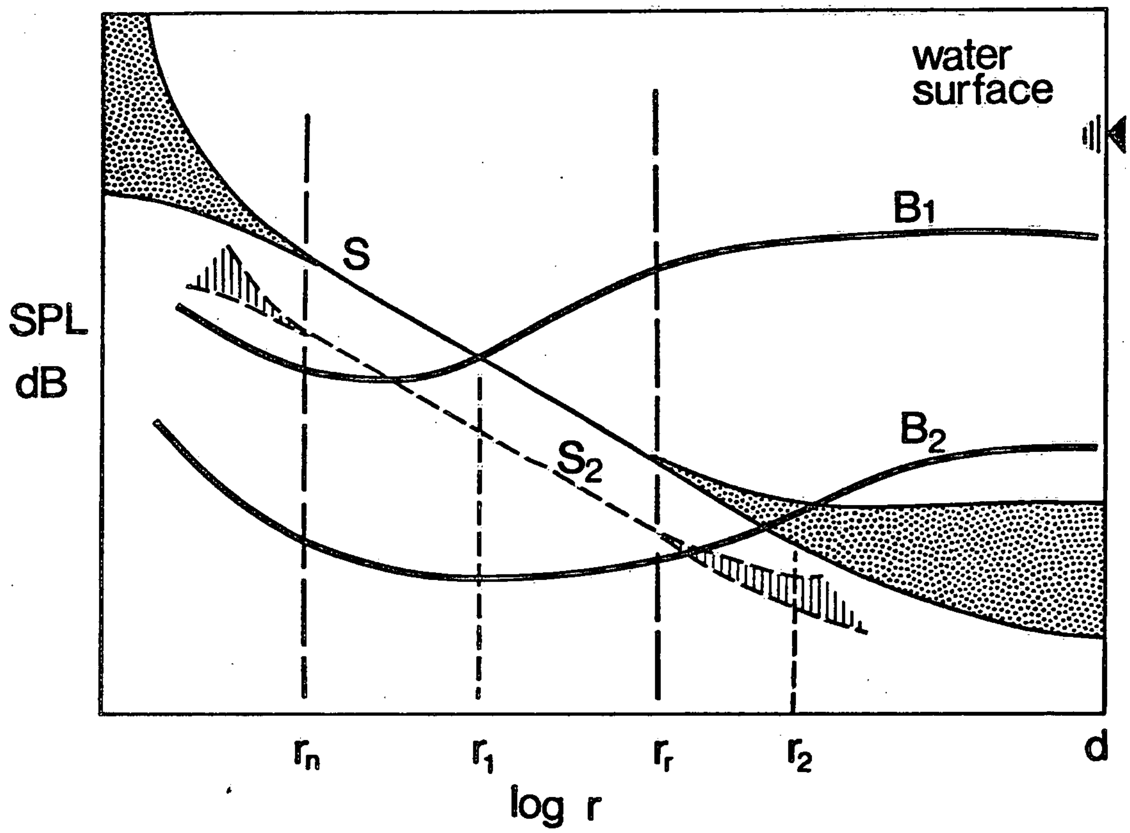


Figure 3. Effects of Background Noise

between r_w and r_1 if B_1 is present, or between r_n and r_r if B_2 is present.

A number of independent sound sources contributing to the background noise in oceans have been identified by Wentz (1962). On the basis of a classification presented by Urick (1967), various possible sound sources in rivers with gravel transport are listed in a chart in Figure 4. However, not all of the sources identified on the chart may be contributing to the observed sound at any time or location, and the contributions of individual sources may vary greatly, with one or two sources dominating and masking the effects of all others.

A component of the background noise which is always present is the noise of the equipment used in the acoustic measurements. It determines the minimum value of noise which can be detected by the instrument and limits noise observations to levels above this value.

The most probable background noise sources are the ambient and the platform noise components due to turbulence and bubbles in the flow, surface splash, and possibly the impact of the suspended sediment particles upon the hydrophone sensor. The propulsion machinery noise can occur if observations are made from a ship whose engines are used to maintain stationary position in the flow.

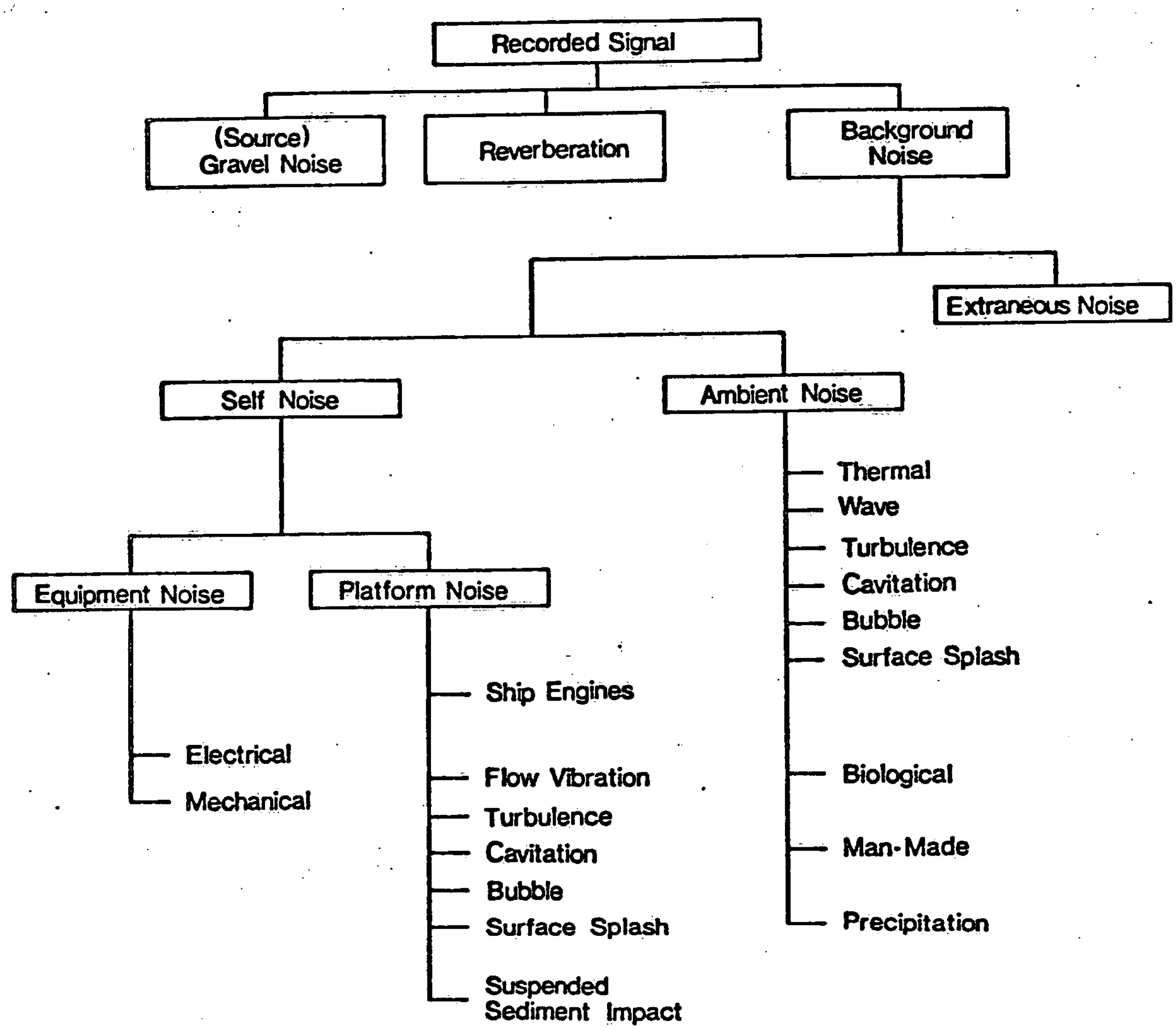


Figure 4. Sources of Noise in River Environments

The sources of background noise least likely to contribute to the noise level in a gravel transporting river are the thermal, wave, biological and man-made components of the ambient noise. Generally, thermal noise levels are very low relative to other sources. Wave produced noise has frequencies below those of interest, and it is unlikely that biological sources could exist in the violent flow of a stream. Also, precipitation noise can be observed only during rainfall periods.

The identity and characteristics of background noise sources are of interest because they provide information for minimizing their effects upon the identification and measurement of pebble generated sound. For example, it may be found that a high level of sound is produced by platform noise. Steps can then be taken to reduce or eliminate this source by redesigning the equipment. Similarly, the location of the hydrophone above the moving bed particles may be influenced by the proximity of the individual background noise sources.

Most importantly, however, the identity of background noise sources can assist in the identification of the gravel generated noise, because generally, all sound sources exhibit individual spectral characteristics.

It must be expected that river bed pebble noise will also exhibit a characteristic spectrum. However its identification may still present difficulties. If Curves S and B_1 in Figure 3 represent the source and background sound pressure levels in a band of frequencies from f_1 to f_2, the background noise will mask the pebble noise when the range of observation is greater than r_1. The same sound but contained in a band of different frequencies from f_3 to f_4, may be represented by the signal and background noise curves S_2 and B_2. The observed SPL of both components is shown to have decreased from those observed in the f_1 to f_2 band, but the background noise no longer masks the signal noise, and identification and observations of the pebble noise are possible throughout the entire free field except near the source.

EXPERIMENTAL DETAILS

Programme

The laboratory experiments were of two categories: (1) those intended to verify some acoustic aspects of the pebble collision generated sound including its transmission underwater and sound field characteristics, and (2), those aimed at disclosing the sound spectrum of potential ambient noise sources present under natural conditions.

In the first category all experiments were quantitative. Sound was generated by pebbles rolling over an inclined bed of identical pebbles. Variables which were controlled included the number of rolling pebbles, the slope of the ramp and, hence, the velocity of the pebbles, and the position of the hydrophone relative to the stationery bed. Average pebble velocities were measured and broad-band recordings were made of the sound produced by pebble collisions from which SPL and frequency spectrum information could be obtained.

The experiments in the second category were of qualitative nature. Attempts were made to simulate flow noise around the hydrophone by towing it in the CCIW tank.

A complete summary of all laboratory experiments is given in Table 1.

Experimental Equipment and Procedures

Rolling Pebble Tests

Noise generated by moving particles was simulated with nearly spherical 40 mm diameter Porox type silica-base porcelain balls normally used for industrial grinding purposes. The manufacturer's specified density of the balls was 2403 kg/m^3.

The stationary bed was 7 balls wide and 59 balls long. The balls were attached by glue to a 12 mm thick foam rubber pad which was attached to the floor of a U-shaped wooden trough. The sides of the trough, intended to prevent the loss of particles over the edge of the ramp, where also lined with foam rubber and prevented generation of sound by collision with the rolling balls. The dimensions of the pebble ramp are given in Figure 5.

The ramp with the stationary balls was placed in 1.20 m of water in the wind-wave flume of the hydraulics laboratory at CCIW. Only two different slopes of the ramp (24° and 27°) could be employed in the experiments because of restrictions imposed by the maximum depth of water in the flume and by the minimum slope of the ramp over which the balls could roll without stopping.

