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ACOUSTIC MEASUREMENT OF BED-LOAD

THEORETICAL FEASIBILITY ANALYSIS

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ACOUSTIC MEASUREMENT OF BED-LOAD

THEORETICAL FEASIBILITY ANALYSIS

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ABSTRACT

An idealized relationship between the rate of bed load transport and the sound pressure level generated by interparticle collisions and measured with an omnidirectional hydrophone located at a finite distance above the river bed is formulated. The transfer function shows the rate of bed load transport to be dependent not only upon the observed sound pressure level but also upon at least six other variables that must be determined independently of the acoustic observations.

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INTRODUCTION AND OBJECTIVES

At present there exists a great demand for a reliable bed-load measurement technique which would improve the accuracy of the existing methods, simplify field procedures and reduce survey costs. One of the possible new approaches is the measurement of bed-load by acoustic observations of the noise generated by river bed pebble collisions.

A collision of two elastic bodies induces a system of waves in each one which, under suitable conditions, are transmitted into the surrounding fluid as acoustic pressure waves. For short periods of time, before the impact generated vibrations become attenuated by internal damping mechanisms, the solid bodies act as sound sources and emit acoustic power which is dependent upon the force of impact and the mechanical properties of the solid.

The force of collision between two pebbles, one which is stationary, is largely a function of the rate of change of the momentum of the moving particle, and hence, its mass and velocity. The mass and velocity of the moving particles, however, are also the key factors which govern the rates of bed-load transport. This suggests the existence of a relationship between the acoustic power generated by interparticle collisions and the rate of bed-load transport.

Although the possibilities of the acoustic approach have been recognised long ago and the existence of a functional relationship between pebble impact noise and sediment transport has been indicated by experiment, no theoretical feasibility studies of the method have been reported to date. Previous studies, although of limited scope, have nevertheless identified some of the practical difficulties which have to be surmounted to ensure the feasibility of acoustic measurement of bed-load. The foremost among these is that the acoustic power of river bed pebbles cannot be measured directly, but must be determined by remote sensing of the sound waves transmitted through the water to the receiver.

As part of a general investigation of the acoustic bed-load measurement method, an attempt was made to develop an analytical model relating the rate of bed-load transport with some acoustic parameter measurable in a natural stream. An idealized model, based on general acoustics theory that was supplemented by experimental measurements to verify the applicability of the theory to impact generated underwater noise is developed and presented in this report.

The primary objective of this study was to establish a theoretical transfer function between the sound pressure levels generated by the collisions of rolling bed particles and the rate of bed-load movement. The transfer function was intended to serve in the assessment of the practical feasibility of the acoustic approach and to assist in the identification of other sediment for flow parameters to be established or measured in conjunction with acoustic observations for bed-load transport measurement.

MODELLING CONCEPTS AND ASSUMPTIONS

The development of the acoustic bed-load transport function was based upon a conceptual model designed to represent as realistically as possible the sediment movement and the behaviour of acoustic waves in underwater environment. However, because of the number and the diversity of variables, and the statistical nature of the sediment transport phenomena, certain idealizations were assumed and incorporated into the model.

The Physical Model

To formulate a relationship between the rate of bed-load transport, the position of the hydrophone in the flow and the positions of sound producing river bed pebbles relative to the hydrophone, a physical model, illustrated in Figure 1, was used.

In the model it is assumed that all particles are spherical and have a diameter D. The stationary pebbles on the river bed are arranged in concentric rings around a central pebble located on a common vertical and at a distance r_o (or n_d pebble diameters) below the acoustic centre of the listening hydrophone. The horizontal radius distance to the centre of any of the rings is R (or n_x pebble diameters).

