Prediction of Crowd Noise

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ABSTRACT

The prediction of crowd noise is a problem faced by acoustic consultants. Although consultants are frequently required to predict noise emissions from activities involving crowds of people, there are no prediction methodologies available. This paper discusses the factors influencing crowd noise with the aim of encouraging discussion about how the problem of predicting crowd noise can be overcome. Some simple analysis is presented to show how different situational factors and crowd characteristics influence the noise emitted by a crowd. Four major factors were found to influence the noise level generated by a crowd of people; an individual's voice effort, the total number of people, whether the source is synchronous or random in time and whether the crowd is directional or has a diffused orientation.

INTRODUCTION

The prediction of noise from crowds is a problem faced by acoustic consultants. Even though consultants are frequently required to predict noise emissions from activities involving crowds of people, there are no prediction methodologies available. The usual approach taken in this instance is to measure noise from a crowd similar to that expected at the proposed facility, and use the results to determine the noise amelioration measures required.

The validity of such an approach will depend on the degree of similarity between the tested crowd and the situation to which the test data is to be grafted. It is rare to be able to find an exact match and it becomes necessary to compromise. For example, it might be necessary to test a smaller crowd and extrapolate the data to greater numbers of people. Equally, it might be difficult to find a crowd of 50,000 people at an outdoor rock concert, so the next best approximation is a football crowd.

The difficulties and uncertainties attached to the testing of a substitute example can be clearly seen in the records of court cases involving opposing noise experts. In such cases, differences of opinion can be frequently distilled down to differences in the original source data on which these opinions have been based. It results in a less than ideal outcome for courts and the community if noise experts cancel each other out of consideration because of erroneous or irrelevant source data.

The authors propose that it should be possible to develop a workable scientific model to predict crowd noise, in much the same way as traffic noise is modelled. As with traffic noise, crowd noise also involves a number of factors. Instead of variables such as vehicle numbers, traffic composition, speed etc, crowd noise has a unique set of variables which enable any crowd situation to be described and quantified.

This paper is a work in progress. It raises more questions than it answers. Its purpose is to stimulate discussion which can ultimately assist in reaching the goal of producing a rigorous and validated model for predicting crowd noise. The purpose of this paper is to examine the factors which influence crowd noise and to suggest some embryonic algorithms to be incorporated into the model.

EXISTING STUDIES

There has been no published research regarding the prediction of crowd noise. Acoustic consultants have relied on measuring noise at a similar type of facility, as presented in the noise impact study for the Main Arena of the 2008 Olympic Equestrian Event prepared by Ove Arup & Partners Hong Kong Ltd (2005).

That study and others like it have used a variety of descriptive parameters to characterise the noise emissions from crowds. For example, Evans (1990) presented data based upon the L_{eq} and L_{DN} parameters, while the City of Seattle (2002) used the L_{25} and L_{max} parameters to describe emissions from sporting events.

A summary of the typical noise levels stated in these noise impact studies is presented in Table 1. In most instances, the number of people undertaking the activity in question (players and spectators) was not given. The noise levels and measurement parameters used to describe the noise emissions from an activity also vary appreciably.

These studies have presented several observations with respect to the character of crowd noise. For example, the Brooklyn Bridge Park Development Corporation (2005) stated that 'another aspect of crowd noise is that it is usually quite intermittent. People do not cheer continuously at gatherings. Rather, the cheers surge and drop during event conditions'. A similar observation was noted by Evans (1990), who stated that even though L_{Aeq} and L_{Amax} are considered to be good descriptors of crowd noise, this type of noise can have a nearly instantaneous increase and decrease in volume. This is different from other intermittent environmental noise impacts such as aircraft flyovers or rail noise, as these sources have a gradual rise and fall in their noise levels.

These observations suggest that crowd noise cannot be encompassed by a single noise parameter and that multiple descriptive parameters may be required to adequately quantify crowd noise.