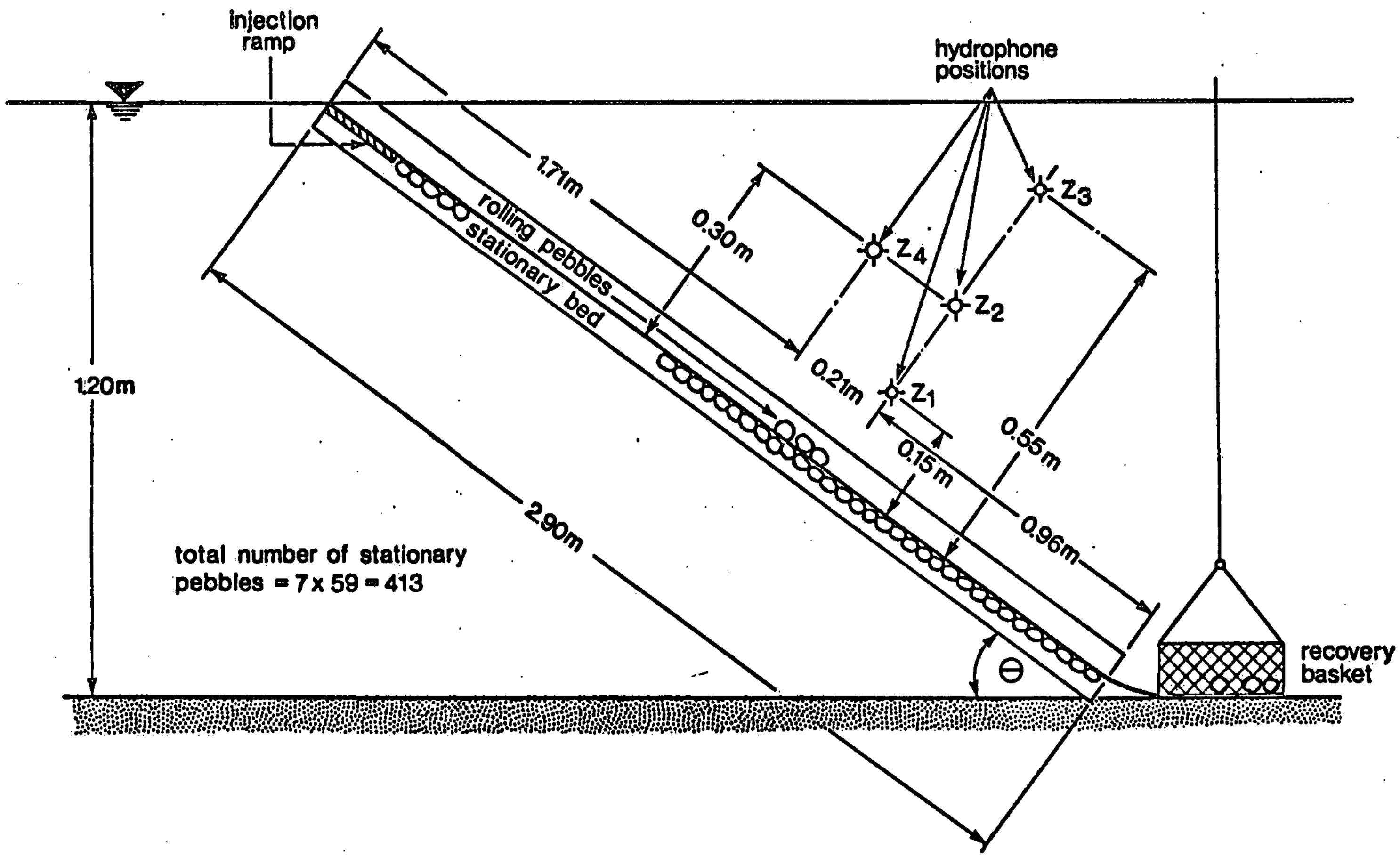
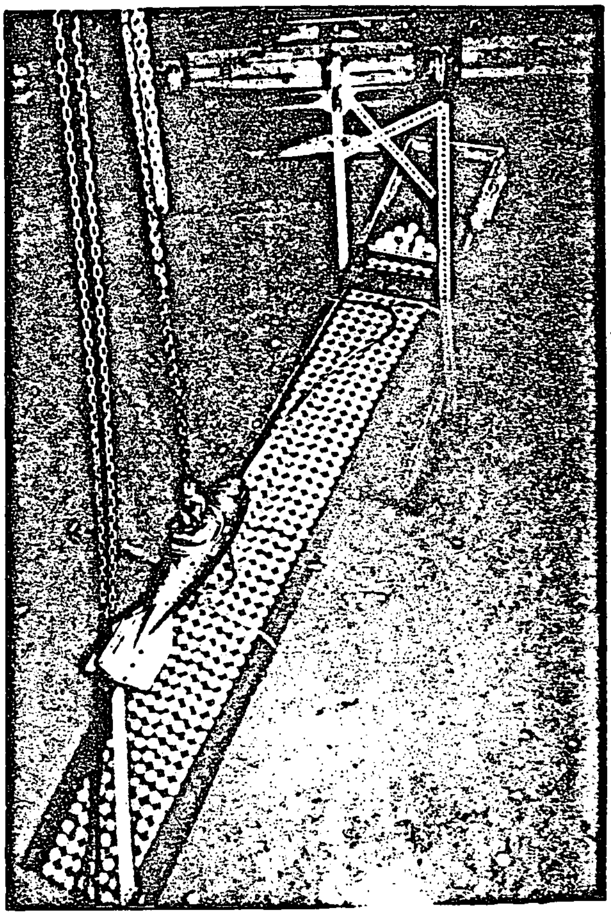
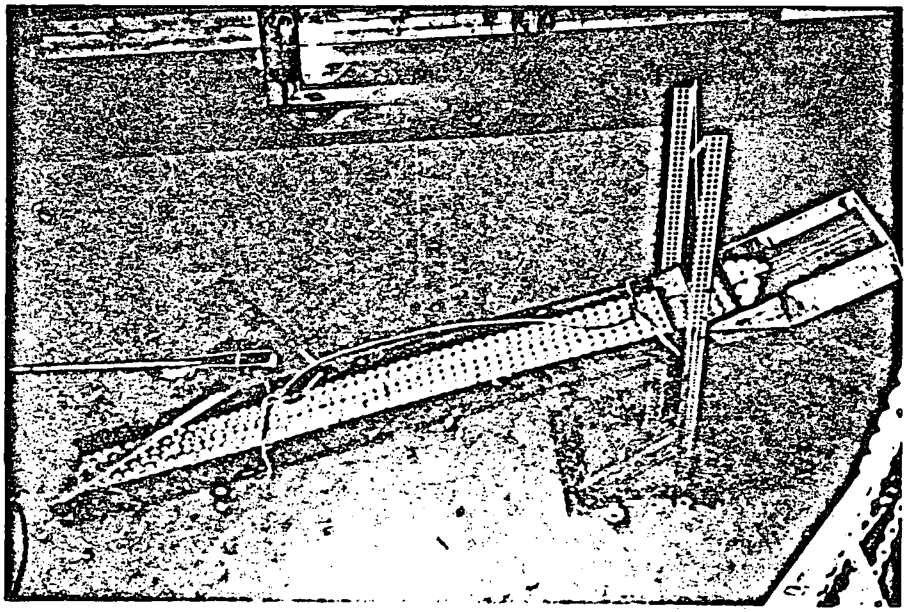


Figure 5 Pebble Ramp Dimensions and Hydrophone Positions.



With Ithaco hydrophone



With ITC hydrophone

Figure 6. Pebble Ramp

TABLE 3. Summary of Laboratory Experiments

Test Group	Date	Number of Tests	Test Type	Measurement System		Test Function*							Remarks
				Hydrophone	Recorder	A	B	C	D	E	F	G	
1	April 5, 1973	4	Rolling pebbles	Ithaco	Uher			✓	✓				Preliminary
2	April 25-26, 1974	15	Rolling pebbles	Ithaco	Uher	✓	✓	✓	✓			✓	
3	"	2	Rolling pebbles	Ithaco	HW5600	✓			✓			✓	
4	"	6	Rolling pebbles	Gould	HW5600	✓						✓	
5	"	9	Rolling pebbles	ITC	HW5600	✓	✓	✓	✓			✓	
6	"	2	Towing Tank	ITC	HW5600					✓	✓		
7	Oct. 20-22, 1974	74	Rolling pebbles	Ithaco	Uher	✓	✓	✓					
8	Dec. 17, 1974	9	Rolling pebbles	ITC	HW 96		✓	✓	✓			✓	
9	Dec. 17, 1974	10	Rolling pebbles	Ithaco	HW 96		✓	✓	✓			✓	

* Test function Code:

A - acoustic wave transmission;

B - rate of collision effect;

C - SPL v.s. transport rate;

D - spectral characteristics;

E - extraneous noise

F - CCIW towing tank noise;

G - Instrument comparison

Collision sound was generated when one or more of the ceramic balls were allowed to roll, under the action of gravity, down the stationary ball platform. In some preliminary tests the rolling balls were injected individually or in pairs. In the majority of tests, however, the balls were arranged on a foam rubber pad immediately above the first row of the stationary balls and held in place by a vertical gate, and were released by manually removing the gate. Up to 25 balls could be injected for observation.

The positions of the ramp in the flume and the position of the hydrophone relative to the ramp were preselected depending upon the purpose of the experiment and are shown in Figure 7 and Table 2.

Acoustic observations were made using three different hydrophone systems. The performance of these systems is described in other reports (Jonys, 1975; White, 1975). Hydrophone sensitivities employed in noise recordings, however, are summarized in Table 3.