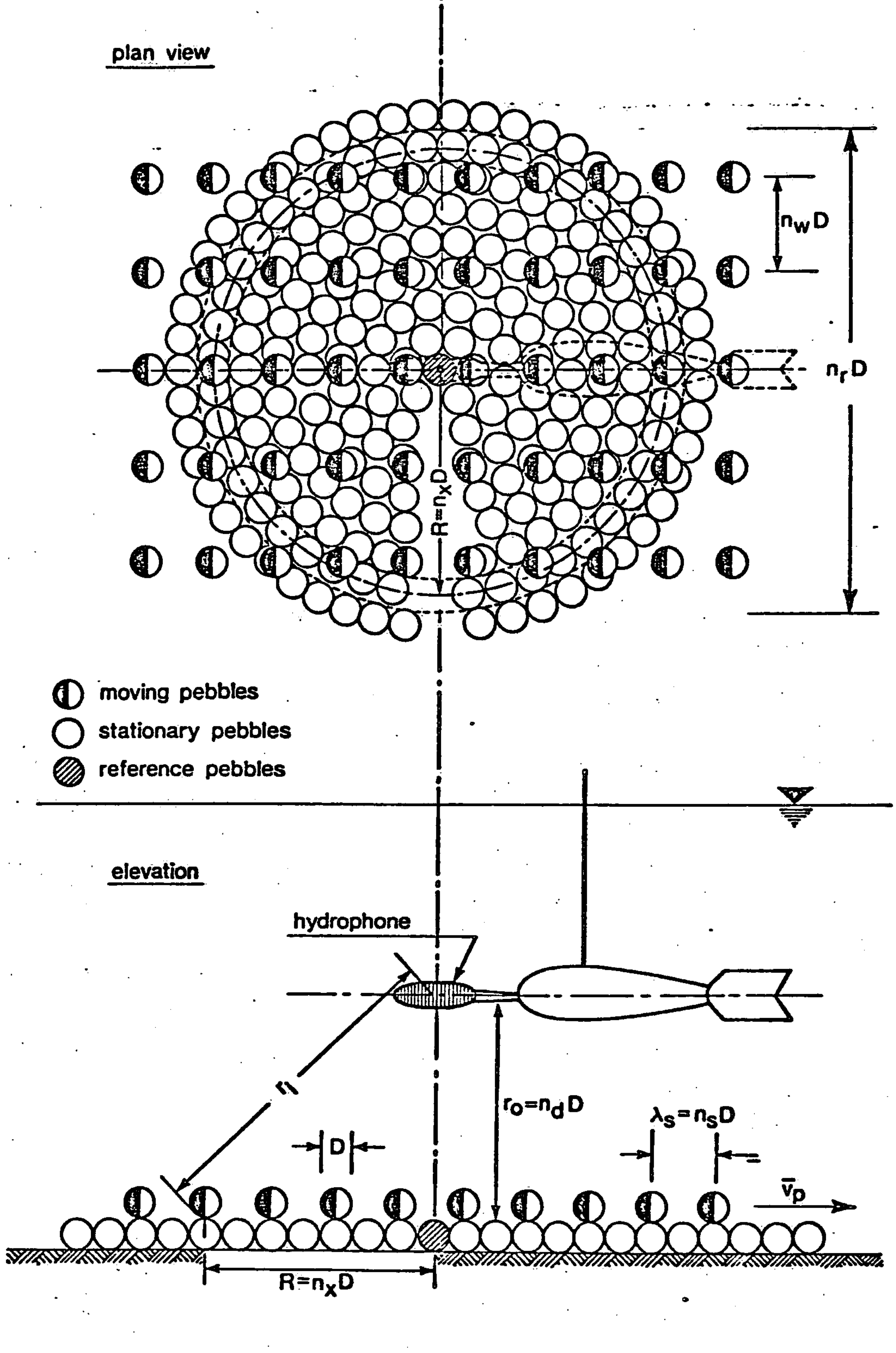

Figure 1 Pebble movement model.

The particles in motion above the stationary bed are arranged in rows spaced on the average, n_w particle diameters apart across the stream. The total width of a moving strip of bed-load occupies a width of n_r pebble diameters. In the direction of the movement, the particles in each row are spaced as λ_s or n_s pebble diameters. The average particle velocity is represented by $\bar{v}_p$.

The particles are assumed to move by rolling or by jumping over an integral number n_j of stationary bed pebbles. When movement is by rolling, n_j equals one. If the pebbles move by jumping, n_j is greater than one. A moving particle collides with an individual stationary particle in its path only once so that when the motion is by rolling, collisions occur with all consecutive particles. If jumping occurs, collisions take place, on the average, with every n_j th bed particle. The pebbles move in a layer one diameter deep.

Assumptions Related to Pebble Sound

The development of the acoustic bed-load transfer function is based upon the following assumptions:

1. Sound is generated by collision of moving particles with stationary particles only. It is considered that collisions between moving pebbles do not occur.