When assessing crowd noise, the comments by Evans (1990) imply that an adjustment of +5dB should be used to account for the impulsiveness of the noise source. This would be consistent with established practice and may be applicable when considering the crowd roar which erupts during periods of excitement at major sporting events.

Table 1. Summary of typical noise levels from crowds

Source	Measurement Parameter	Value @ Distance
Youth Baseball	L_{25}	52dB(A) @ 30m
Practice[1]	L_{max}	68dB(A) @ 30m
Youth Baseball	L_{25}	52dB(A) @ 30m
Game[1]	L_{max}	68dB(A) @ 30m
Adult baseball	L_{25}	52dB(A) @ 30m
Game[1]	L_{max}	68dB(A) @ 30m
Youth Soccer	L_{25}	52dB(A) @ 30m
Practice[1]	L_{max}	68dB(A) @ 30m
Youth soccer	L_{25}	52dB(A) @ 30m
Game[1]	L_{max}	68dB(A) @ 30m
Adult Soccer	L_{25}	52dB(A) @ 30m
Game[1]	L_{max}	68dB(A) @ 30m
Softball Game[2]	L_{max}	70dB(A) @ 105m
Baseball	L_{50}	58dB(A) @ 83m
Game[3]	L_{max}	72dB(A) @ 83m
Football	L_{eq}	65dB(A) @ 120m
Stadium[3]	L_{50}	60dB(A) @ 120m
	L_{max}	79dB(A) @ 120m
Crowd of 200 Cheering[4]	Unknown	75dB(A) @ 90m

Source: ([1]City of Seattle (2002), [2]County of Sacremento (1998), [3]Brown-Buntin & Associates (2005), [4] Brooklyn Bridge Park Development Corporation (2005))

DESCRIPTIVE PARAMETERS FOR CROWD NOISE

Before an attempt can be made to predict crowd noise, it is necessary to select the most appropriate descriptive parameter(s). As stated previously, studies have suggested that more than one noise parameter is required to adequately describe crowd noise.

In complaints about crowd noise, complainants are not necessarily consistent in the way that they describe the intrusiveness of the noise. In some instances, the complaint is with the *constant unescapable babble* but in other cases, the disturbance is caused by *frequent loud intrusive noises*. Clearly crowd noise can be both of these.

Crowd noise can therefore be considered to consist of two components:
1. A babble due to multiple, simultaneous, random conversations; and
2. Transients due to events such as people laughing, yelling or cheering.

The first component would typically be represented by L_{eq} parameter. This parameter is considered appropriate as the babble component of crowd noise is quasi-steady with random but minor variability as the number of people talking at any instant changes. An energy-average across these peaks and troughs would give a fair representation of the babble component to be expected from a crowd.

Finding an appropriate measurement parameter for the transient noise peaks presents more of a problem. There is a temptation to apply a statistical measurement parameter (L_N). However, experience has shown that the appropriate percentile (N) varies considerably between different types of crowd. For example, for a crowd of around 200 people at a hotel, the typical transient noise event could be approximated by an L_{10} reading. Whereas for a crowd of 40,000 at a football match, synchronised cheering events would be closer to L_{01}.

To avoid unnecessary complication at this early stage of development, it is considered appropriate to use the average maximum level ($_{ave}L_{max}$) to quantify the crowd transients.

To adequately predict the noise emissions from a crowd, expressions are therefore required for both the L_{eq} and $_{ave}L_{max}$ components.

FACTORS INFLUENCING CROWD NOISE

To derive an expression to predict crowd noise, it is first necessary to determine all of the factors which have an influence.

A schematic diagram of the factors influencing the sound power level of a crowd are shown in Figure 1. It can be seen in this figure that four main factors are proposed:
1. An individual's voice effort, K_E;
2. The total number of people in the crowd, K_N;
3. Whether the source is synchronised or random with time, K_T; and
4. Whether the crowd is directional or has a diffused orientation, K_D.