In a typical rolling pebble experiment, broad-band recording of sound was obtained from immediately prior to the injection of the pebbles until they came to rest in the recovery basket at the foot of the ramp. The signal was also passed through the Ithaco signal conditioning apparatus and recorded on paper chart. Preselected positions of the rolling balls on the ramp were marked on the chart during the recording for determining the position of the sound source from the

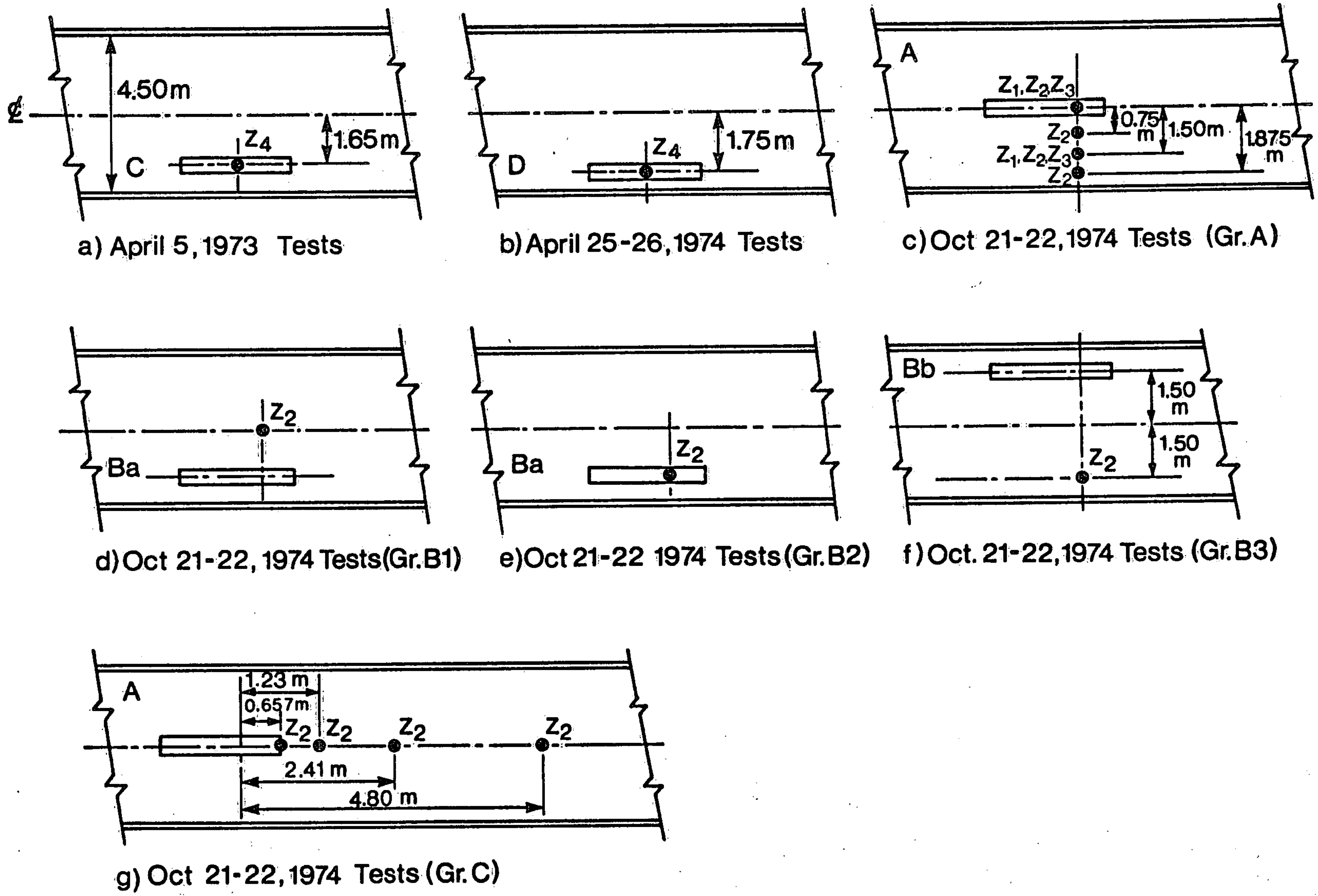


Figure 7 Hydrophone and Ramp Positions in the Wind-Wave Flume.

TABLE 2. Summary of Rolling Pebble Experiments

Test Group	Number of tests	Hydrophone Position*	Ramp Position*	Ramp Slope Angle θ	Number of Rolling Pebbles**	Remarks
1	3	Z_4	C	24°	52, 50	
2	15	Z_4	D	23.8°	1,3,6,9,12,14,15,16,18,19	
3	2	Z_4	D	23.8°	9	
5	6	Z_4	D	23.8°	1,3,6,9,12,15	
7	9	Z_4	D	27.1°	1,3,6,9,12,15	
10	74	Z_1, Z_2, Z_3	A,Ba,Bb	24°, 27°	1,3,9,5,10,15,20,25	
11	9	Z_2	A	23.8°	5,10,15,18,20,25	
12	10	Z_2	A	23.8°	5,10,15,20,25	

* Hydrophone and ramp positions are indicated in Figures 1 and 2.

** At least one test was made with each of the number of rolling pebbles indicated.

TABLE 3. Summary of Hydrophone System Sensitivities

Test Group	Date	Hydrophone	HP Sensitivity	Gain	System Sensitivity
1	April 5,1973	Ithaco	-64	0	
2	April 25-26, 1974	Ithaco	-64	0	
3		Ithaco	-64	0	
4		Ithaco	-64	0	
5		Gould	-58	-9	
6		Gould	-58	-9	
7		ITC	-63	-9	
8		ITC	-63	-9	
9		ITC	-63	-9	
10	October 21-22,1974	Ithaco	-64	0	
11	December 17, 1974	ITC	-63	0	
12	December 17, 1974	Ithaco	-64	0	

hydrophone.

Frequency analysis of the recorded signal was made using the Ithaco filter system in one-third or one octave bands.

Towing Tank Tests

To isolate platform noise, the hydrophones were towed at velocities up to 2.7 m/s through still water in the CCIW towing tank. Because of the relatively high level of noise produced by the towing carriage, recordings were made also of the carriage generated noise alone, with the hydrophone stationary near the midpoint of the towing tank.

RESULTS AND ANALYSIS

Sound Level Variation

The variation of SPL with the number of sound generating pebbles was determined by observing the SPL at the time when the centre of the group of N_B rolling balls was located directly under the hydrophone. The centre of the group of pebbles was considered to be the acoustic centre of the sound. No attempt was made to apply a range correction for the particles moving at edges of a group because the maximum number of pebbles used in experiments increased the range of edge particles by only 5%, and this increase was not considered to be significant to warrant correction.

The experimental results showing the variation of a broadband SPL with the number of rolling particles N_B and obtained with hydrophone ranges of 0.30 and 0.325 m are presented in Figure 8 (a) and (b).

The reproducibility of SPL measurements for any N_B was within a band of 3 dB in any one group of observations and within 5 dB between different groups using the same hydrophone. In view of the nature of the acoustic environment and of the sound generating sources, this was considered to be satisfactory.