2. The location of a collision source is at the stationary bed particle.

3. All collisions generate equal acoustic power.

4. Collision generated acoustic power is a non-linear function of the average particle transport velocity.

5. The receiving hydrophone has omnidirectional characteristics.

6. The receiving hydrophone is located in the free field part of the acoustic far field.

7. Collision generated sound has continuous frequency spectrum characteristics.

8. Sound attenuation between source and receiver is due to non-directional wave divergence and is negligible because of turbulence, velocity gradients and temperature variations, etc.

9. Multiple collision source sound pressure levels are additive in the same way as continuous sources if the frequency of collisions exceeds 50 Hz.

10. Background noise levels do not mask pebble generated sound.

11. Moving and stationary pebbles are of identical size.

Assumptions 1, 4, 6, 7 and 9 are supported by experiments reported by Jonys (1975).

ACOUSTIC BED-LOAD TRANSPORT FUNCTION

Bed-Load Transport Relationship

In the transport model it is assumed that bed particles move downstream in rows separated by a distance λ_w, which can also be expressed by

$$\lambda_w = n_w D \tag{1}$$

where n_w = separation distance between rows (or the width of channel occupied by a row) in numbers of particle diameter D.

The rate of bed-load transport in the width λ_w can be given by

$$g_{ws} = f\ m \tag{2}$$

where f = the frequency of passage of the particles past a reference line, and

m = mass of one particle.

The mass of a spherical pebble can be expressed by

$$m = \rho_s \frac{\pi D^3}{6} \tag{3}$$

where ρ_s = density of particle.

The passage frequency f depends upon the average velocity of particles $\bar{v}_p$ and the spacing λ_s between particles in the direction of the movement as follows:

$$f = \frac{\bar{v}_p}{\lambda_s} \tag{4}$$

Substituting equation (4) into equation (2):

$$g_{ws} = \frac{m v_p}{\lambda_s} \tag{5}$$

from which the rate of transport per unit width of channel can be determined by dividing by λ_w:

$$g_s = \frac{g_{ws}}{\lambda_w} = \frac{m\bar{v}_p}{\lambda_s \lambda_w} = \frac{fm}{\lambda_w} \qquad (6)$$

Collision Frequency and Transport Rate

Because collision between stationary and moving bed particles is considered as the only sound generating mechanism, the frequency of collisions can provide a measure of the frequency of the particle passage past a stationary reference particle or a row of particles. The frequency of collisions with the specific reference particle, however, depends not only upon the frequency of particle passage but also upon the occurrence of impact. The occurrence of impact depends upon the length of the jump which the moving particles may experience between collisions.

The jump length λ_j between collisions can be expressed by

$$\lambda_j = n_j D \qquad (7)$$

where n_j = length of jump in number of particle diameters.

The average frequency f_c^1 of collisions with a reference bed particle in the path of a moving row of particles can then be estimated from

$$f_c^1 = \frac{f}{n_j} \qquad (8)$$

for a row of moving particles, contained in a width λ_w of the channel. The frequency of collision with any one of the stationary particles in the reference row perpendicular to the direction of motion is

$$f_c = \frac{f}{n_w n_j} \qquad (9)$$

which, substituted in equation (6) yields

$$g_s = f_c \frac{n_j m}{D} \tag{10}$$

Equation (10) expresses the relationship between the rate of bed-load transport per unit width of channel and the frequency of collisions with any one stationary bed particle.

Frequency of Collisions - SPL Relations

To express the relationship between the number of collisions and the total sound pressure level at a point above the bed, a concentric arrangement of the stationary bed particles in rings around the vertical axis passing through the observation point is employed. The total number of pebbles in any circular ring i located at a radius of N pebble diameters from the centre, can be estimated from

$$N_i = 2\pi N \tag{11}$$

When the width of the stream of moving particles is $n_r D$ and extends equal distances to both sides of the ring, and N is greater than $\frac{n_r}{2}$, the number of pebbles in the two segments of a ring i can be determined from

$$N_i = 2\pi N \left(1 - \frac{2 \cos^{-1}\left(\frac{n_r}{2N}\right)}{\pi} \right) \tag{12}$$

The total number of collisions per unit time in any ring or ring segment i can then be estimated from

$$F_i = f_c N_i \tag{13}$$

It has been demonstrated experimentaly by Jonys (1975) that if the frequency of sound producing collisions exceeds 50 Hz and all collisions occur at the same distance from the hydrophone, an equivalent sound pressure level SPL_{eq} due to one collision per second can be determined theoretically from equation (14):

$$SPL_{eq} = SPL^1 - 10 \log F^1 \qquad (14)$$

where SPL^1 = the observed sound pressure level generated by all collisions at a fixed range from the observation point, and

F^1 = frequency of noise contributing collisions.