The type of activity (ie: sporting, social, formal) influences an individual's voice effort, whether the crowd is synchronised or random in time and the directional orientation of the noise. The overall source sound power for a crowd is therefore a function of these variables, ie:

$$L_{WA\ (crowd)} = f\left(K_E,\ K_N,\ K_T,\ K_D\right) \quad (1)$$

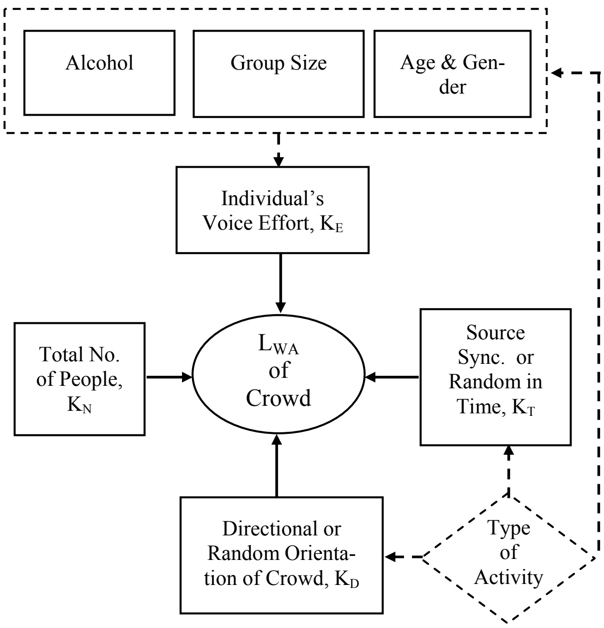

Figure 1. Factors influencing crowd noise

Individual's voice effort

An individual's voice effort, K_E, primarily depends on the situational factors of the crowd. All crowds are made up of smaller groups of people who directly interact with each other. Within this small group, factors such as the background noise level, number of people in the grouping, age, gender and alcohol all contribute to an individual's voice effort. An example of this is the investigation by Pearsons et al (1977), which showed that the voices of men shouting a sentence were around 7dB higher than the voices of women. The noise from a crowd consisting entirely of males would therefore be expected to be louder than that of an equivalent crowd of females.

Conversely, if you observe a mixed group of young people, particularly where alcohol is involved, the females would normally be found to dominate the transient noise emissions. Based on the observations of the authors, it is concluded that group size, age, gender and alcohol all influence noise emissions. However, more work is required to isolate and quantify the effects of each of these factors.

Another obvious and important factor affecting voice effort is the level of background noise. As a crowd increases in size, the babble or background component also increases. To maintain communication with others in the group, the individual's voice effort increases. The increased effort appears to apply to noise transients such as laughter and exclamations as well as the conversational component.

Lazarus (1986) presented equivalent sound levels at a distance of one metre from the speaker's mouth for different vocal efforts. These sound levels are presented in Table 2. Lazarus found that people tended to speak more quietly in private quarters where the rooms were smaller and more sound absorbing, the speaker-hearer distance is shorter and the ambient noise levels are lower. He determined that in general, only speech levels greater than raised normal speech (60dB(A)) would normally be expected in public places and workplaces.

Lazarus (1986) also conducted a review of research into voice effort at different ambient noise levels. The voice efforts from 11 different articles were normalised to a distance of one metre from the mouth and plotted against ambient noise. He found that a range of 20dB existed between different voice efforts for nominally the same ambient noise level. This difference was attributed to variances in the recognition words used and the different types of ambient noise.

Lazarus found that the voice effort varies according to ambient noise. For background conditions exceeding around 45dB(A), the required voice effort increases by approximately 0.6dB per 1dB increase in ambient noise level. The required voice effort in L_{WA} is shown plotted against the background noise level in Figure 2.