The results show that the relationship between SPL and N_B is

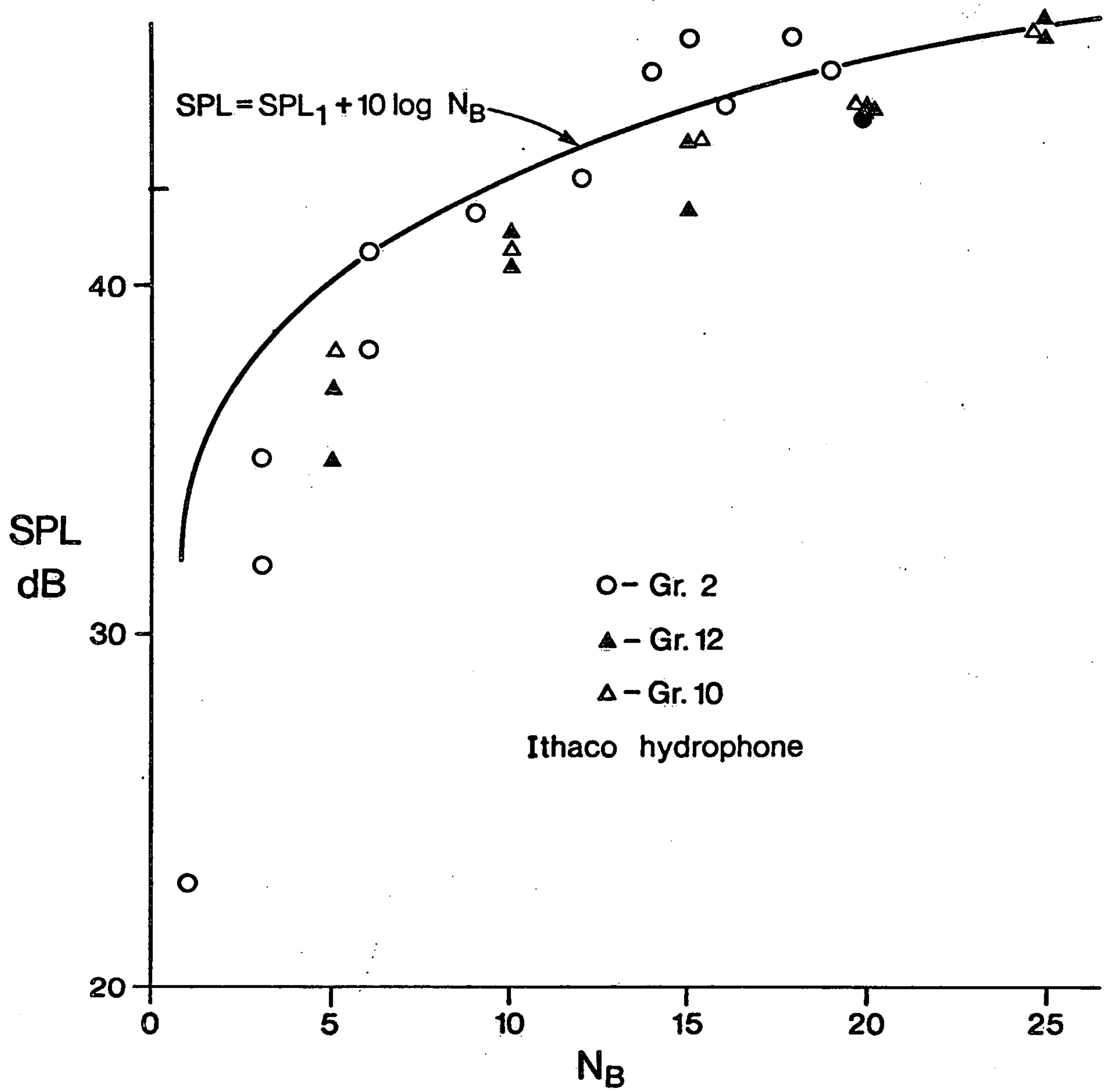


Figure 8(a). SPL Variation with Number of Rolling Pebbles N_B

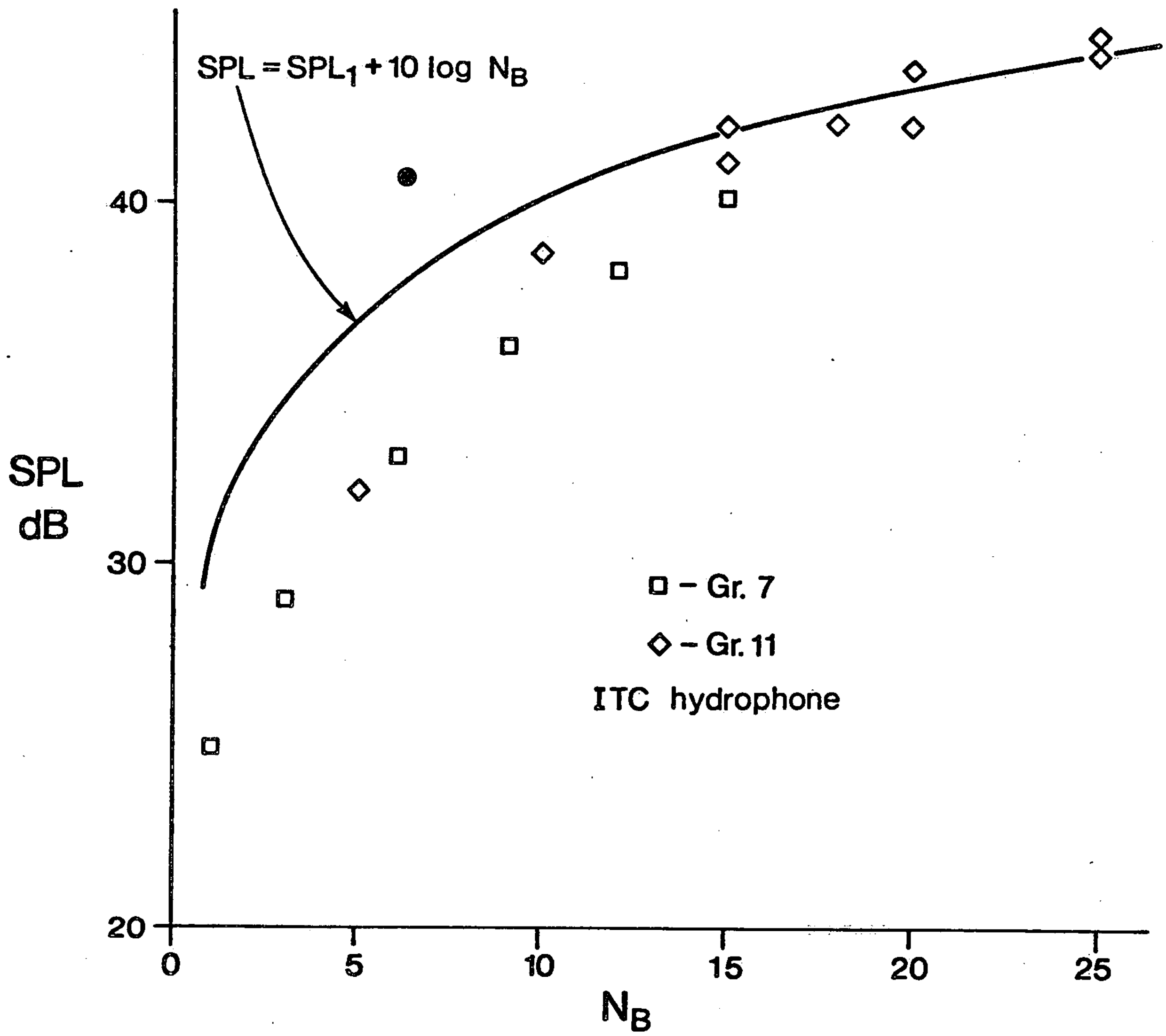
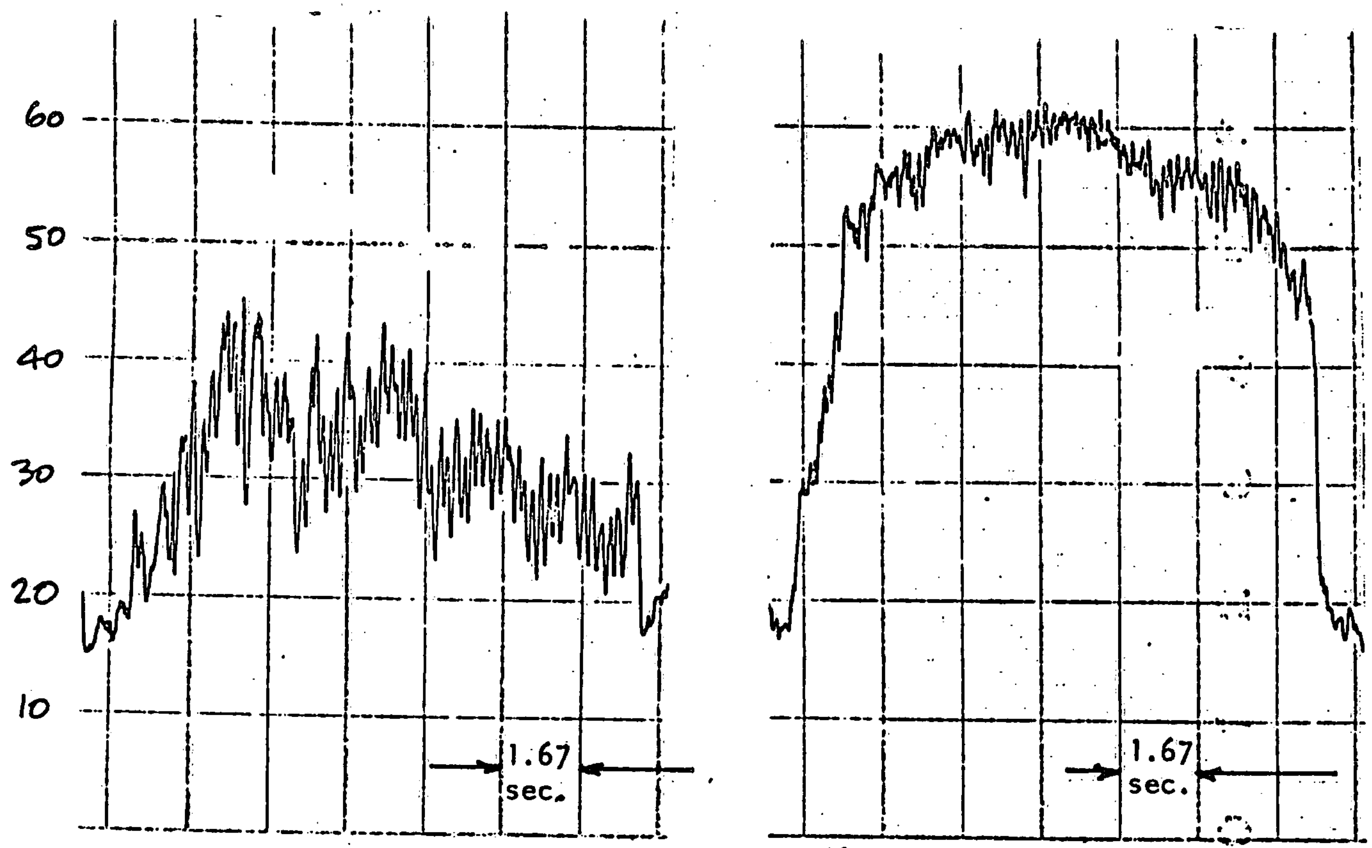


Figure 8(b). SPL Variation with Number of Rolling Pebbles N_B

nonlinear and that the rate of change of SPL with N_B ($\Delta SPL/_{\Delta N_B}$) is very large at low N_B and decreases as N_B increases. Because this trend agrees qualitatively with the multiple source effect, the experimental results were compared with theoretical results obtained from equation (2) assuming N_B to represent the number of sources n. The theoretical curve was chosen to equal the observed SPL at N_B=25. An equivalent SPL_1 for N_B=1 was then calculated from equation (2) and used in determination of SPL for different N_B values. For the Ithaco and ITC hydrophones, the SPL values at N_B=25 were 47 and 44 dB and yielded equivalent one pebble SPL_1 values of 33 and 30 dB respectively.

The theoretical and experimental results were found to correspond when N_B was greater than 12 or 15. Below these N_B values the theoretically predicted sound pressure levels were higher than those observed experimentally.

The discrepancy between theoretical and experimental results at low N_B is possible for a number of reasons. Foremost is the fact that rolling pebbles produce impact type of sound but equation (2) is applicable to continuous sound sources. The chart recording the acoustic record shown in Figure 9 (a) indicates that during the passage of one pebble from the top to the bottom of the ramp, all 59 collisions with stationary pebbles were detected. However, the chart recorder may not have had the response to record the peak values of the collision noise and the measured SPL was below the true average value. For



(a) 1 ball

(b) 9 balls

Figure 9 Recorder Output

9 rolling balls the noise record chart in Figure 9 (b) indicates that the contribution of individual collisions were integrated into continuous sound.

It is also possible that the force of collisions between particles was not constant and that at the time of an observation the measured SPL at low N_B was below the true mean value.

The experiments, nevertheless, confirm that a relationship exists between the number of rolling particles and the SPL they produce. Furthermore, except at low N_B, this relationship appears to have the same functional form as the theoretical relationship for multiple continuous sources given in equation (2).

Collision Frequency and Equivalent SPL

In the development of the theoretical relationship between the rates of sediment transport and the level of noise produced by the pebbles, it was necessary to consider the frequency of sound producing collisions, and also the level of sound generated by a single collision.

The frequency of collisions was determined from

$$F_c = \frac{N_B \bar{V}_p}{D} \qquad (3)$$

where F_c is the frequency of particle collisions Hz, N_B is the number of pebbles in the group, $\bar{V}_p$ is the average velocity of the group of rolling pebbles, and D is the diameter of the pebbles. Equation (3) is based on the experimental observation that a rolling pebble collides only once with each stationary pebble in its path.

The equivalent sound pressure level SPL_{eq} due to one collision per second was calculated from

$$SPL_{eq} = SPL - 10 \log F_c \qquad (4)$$

where SPL represents the total measured sound pressure level due to a source producing sound by collision at a frequency of F_c.

The experimental results, are presented in Figures 10 (a) and 10 (b). Although the data points show scatter, the results indicate that SPL_{eq} tends to become a constant as F_c increases. For the Ithaco hydrophone, the observed SPL_{eq} values fall in a band of 5 dB when F_c is greater than 60 Hz. For the ITC hydrophone, the scatter band for $\bar{V}_p$=0.29 m/s and F_c between 60 and 180 Hz is only 3 dB. The results also show that SPL_{eq} decreases from the values in the constant range as F_c decreases from about 40 Hz.

With the measurement and recording systems used in this investigation it appears that continuous sound analysis techniques become applicable when the frequency of particle collisions exceeds 50 Hz. Although this value is considerably greater than the 10 Hz minimum suggested by Beranek (1971) it nevertheless indicates that the concept of an equivalent sound pressure level and continuous sound analysis methods can be used in estimating the total contributions of multiple collisions such as occur among river bed pebbles.

Pebble Velocity Effects

As shown in Figure 10 (b), group 7 tests with $\bar{V}_p$=0.31 m/s produced SPL_{eq} values below those from group 11 tests where the $\bar{V}_p$ was 0.29 m/s. Further analysis of data from group 10 tests using identical N_B = 9 for comparison and presented in Table 4, also indicate that SPL_{eq} values decreased with the increase in the average pebble velocity $\bar{V}_p$.

TABLE 4. SPL_{eq} Variation With $\bar{V}_p$

$\bar{V}_p$ m/s	F_c Hz	SPL dB	SPL_{eq} dB
0.29	65.25	51	33
0.35	78.25	49	30

Although the available experimental data is very limited and must be verified for other pebble velocities, the results confirm previously discussed reasons for the decrease in the acoustic power with increasing particle velocity.