Assuming that SPL_{eq} is a function only of the average velocity of particles, and hence, is a constant in a given flow situation, the sound pressure level contribution SPL_i at hydrophone location due to all collisions in a ring i at range r_i can be calculated from equation(15):

$$SPL_i = SPL_{eq} + 10 \log F_i - 20 \log\frac{r_i}{r_o} \qquad (15)$$

where r_o = the distance between the hydrophone and the bed of the river and is used as reference range.

The term $20 \log\frac{r_i}{r_o}$ represents the SPL attenuation due to wave divergence. Equation (15) can also be expressed in terms of f_c and N_i:

$$\frac{SPL_i}{10} = \frac{SPL_{eq}}{10} + 2 \log r_o + \log \frac{f_c N_i}{r_i^2} \qquad (16)$$

The total SPL at hydrophone location is determined by addition of the squares of the rms pressures due to contributions from each of the pebble rings. Since

$$SPL_i = 20 \log \frac{P_i}{P_o} = 10 \log \frac{P_i^2}{P_o^2}$$

$$\frac{P_i^2}{P_o^2} = \text{antilog} \frac{SPL_i}{10} = 10^{SPL_i/10} \tag{17}$$

where p_i = rms sound pressure due to collisions in ring r_i, and

P_o = reference pressure of 1 μ bar

An expression for the total sound pressure can then be obtained from

$$\frac{P_T^2}{P_o^2} = \sum_{i=1}^{i=k} \frac{P_i^2}{P_o^2} = \sum_{i=1}^{i=k} 10^{SPL_i/10} \tag{18}$$

or in terms of SPL by

$$SPL = 10 \log \frac{P_T^2}{P_o^2} = 10 \log \sum_{i=1}^{i=k} 10^{SPL_i/10} \tag{19}$$

where k = the number of noise contributing pebble rings .

Substituting SPL_i from equation (16) into equation (19) an expression for the frequency of collisions with any one stationary bed pebble is given by equation (20):

$$f_c = \frac{10^{SPL/10}}{r_o^2 \cdot 10^{SPL_{eq}/10} \cdot \sum_{i=1}^{i=k} \left(N_i / r_i^2 \right)} \tag{20}$$

Sediment Transport Transfer Function

The transfer function between the observed SPL and the rate of bed-load transport is obtained by substituting equation (20) into equation (10):

$$g_s = \frac{m\, 10^{SPL/10}}{r_o^2\, D} \cdot \frac{n_j}{10^{SPL_{eq}/10} \sum_{i=1}^{i=k} \left(N_i / r_i^2 \right)} \qquad (21)$$

NUMERICAL SIMULATION

To show how the various factors affect the acoustic measurements of pebble generated noise, equation (20) was programmed for numerical simulation by computer. The parameters which were investigated were the distance of the hydrophone to the river bed, the aerial concentration of moving pebbles, the effect of particle saltation and the influence of the average particle velocity.

Hydrophone Range Effect

The effect of the distance of the moving bed from an omnidirectional hydrophone upon the observed SPL is illustrated in Figure 2. The curves represent the computed SPL values due to all collisions contained in an area of river bed defined by a radius of N pebble diameters. The rates of bed-load transport g_s are the same for all curves and were calculated assuming identical SPL_{eq}, and $n_j = n_s = n_w = 1$. The distance of the hydrophone to the bed for the B curves was four times greater than for the A curves.

Curves A and B represent the variation of SPL due to collisions up to a radius of N = 400D, for a total width of the moving strip of bed load of 800D. Curves A^1 and B^1, diverging from A and B at N = 20D, represent calculated SPL when the moving strip of bed-load is only 40D wide.