Table 2. Equivalent sound levels of speakers at a distance of 1m from the speaker's mouth for indicated vocal efforts

Voice Effort	Average Speech Level (dB(A))
Whispering	36
Soft Speaking	42
Relaxed Speaking	48
Relaxed Normal Speaking	54
Raised Normal Speaking	60
Raised Speaking	66
Loud Speaking	72
Very Loud Speaking	78
Shouting	84
Maximal Shout	90
Maximal Shout (Individuals)	96

Source: (Lazarus (1986))

An interesting outcome of the Lazarus finding is that the voice effort does not increase to maintain a constant signal to noise ratio (which would imply a slope of 1dB/1dB). This is again consistent with observations. As the crowd noise increases, individuals do their best to communicate above the noise. But eventually their voices become drowned out by the background noise and they resort to speaking closer to the receiver's ears.

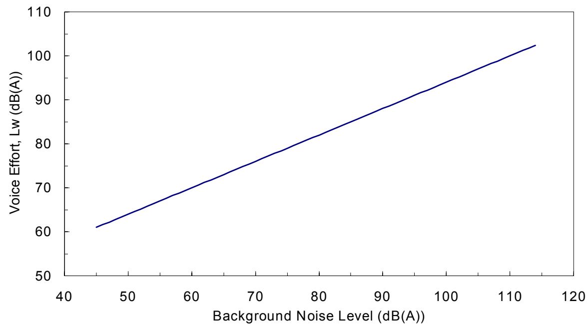

Figure 2. Variance of voice effort with background noise level (Source: Lazarus (1986))

An individual's voice effort is dependent on the background noise level, which is in turn dependent on the type and size of crowd. For example, a person at a funeral would require less voice effort to communicate with nearby individuals than a person at a football match.

The background noise level associated with each different type of crowd and crowd size is presently being determined through measurements. Two measurement techniques have been developed to accomplish this as presented later in this paper.

Number of people

Based on first principles, it would be expected that as the crowd size increases, the sound power level would increase logarithmically, ie:

$$K_N \propto 10 \log N \qquad (2)$$

where N is the total number of people in the crowd.

Initial test data would suggest that this relationship generally holds for the quasi-steady or babble component of crowd noise and also for events which occur in unison such as cheering at a football match. However, it does not hold for random transient noise peaks such as might occur in a crowd in a hotel or club.

Random or synchronised crowds

A random crowd is one in which there is no unifying influence. It would normally consist of a number of sub-sets or groups such as table groupings at a restaurant or groups of two or more at a hotel or social gathering. The identifying characteristic of such a crowd is that each group behaves independently and thus the resulting noise output is random.

A synchronised crowd is one which has some outside influence which can control and unify the noise emissions. Such influences include sporting events where crowds may cheer in unison in response to some spectacular occurrence. Concert crowds also unify at times of acclamations. A normally random crowd such as a crowd of club patrons can also produce a unified response if there is an important sporting event on a video screen.

Whether a crowd is random or synchronised will affect their noise output. However the most influence is on the peak transient events which are quantified by the $_{ave}L_{max}$ parameter.

The relationships between the $_{ave}L_{max}$ and L_{eq} parameters for different crowd sizes are qualitatively shown in Figure 3. The babble component (L_{eq}) is essentially the same for both random and synchronised crowds as shown by the solid line which increases according to the $10 \log N$ relationship.

For the random crowd, the transient noise events ($_{ave}L_{max}$) are initially above the L_{eq} at low crowd numbers, but increase at a lower rate which is consistent with the Lazarus findings. Eventually the transients for a random crowd become swamped by the babble at crowd sizes around 200 to 500 people whereafter you tend only to hear the babble with no discernable individual outbursts.

For the synchronised crowd, the unified cheers are much louder than the transient outbursts of the random crowd and also increase at a rate proportional to $10 \log N$.

The appropriate values of the y-axis intercepts C1, C2 and C3 and the gradient of the $L_{max\ (random)}$ line are still the subject of investigation.