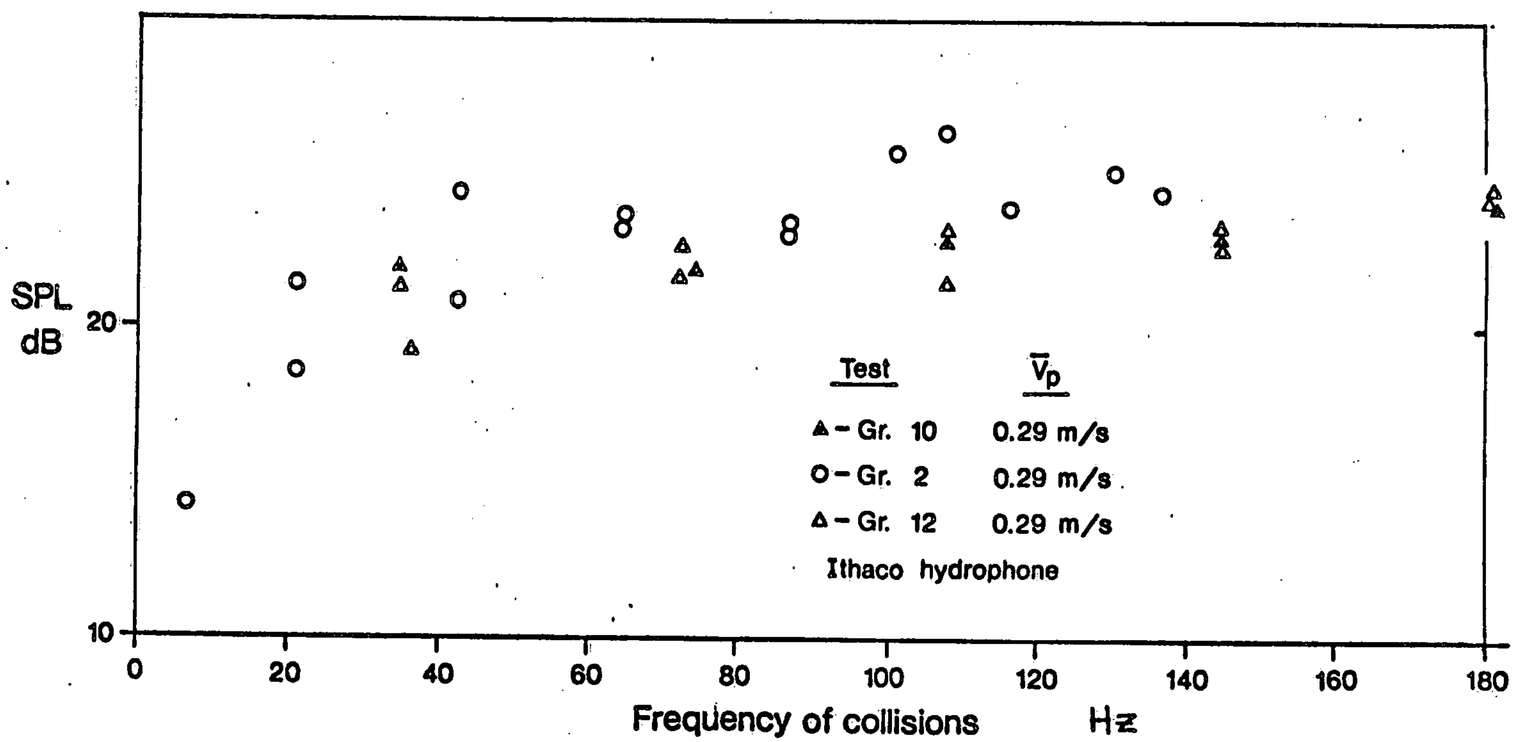


Figure 10(a). One Collision Equivalent SPL Variation With Frequency of Pebble Collisions.

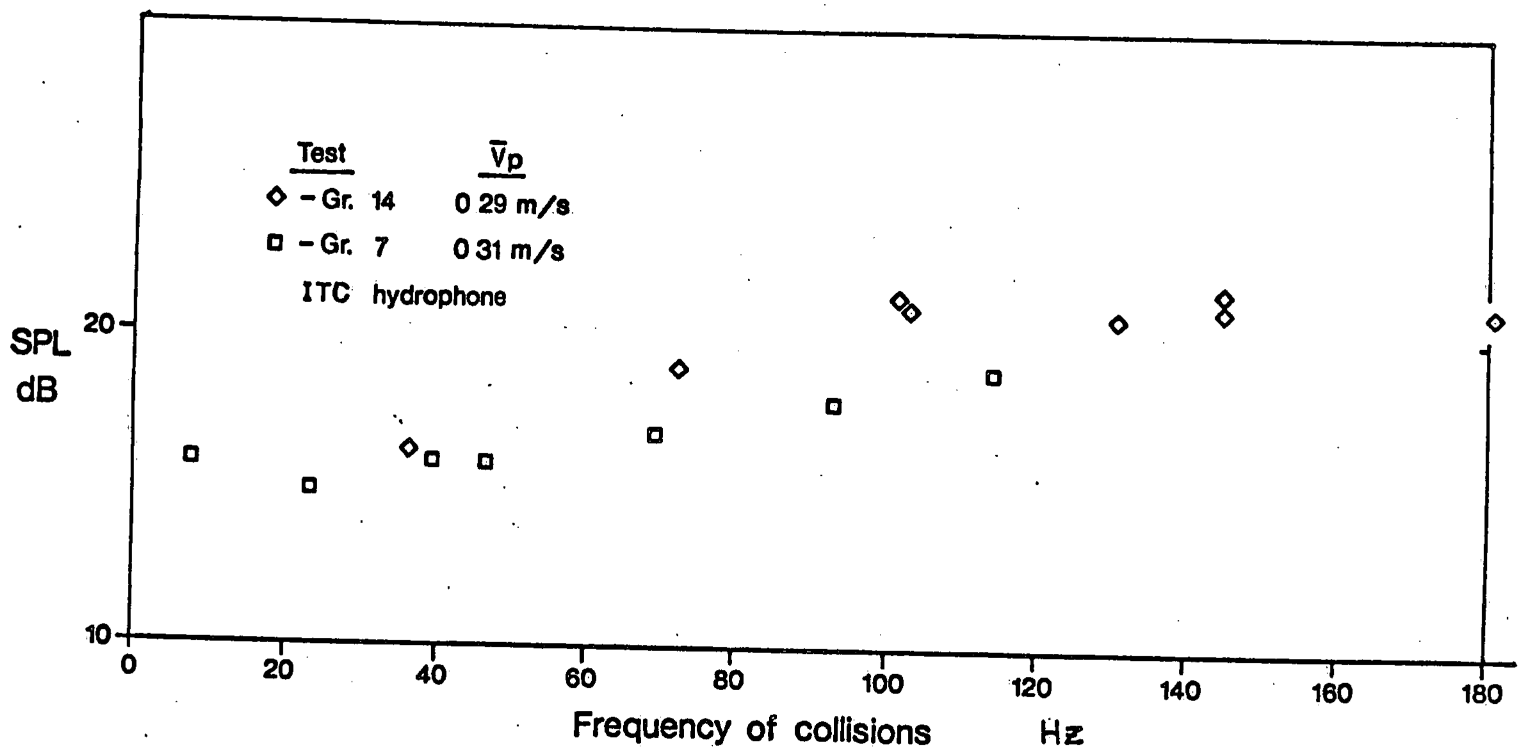


Figure 10(b). One Collision Equivalent SPL Variation With Frequency of Pebble Collisions.

Sound Field Characteristics

The characteristics of the sound fields generated by rolling pebbles were investigated by observing SPL at six positions from a fixed point on the stationary pebble ramp. The distances of the hydrophone to this point were varied from 0.15 m to 4.80 m with each new position approximately double in distance from the previous. The hydrophone was located at a depth of 0.67 m below the surface of water for the range of 0.15 m and 0.53 m for all other observations.

The results, summarized in Figure 11, include observations of SPL generated by N_B values of 1, 3 and 9 on a ramp slope of 24^o. The ordinate axis represents SPL values relative to an arbitrary reference level. This permitted the superimposition of sound data from different N_B for the composite result.

All individual data points are contained within a band of 6 dB up to $^r/r_o$ value of 4.2 which represents an actual range r of 1.26 metres. Furthermore, the data band lines have a negative slope of 6 dB per doubling of the range of observation. For $^r/r_o$ values larger than 4.2, the observed SPL fall above the upper band line.

The results indicate that an acoustic free field illustrated in Figure 2, was established in the still water up to a range of 1.26 m from the centre of the group of the noise generating pebbles. Above this range the reduction of the slope from 6 dB per octave indicates

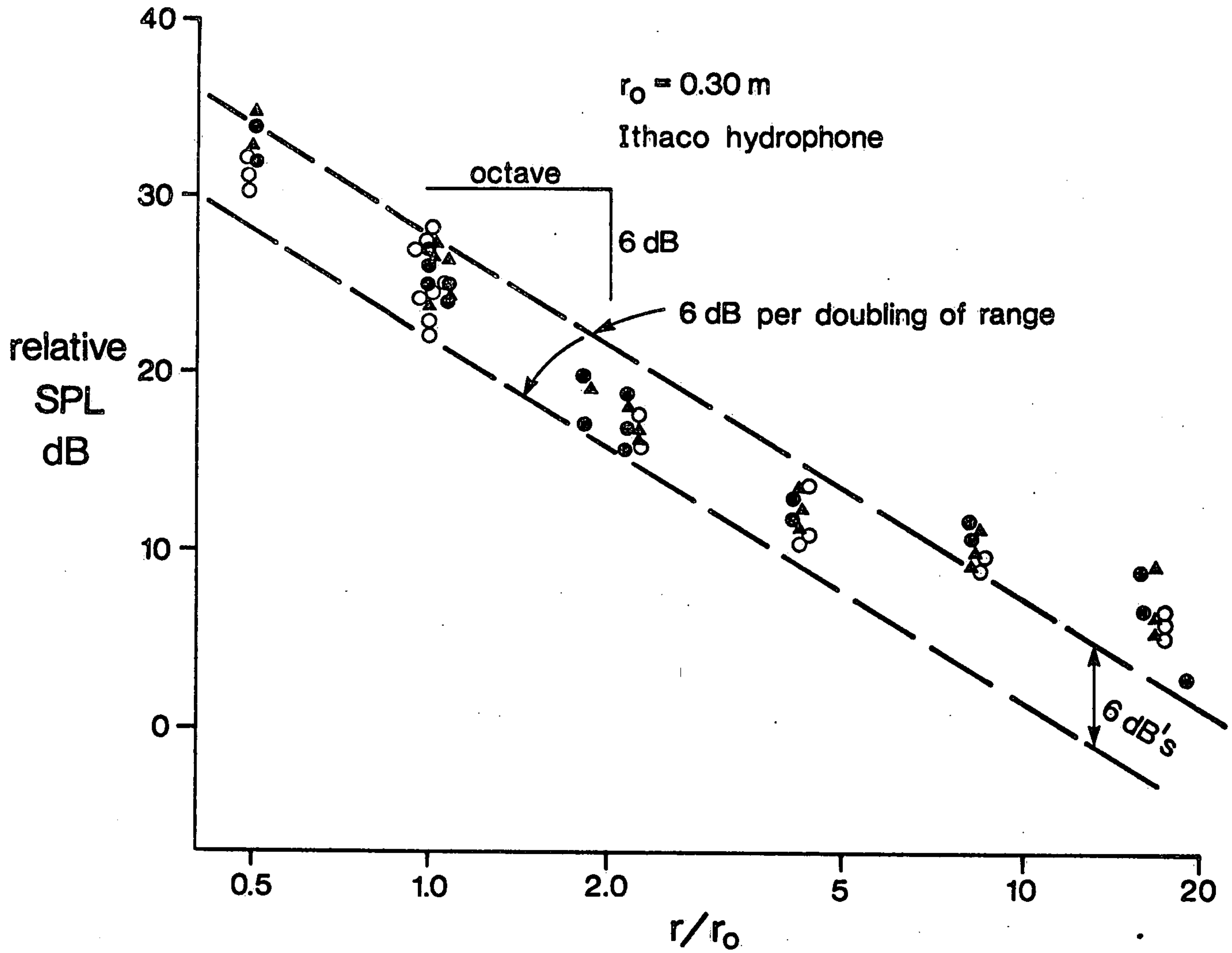


Figure 11. Sound Pressure Level Attenuation With Distance From Source.

that reverberation effects, due to the reflection of sound waves from the boundaries of the enclosure, were being detected. Furthermore, the results suggest that the pebble generated sound is, on the average non-directional, because only the spherical or hemispherical radiation of the pressure waves from the source could produce an attenuation of 6dB for each doubling of the range.