When $N = D$, the difference in SPL between the two curves for ranges r_A and $r_B = 4r_A$ is 12 dB. However, as SPL increases with N, the difference between the calculated SPL decreases and at $N = 400D$ is reduced to approximately 2 dB. This is because relative to the SPL produced by the pebble directly below the hydrophone, the same pebble ring contributes more sound to the hydrophone further away from the riverbed. If the hydrophones are at r_A and at $r_B = 4r_A$ from the bed and if the ranges of the hydrophones to a ring i of radius N_iD are r_A^1 and r_B^1 respectively, the ratio r_A^1/r_A will always be greater than r_B^1/r_B. Because sound attenuation due to divergence from the source is determined by this ratio, relatively more sound will be attenuated to the lower hydrophone location. This result is of practical significance because the placement of omnidirectional hydrophones at different distances from the river bed for identification of near bed noise may not be useful for large widths of moving pebbles.

For a limited strip width of moving particles, represented in Figure 2 by curves A^1 and B^1, the SPL contributions from the distant ring segments become negligible by a combined effect of distance attenuation and a constant number of collisions as the ring radius increases. Hence, the SPL rapidly approach saturation values. However, the difference of 5 dB between the two curves A^1 and B^1, shown in Figure 2, represents a specific case and would vary depending upon the width of the moving gravel strip.

The Effects of Aerial Concentration and Saltation of Pebbles

The influence of the aerial concentration of the moving particles, represented by values n_s and n_w, and the effects of the length of particle jump n_j, are illustrated in Figure 3. Theoretical prediction of SPL was made for four different n_j, and four aerial concentrations ranging from 1 when the lateral and transverse distances between the pebbles is zero or $n_s = n_w = 1$, to an areal concentration of 1/64 when $n_s = n_w = 8$. SPL_{eq} for all calculations was assumed to be constant and the width of the moving stream of particle was chosen to be 40D. The results show that for any constant n_j, doubling of the rate of transport g_s corresponds to an increase of 3 dB in SPL. Similarly, when the particles begin to saltate, any doubling of the jump length decreases the SPL by 3 dB for the same rate of transport.

Forces of Collision and Saltation Effects

The effects of the force of interparticle collision and of aerial concentration of the moving particles, for movement without saltation ($n_j = 1$), are illustrated in Figure 4. On the basis of physical arguments and experimental evidence presented by Jonys (1975) it was assumed that the equivalent one collision sound pressure level is a nonlinear function of the average particle velocity $\bar{V}_p$ and can be represented by equation (22):

$$SPL_{eq} = C_1 - C_2 \left(\log \bar{V}_p + C_3\right)^2 \tag{22}$$

The function is a logarithmic parabola, which depending upon the values of the constants C_1, C_2 and C_3, gives a rapid increase in SPL_{eq} at low $\bar{V}_p$ followed by a gradual decrease in SPL_{eq} as $\bar{V}_p$ increases. For the numerical simulation, the values of the constants were obtained from experimental data with 40 mm diameter ceramic spheres ($C_1 = 50$, $C_2 = 0.85$, and $C_3 = 36$) yielding $SPL_{eq} = 0$ at $\bar{V}_p = 0.01$ m/s and a maximum $SPL_{eq} = 50$ for $\bar{V}_p = 0.141$ m/s.

The simulation results, presented in Figure 4, illustrate that a wide range of SPL values can be observed for the same rate of transport depending upon the values of $\bar{V}_p$. Conversely, large errors in estimation of g_s can be incurred from SPL observations if no consideration is given to the SPL_{eq}.