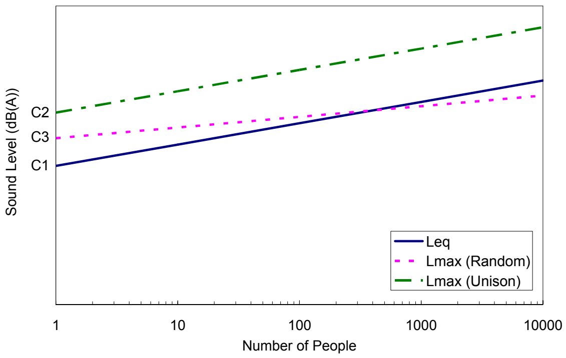

Figure 3: Difference in the L_{max} noise level due to the crowd being random or in unison

Directional or diffused orientation

Each individual making up a crowd will have his or her own orientation with respect to the receiver. This orientation will range from directly facing the receiver ($\theta = 0^o$) to facing directly away from the receiver ($\theta = 180^o$). Overall, every member of a crowd could face the same direction at a certain angle to the receiver, or each member could have a random orientation.

To determine the influence of the direction an individual faces in a crowd, a theoretical study has been undertaken, based upon the directivity and average speech spectrum of the human voice.

The directivity of the human vocal source has been examined in the horizontal plane as this is considered to be the most important directivity for crowd noise. Measurements of sound pressure level emanating from the mouth have been made at different azimuths by researchers such as Dunn and Farnsworth (1939), Moreno and Pfretzschner (1979) and Studebaker (1985). An average of these results has been used to determine the directivity of the human vocal source across the 250Hz to 8kHz frequency bands as presented in Figure 4. In this figure, 0^o azimuth corresponds to the individual directly facing the receiver. The values for 45^o, 90^o, 135^o and 180^o are referenced back to the level measured at 0^o azimuth.

The directivity of an individual depends not only on the directivity of the human vocal source, but also on the speech spectrum. Each individual would be expected to have a different speech spectrum depending on their age, gender and vocal effort. In this instance, the long-term average speech spectrum presented by van Heusden, Plomp and Pols (1979) has been used as presented in Figure 5. This is similar to the spectrum found by Lazarus (1986) for a "normal to raised voice".

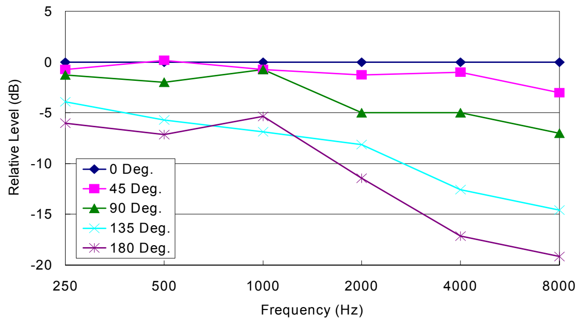

Figure 4: Directivity of the human vocal source (Source: Studebaker (1985))

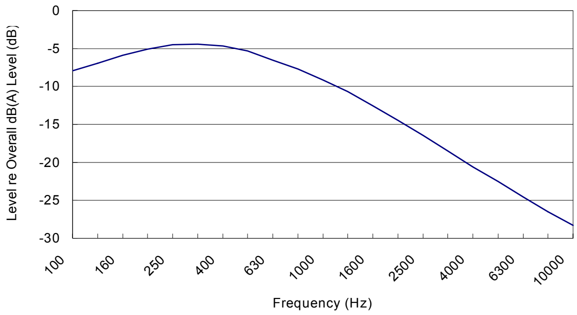

Figure 5: Long-term average speech spectrum (Source: van Heusden, Plomp and Pols (1979))

Using the data presented in Figures 4 and 5 a Matlab program has been written to calculate the variance in sound pressure level experienced at a receiver for different crowd orientations. The scenarios considered were:

1. All members of the crowd directly facing the receiver (0^o azimuth);
2. All members of the crowd facing 45^o to the receiver;
3. All members of the crowd facing 90^o to the receiver;
4. All members of the crowd facing 135^o to the receiver;
5. All members of the crowd facing 180^o to the receiver;
6. Random orientation of the crowd members.