Pebble Sound Spectrum

The characteristics of the frequency spectrum of the ceramic balls used in the laboratory experiments were determined from numerous recordings of sound generated by groups of pebbles rolling down the test ramp. The results presented in this chapter, however, were taken from test groups 11 and 12 only because similar results were obtained from other tests.

In test groups 11 and 12, sound recordings were made using the Ithaco and ITC hydrophones and a Honeywell 96 tape recorder. Sound data were determined with the hydrophones located at a range of 0.30 m to the centre of a group of rolling pebbles. The number of pebbles N_B in the tests was varied from 5 to 25. Spectral information was obtained by playing back the recorded broad-band (0.05 - 40 kHz) signal through every second of the one-third octave pass bands of the Ithaco filter in the range from 0.05 to 10 kHz.

The results of the tests, presented in Figure 12 (a) to (d),

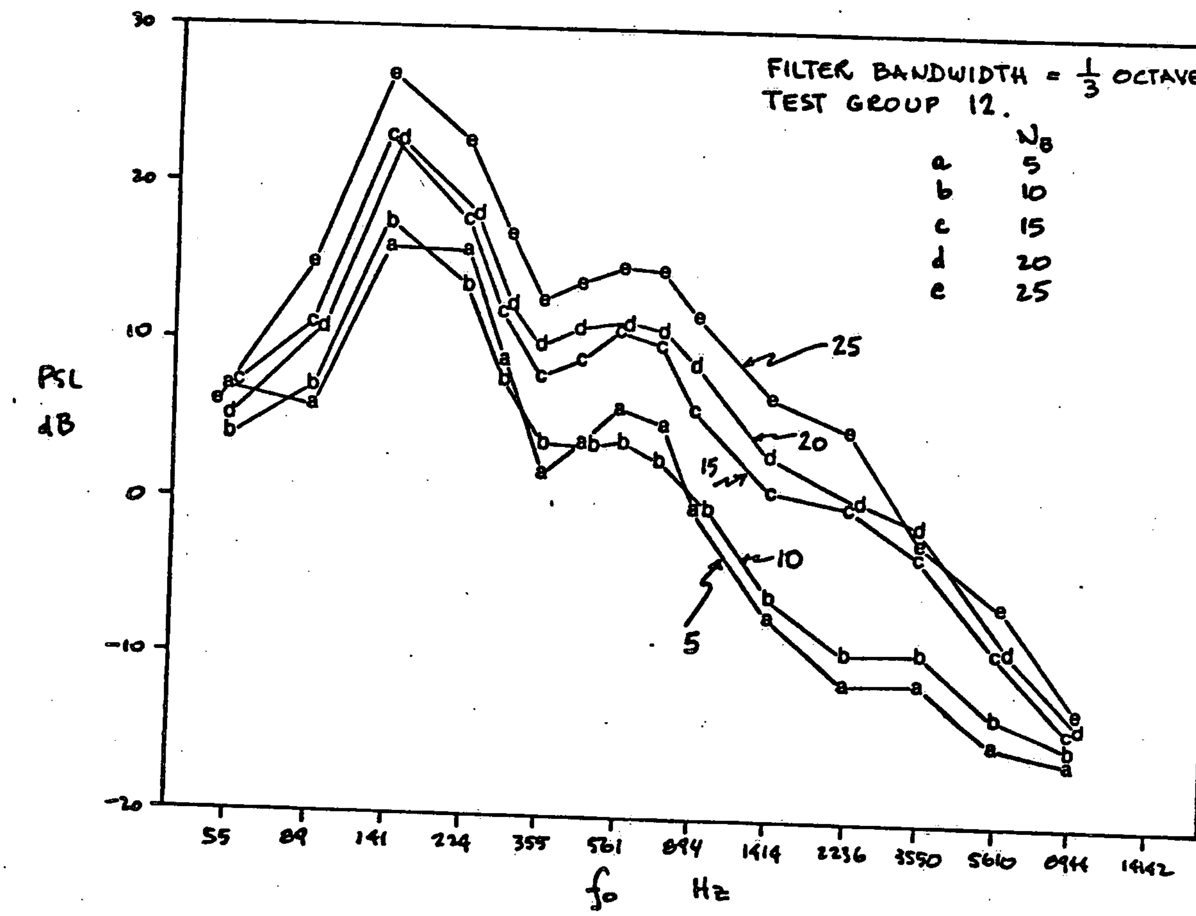


Figure 12(a). Pebble Noise Spectra - Ithaco Hydrophone.

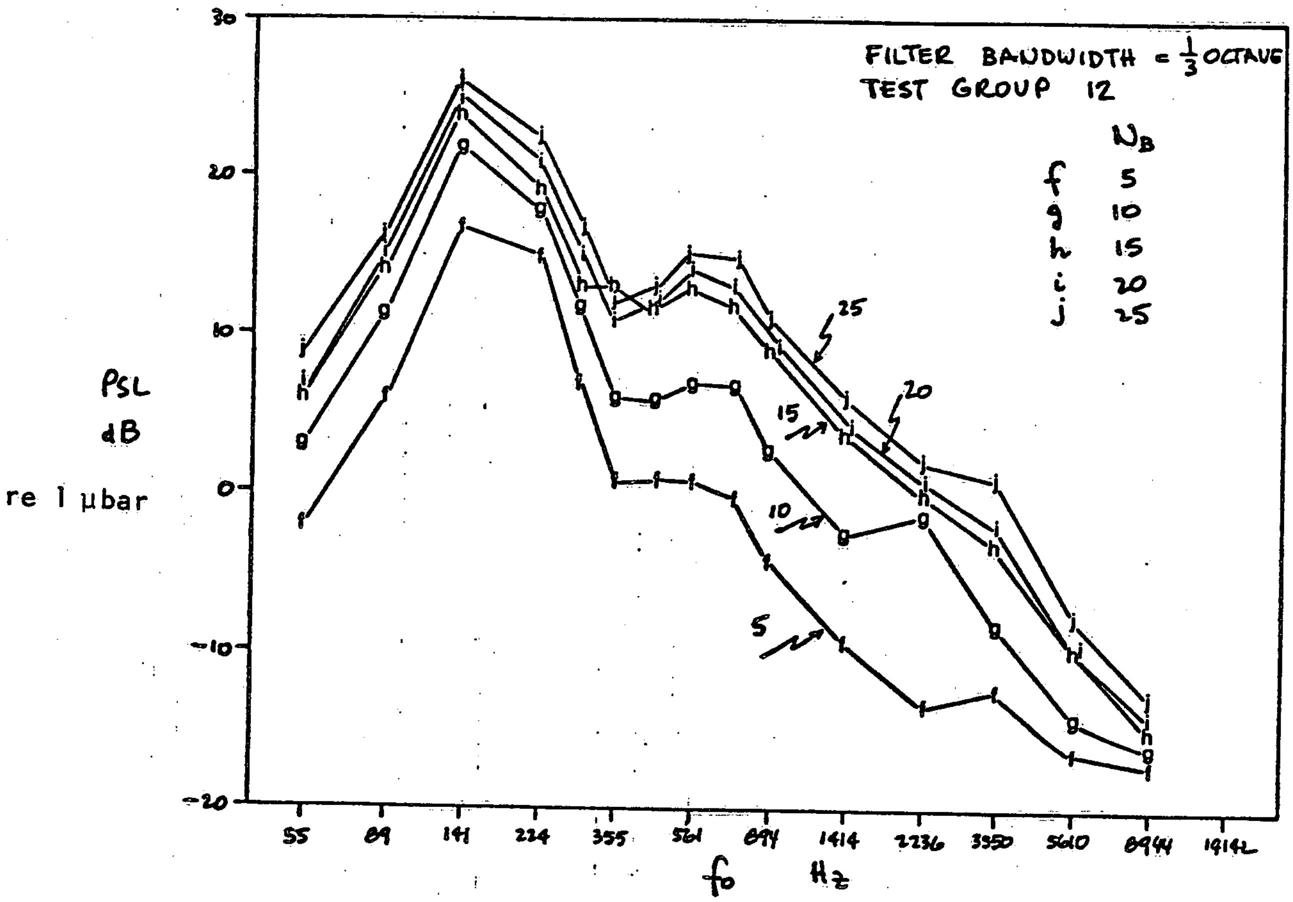


Figure 12(b). Pebble Noise Spectra - Ithaco Hydrophone.