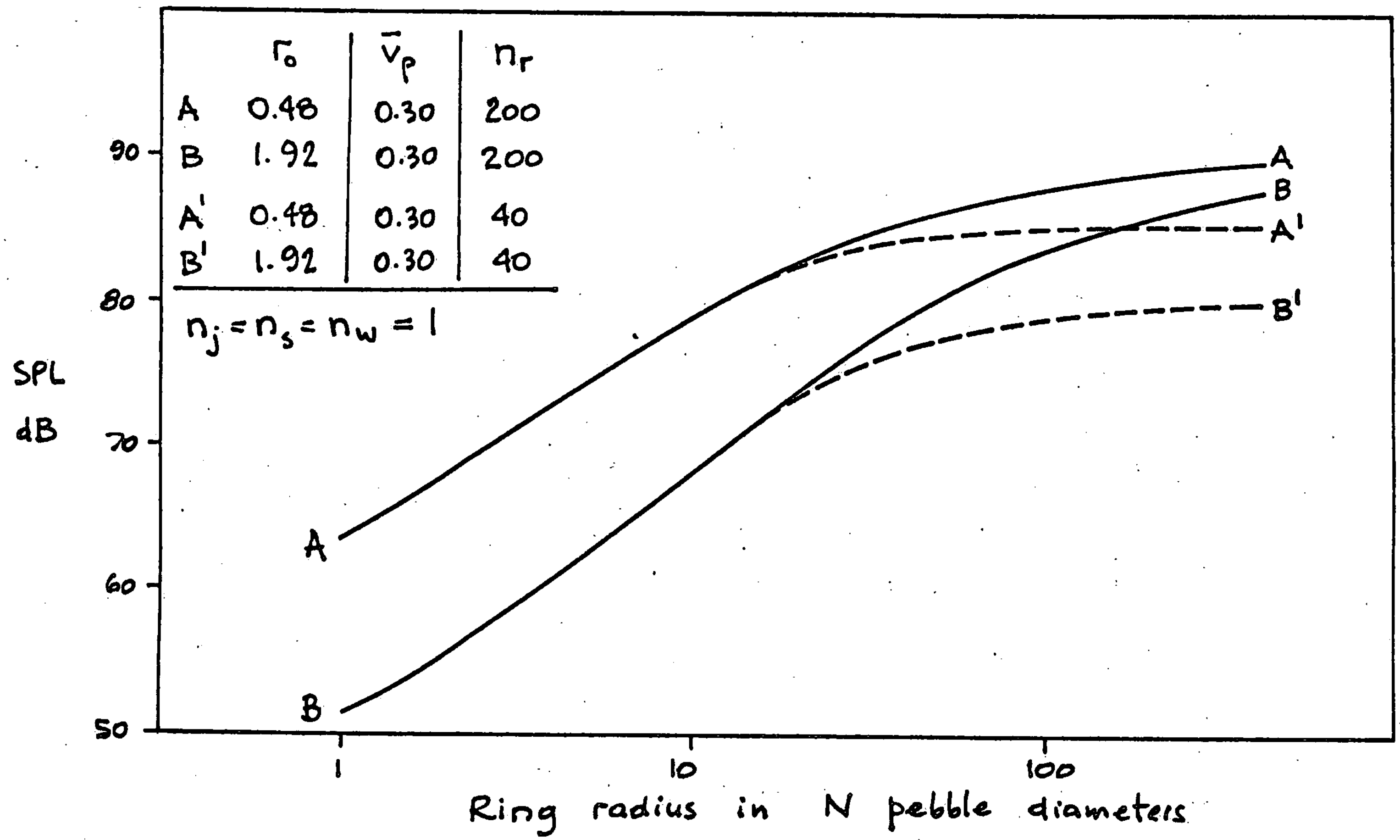

Figure 2 SPL variation with distance of hydrophone from the bed, and width of moving bed.