The effect of all crowd members facing a certain direction is presented in Figure 6. The values are relative to the noise level at the receiver if all crowd members directly faced it. It can be seen in this figure that for a crowd facing $\pm 45^o$ to the receiver the noise level at the receiver would be approximately the same as if the crowd was directly facing the receiver. If the crowd was positioned $\pm 90^o$ to the receiver, an adjustment of approximately –2dB would be required, while adjustments of approximately –6dB and -7dB would be required for a crowd $\pm 135^o$ and 180^o to the receiver, respectively.

To determine the effect of a crowd consisting of individuals with a random orientation, the random number generator in Matlab was used to generate different sized crowds of people with random orientations. The overall sound level produced by these crowds were then simulated 1,000 times and an average taken of these levels. These averages across crowd sizes from 10 to 10,000 people are presented in Figure 7, along with the 95% confidence limits. It can be seen in this figure that a difference of approximately –3dB relative to the noise level at the receiver if all crowd members directly faced it.

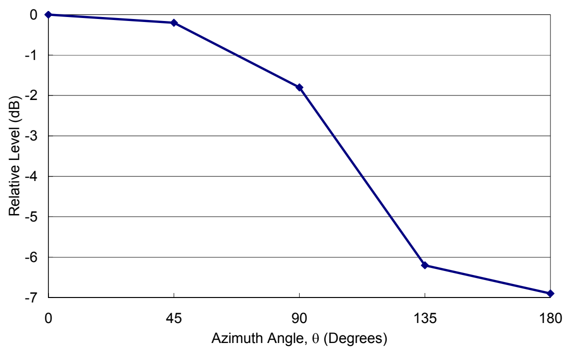

Figure 6: Effect of crowd orientation (all members facing the same direction)

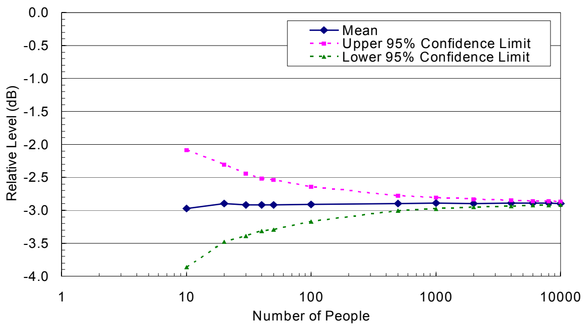

Figure 7: Overall sound level from a crowd with a random orientation of individuals

MEASUREMENT OF CROWD NOISE

To determine how factors such as an individual's voice effort, the number of people and whether the source is random or in unison effect crowd noise, two measurement techniques for crowd noise have been implemented by the authors. These techniques are based upon reverberation measurements and free-field measurements.

Reverberant field measurements

The sound pressure level of a crowd can be measured by taking a time and space average of a crowd inside an enclosed space such as a restaurant, hotel or refectory. The sound power can then be calculated using the equation (Bies & Hansen 2003).

$$L_W = L_p - 10\log_{10}\left[\frac{D_\theta}{4\pi r^2} + \frac{4}{R}\right] \tag{3}$$

where D_θ is the directivity factor, r is the room radius and R is the room constant.

Assuming a reverberant field only, $D_\theta = 0$ and the first term inside the brackets of equation 3 disappears. To find R, reverberation time measurements along with measurements of the room surface area and volume can be substituted in Sabine's reverberation time equation to find the total mean absorption coefficient for the room, $\overline{\alpha}$. This coefficient can then be substituted into the equation

$$R = \frac{1-\overline{\alpha}}{S\overline{\alpha}} \tag{4}$$

where S is the surface area. The value of R needs to be adjusted to account for the additional absorption provided by people inside the room. In this instance, the values of average absorption per person presented in Ver and Beranek (2006) have been used.

Although this technique can be used to measure the sound power of a crowd, unless the microphone is kept a distance greater than the room radius (approximately 3m) away from an individual speaker, the direct sound component will also be measured. Practicalities of room design mean that in most cases, the microphone will be in the direct field of individual speakers. Therefore, this technique is unsuitable for measuring the L_{Amax} level of a crowd and should only be used to measure the L_{Aeq} level over a long time period.