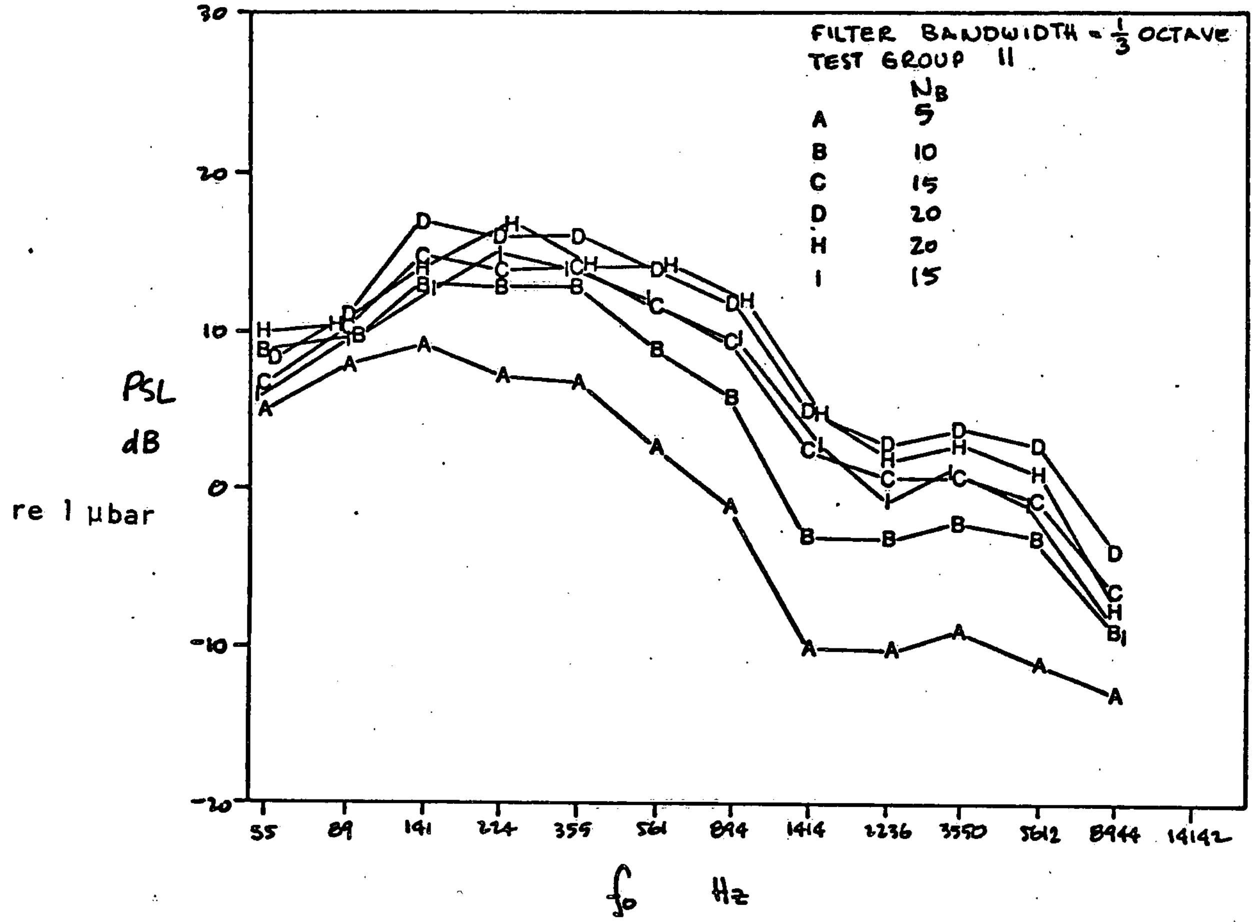


Figure 12(c). Pebble Noise Spectra - ITC Hydrophone.

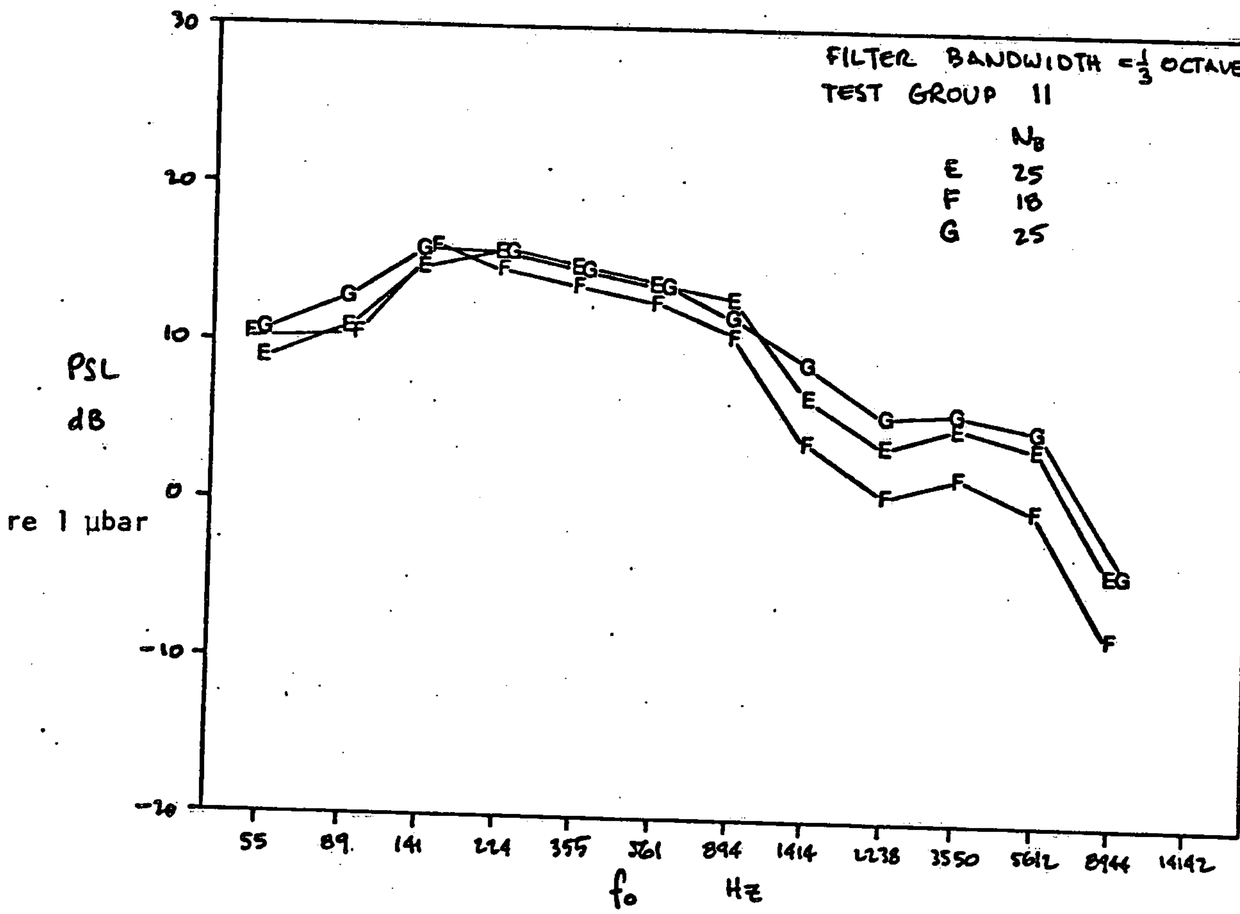


Figure 12(d). Pebble Noise Spectra - ITC Hydrophone.

show the variation of the pressure spectrum level with frequency. The PSL represents the effective SPL of the signal contained in a band 1 Hz wide as determined from equation (5).

$$PSL = SPL_b - 10 \log \Delta f \qquad (5)$$

where SPL_b is the sound pressure level in the 1/3 octave band and Δf is the band width in Hz centered at a frequency f_o and determined from

$$f_o = \sqrt{f_1 f_2} \qquad (6)$$

where f_1 and f_2 are the high and low pass frequencies of the filter band.

From the spectrographs which cover the frequencies from 50 Hz to 10 kHz, the pebble noise spectra were found to be continuous. However a substantial difference was found to exist between the spectra determined by the Ithaco and the ITC hydrophones. The spectrographs obtained with the Ithaco hydrophone show a maximum at about 140 Hz as well as a secondary peak at about 560 Hz. In addition, there appears to be a small increase of PSL from the general trend of the spectrum curve in the vicinity of 2.24 kHz. The ITC hydrophone results, however, show that the maximum PSL occurs in the 140 to 220 Hz frequency band, and that the peak is much more gradual and less pronounced than the peak determined from Ithaco hydrophone measurements. Furthermore, only one secondary peak at about 3550 Hz was found with the ITC hydrophone.

No attempt was made to resolve the discrepancy between the results obtained by the two hydrophones. Measurements, however, were made with the hydrophones deliberately positioned at identical locations relative to the water surface, flume boundaries and pebble ramp. The method of pebble injection, and the average pebble velocity were also identical. Hence, it is unlikely that the differences were due to experimental errors. It is possible, however, that the Ithaco hydrophone output is affected by the variations of its sensitivity with signal frequency because of placement of the sensor in the hollow of the lead weight.

Generally, the spectrographs show that PSL increases with N_B, but that the forms of the spectrographs, produced by different N_B and determined by the same hydrophone, are similar. The variations of PSL with N_B were evaluated for every frequency band where data was available. The relative variation of PSL with N_B in all frequency bands, obtained by superimposing data points from different bands is given in Figure 13. The two lines are 3 dB apart and are sloping at 3 dB per octave (i.e. doubling of N_B). Although some data scatter is present, the majority of data points fall between the band lines indicating that doubling of the number of the rolling pebbles increased the PSL by a constant 3 dB when N_B was greater than 10. This confirms the theoretical result which can be obtained from equation (2) by substituting N_B for n. Furthermore, the results are independent of the frequency band - a condition which must be satisfied in pebble noise identification and measurement when background noise is present.

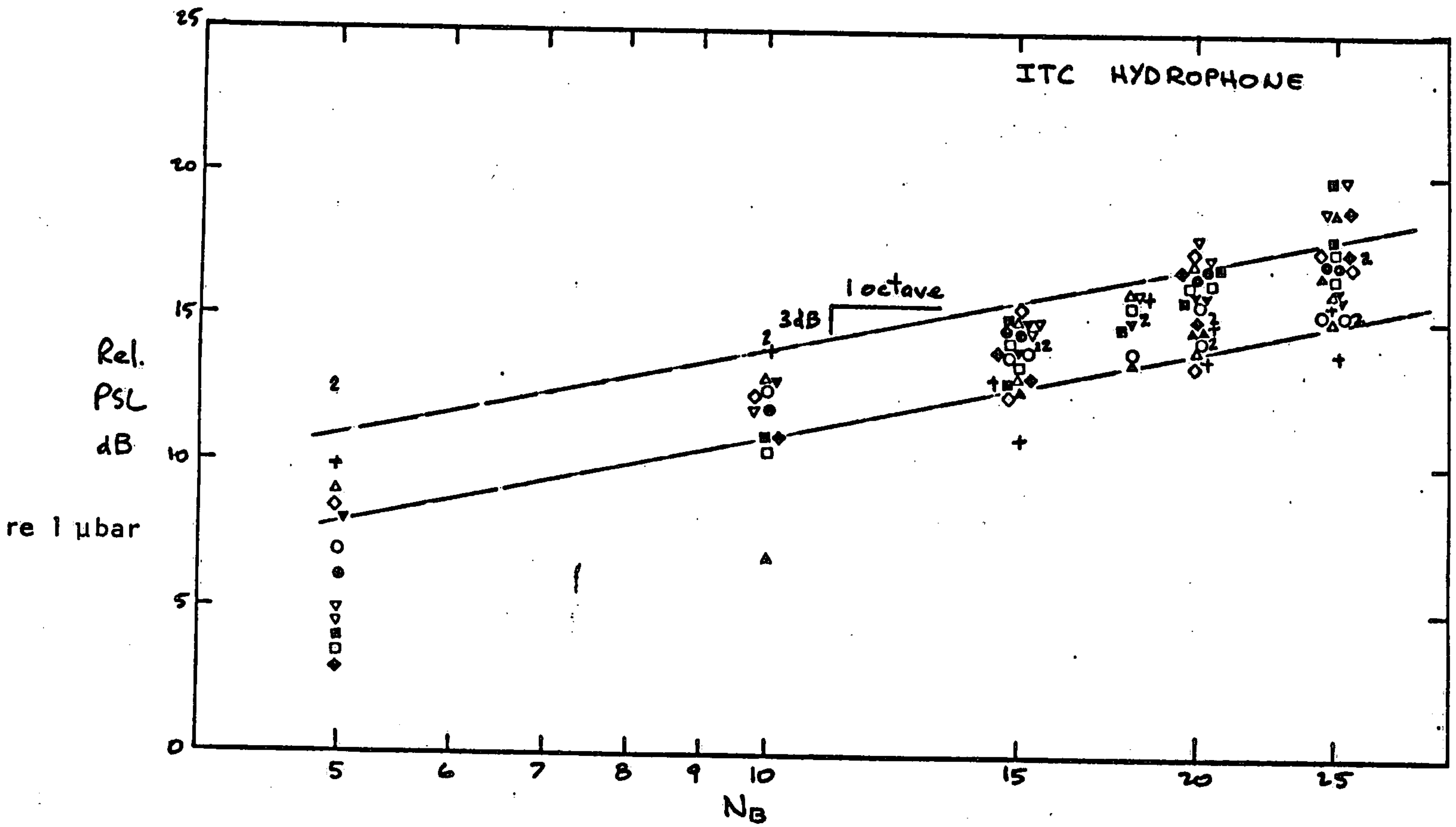


Figure 13. Relative Increase in PSL With Number of Rolling Pebbles.