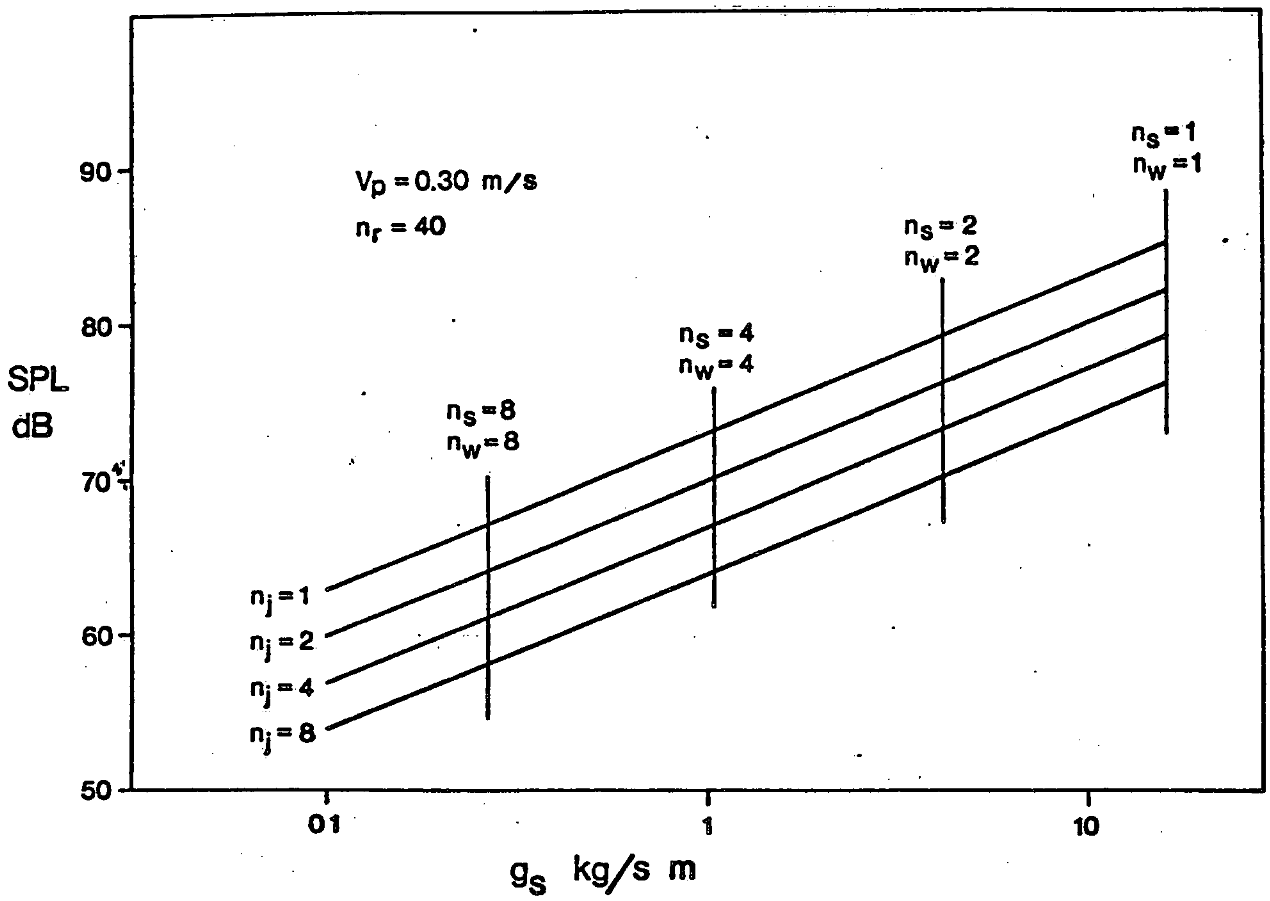

Figure 3 SPL - g_s variation for different pebble jump lengths and different aerial concentrations.

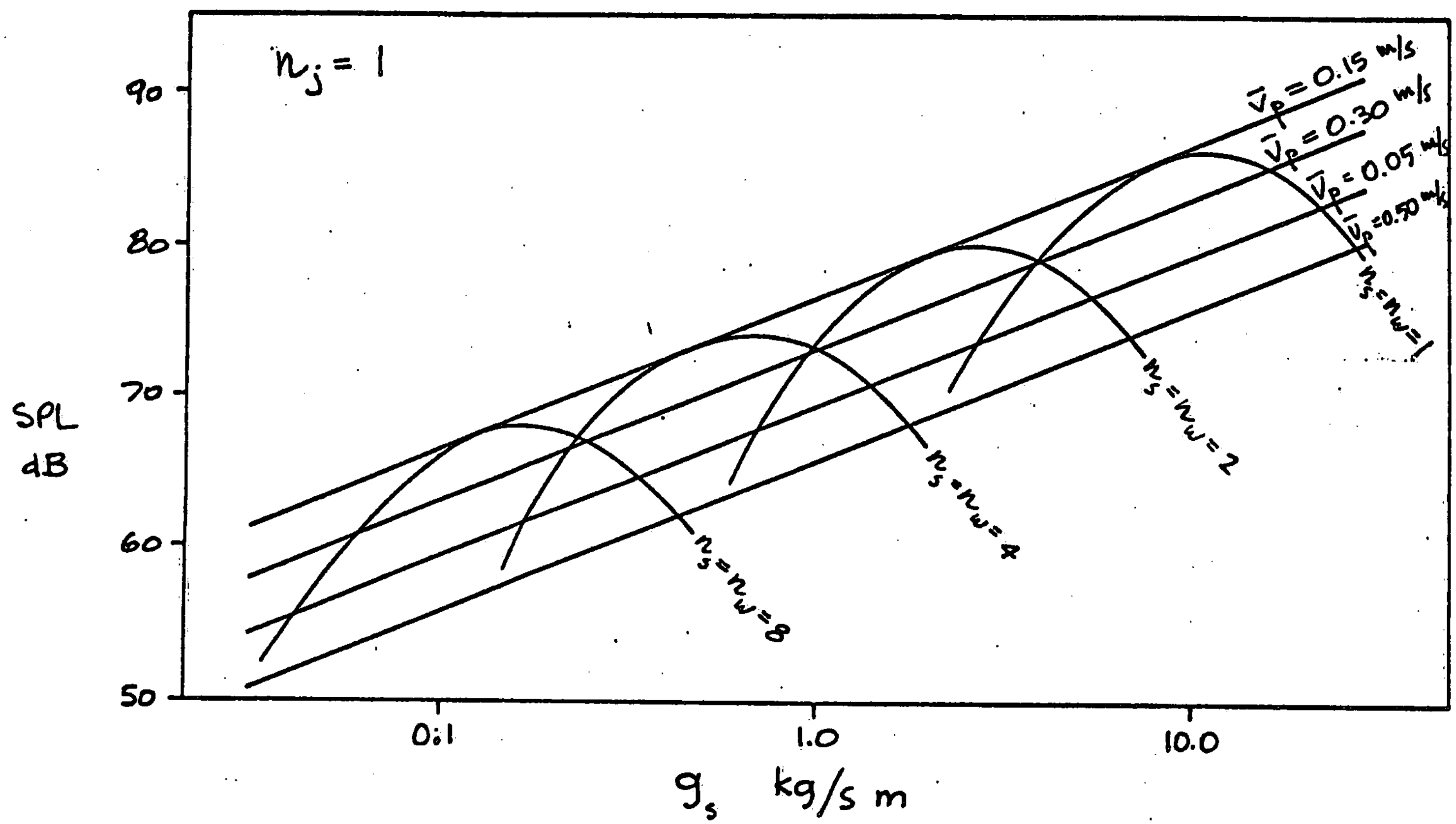

Figure 4 SPL - g_s variation for different pebble velocities and aerial concentrations.

DISCUSSION AND ANALYSIS

The results of the numerical simulation of the theoretical bed-load transfer function show the limitations of the general SPL measurement approach used in the present investigation. It can be seen that without consideration of the physical transport conditions, SPL observation of the bed pebble noise can represent a large range of bed-load transport rates.

The transfer function, presented in equation (21) shows that even in an idealized model, the prediction of bed-load transport rate g_s depends upon seven variables. In a field situation, the number of these variables is even larger to account for the variability of bed particle characteristics and their distribution on the riverbed. At present, of the seven independent variables required to determine g_s, only four can be measured or controlled. These include the SPL and the distance of the hydrophone from the river bed r_o which can be set by the observer. It is also possible to obtain samples of bed material and to measure the mass m and the characteristic dimensions D of the pebbles.

There are at present no means to determine the degree of pebble saltation represented by the jump length n_j, or the aerial extent of the moving stream of bed-load measured in equation (21) by the index k. Most importantly, the level of sound generated by a collision SPL_{eq}, and providing a measure of the acoustic power radiated by a pebble, cannot be measured in a river.

A reduction of the number of the unknown variables may be possible in some situations. For example, it might be possible to confirm visually that the movement is by rolling only, thereby establishing that $n_j = 1$. Perhaps it may be possible to determine the average velocity of the moving pebbles $\bar{V}_p$ and by reproducing the movement of a sample of pebbles in a laboratory to establish the characteristic level of collision sound SPL_{eq}. Finally, with the use of a directional hydrophone an attempt could be made to observe pebble collision sound originating from a finite area of river bed, thereby determining the value of the index k.

SUMMARY AND CONCLUSIONS

A relationship between the rate of bed-load transport with the level of sound generated by interparticle collisions of moving pebbles was formulated. It represents a general case in which the acoustic information is provided by the measurement of sound pressure level (SPL) at a finite distance in the flow above the bed of a river with an omnidirectional hydrophone

The relationship shows that the rate of bed-load transport is a function of at least seven independent variables which, in addition to the measured SPL, are the size and mass of the bed pebbles, the position of the hydrophone relative to the river bed, a measure of particle saltation, the aerial extent of the moving bed, and the average acoustic power generated by a single collision between a moving and a stationary particle.

Because in practice the saltation of the pebbles, the aerial extent of the stream of the moving bed and the acoustic power generated by the pebbles, cannot be readily measured, the acoustic observation approach of bed-load measurement employed throughout this investigation, must be considered to be non-feasible at the present time.

REFERENCES

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