Towing Tank Test Results

To determine the characteristics of the platform noise which can be generated by the flow around the hydrophone and its underwater support system, both the Ithaco and ITC hydrophones were towed through still water in the CCIW towing tank.

The results with the Ithaco hydrophone were inconclusive. At velocities comparable to those at which gravel movement takes place in rivers the excessive noise generated by the towing carriage exceeded the upper limit of the instrument range and could not be interpreted.

The signal from the ITC hydrophone, however, was attenuated and observations were made at velocities of 1 and 3 m/s. In addition, the carriage noise spectrum was determined by the hydrophone stationary midway between the ends of the towing tank.

The results, presented in Figure 15, show that the observed PSL were identical for the towed and stationary hydrophone conditions. This indicates that the observed PSL was due to the noise of the towing carriage which masked all noise which could have been generated by the hydrophone platform.

For the Ithaco hydrophone, however, towing tests have been carried out in the old Calgary towing tank by Tywoniuk (1971). His data was used in calculating the PSL at the two velocity of 2.74 m/s and is presented, for reference, in Figure 14.

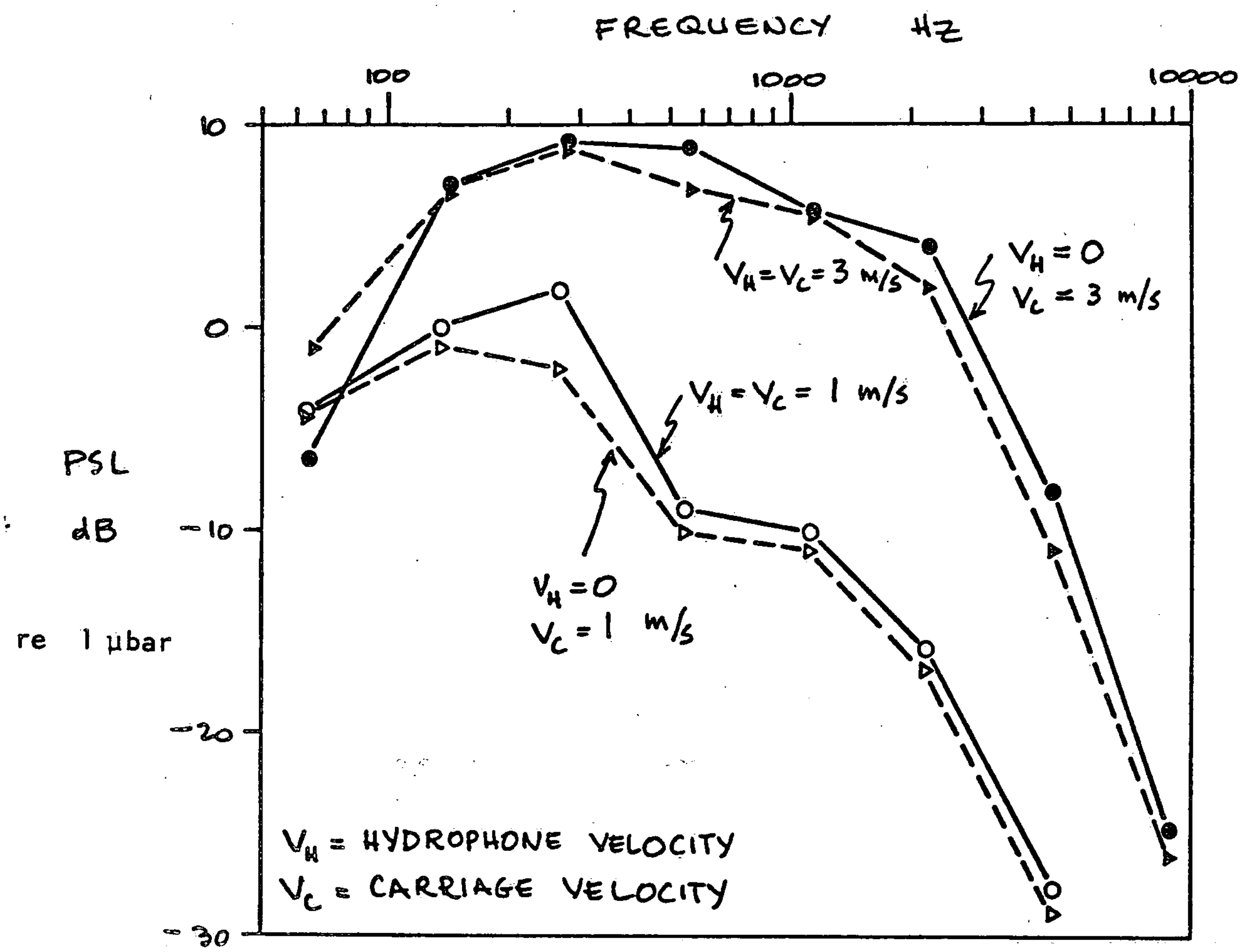


Figure 14 . CCIW Towing Tank Noise Spectre - ITC ydrophone.

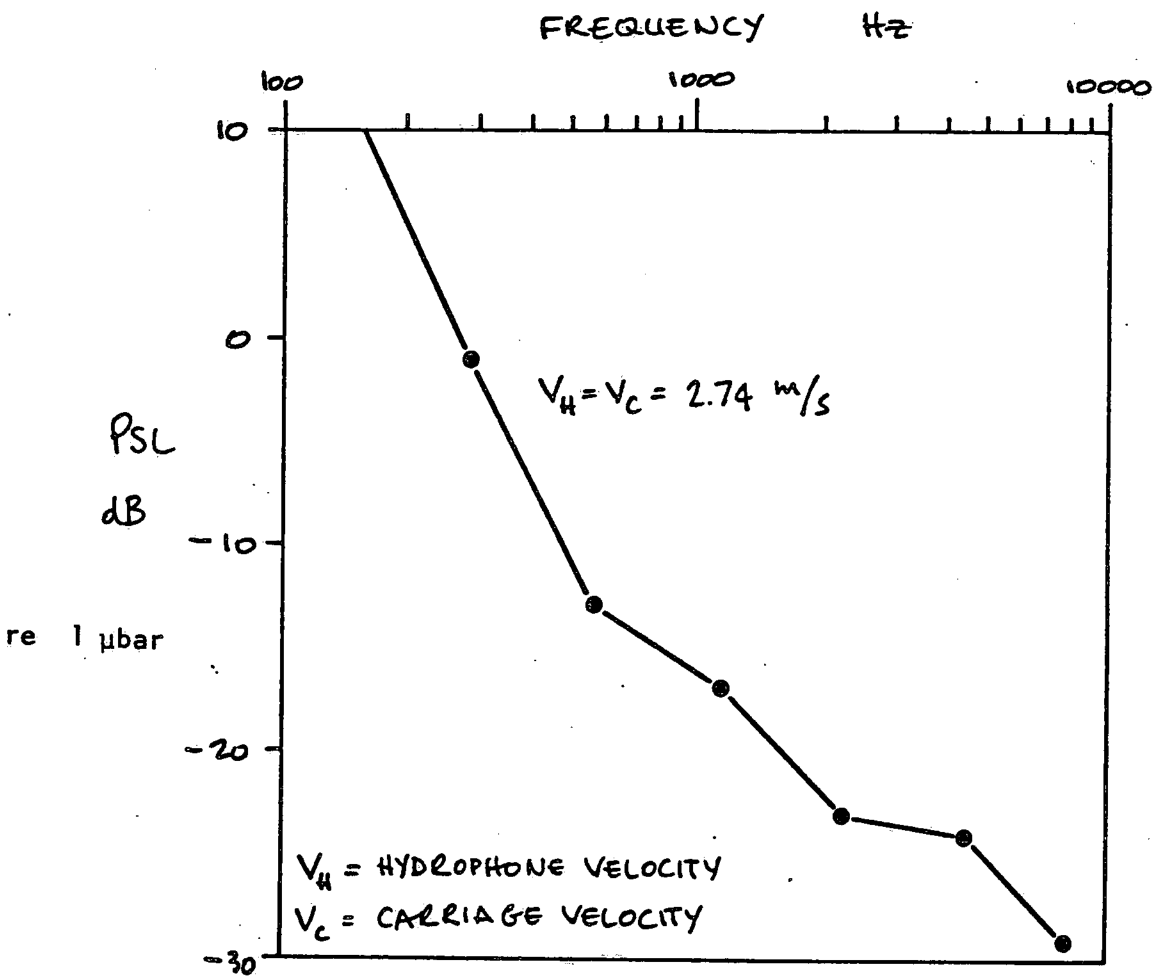


Figure 15. Calgary Towing Tank Noise Spectra - Ithaco Hydrophone.
(from Tywoniuk, 1971)

SUMMARY AND CONCLUSIONS

A series of experiments were undertaken to verify some theoretical aspects of impact generated noise in underwater environment. The results of the acoustic aspects of the study were intended for application in the development of a theoretical relationship between the noise generated by sediment particle collisions and the rate of bed-load transport.

All observations were made in still water with a free surface. Gravel collision noise was simulated by ceramic balls rolling under gravity on a bed of similar balls. The size of the moving and stationary balls was identical.

Observations were made using three different hydrophones, one of which was used for reference only. Recordings of the observed sound were made, at various times, on three types of tape recorders. Spectral analysis were made using one or one-third octave passband filters. All acoustic observations were made in terms of sound pressure levels (SPL) in decibels re 1 μbar.

From the results of the rolling pebble experiments the following was concluded:

1. SPL at a point in water due to noise generated by collision of pebbles increases with increasing number of rolling pebbles in accordance with the theoretical function applicable for the determination of total SPL by a number of separate and continuous sound sources provided, however, that the number of rolling pebbles is greater than 10 or 15.

2. The multiple source function is not affected by the width of the frequency passband in the calculation of total SPL from contributions by individual pebble collisions.

3. An equivalent one pebble generated SPL can be calculated from total SPL if the number of rolling pebbles exceeds 10 or 15.

4. With the instruments used,the frequency of pebble collisions above which the impact noise effects become unimportant and the sound assumes continuous characteristics was found to be about 50 Hz.

5. The acoustic directivity of the pebbles as sound sources appears to be omnidirectional or is averaged when multiple collisions take place.

6. A free field part of the far field was found to exist in the experimental environment up to about 1.5 m from the source.

7. The SPL generated by a collision is a function, among others, of the velocity of the pebble.

8. The ceramic pebbles generate a pressure spectrum which is continuous and has a maximum between 100 and 300 Hz.

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