Free-field measurements

Free-field measurement of crowd noise is simpler than reverberation field measurements. Additionally, it is possible to measure booth the L_{Amax} and L_{Aeq} levels if the measurements are made in the far-field.

The measured sound pressure levels can be converted into sound power using the equation

$$L_W = L_p + 20\log_{10} d + C \tag{5}$$

where the constant $C = 8$ for a hemispherical source or $C = 5$ for a quarter sphere source and d is the distance from the source to the measurement positions.

MEASUREMENT RESULTS

Several measurements of crowd noise were made by Lee (2005) of noise inside a restaurant and university refectory. The data of Lee have been re-processed using the reverberant technique and are shown compared with measurements made by the authors in a bowls club bar room as presented in Figure 8. The crowds encountered in these areas ranged from 12 people to around 85 people. In each instance, the individuals making up the crowd were considered to be in an informal social situation which entailed a lot of talking by individuals. In this instance, the crowd can be considered to be made up of a number of random noise sources.

The results presented in Figure 8 clearly show a trend in crowd noise levels increasing with Log_{10}N . The data from the different locations agree quite well with each other for the same number of people. However, additional data needs to be collected from a number of sources before the results can be used to determine the unknown crowd noise prediction parameters.

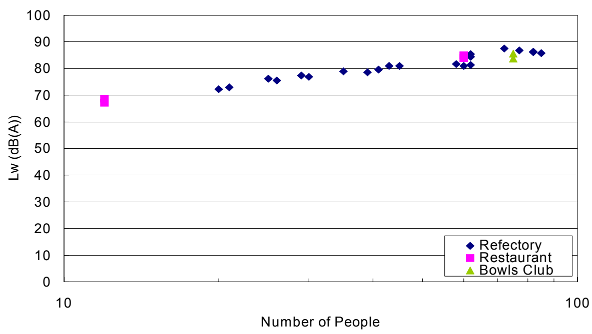

Figure 8: Crowd noise measurement results (Restaurant and refectory data are from Lee (1995))

CONCLUSIONS

This paper has presented a discussion of the major factors thought to influence the noise emitted by a crowd. Based upon a simple analysis, it has been proposed that four major factors influence the noise emitted by a crowd:

1. An individual's voice effort;
2. The total number of people in the crowd;
3. Whether the noise from individuals is synchronised or random with time; and
4. Whether the crowd noise is directional or has a diffused orientation.

Each of these factors has been discussed to determine what influence each could have on the noise level emitted by a crowd. Previous studies have shown that an individual's voice effort depends on more than just the ambient noise level and that the number of people in a crowd also affects an individual's voice effort. Whether a source is in unison will have a greater effect on the emitted sound level than if it is random in time and the direction of the crowd can change the emitted noise level of the crowd by up to –7dB.

Two techniques have been presented for measuring crowd noise. Using these techniques, it is intended that a body of data will be collected which will enable the functional relationship between the various factors influencing crowd noise to be determined. Once this has been done, the model for crowd noise can be refined and an expression finalised which will enable all types of crowd noise to be predicted.

REFERENCES

Bies, D.A. & Hansen , C.H. (2003) *Engineering Noise Control 3rd Edition*, Spoon Press, London

Brooklyn Bridge Park Development Corporation (2005), *Brooklyn Bridge Park Project: Draft Environmental Impact Statement (DEIS)*, New York, Available online at http://www.empire.state.ny.us/bbpdc/DEIS/17_Noise.pdf [Accessed 12 June 2006]

Brown-Buntin & Associates (2005), 'Environmental Noise Analysis, Bradshaw Christian High School' In: *Bradshaw Christian High School Environmental Impact Report*, Available online at: www.dera.saccounty.net/01-0834%20Bradshaw/01-0834BradshawDEIR.pdf [Accessed 12 June 2006]

City of Seattle (2002), *Sand Point Magnuson Park Drainage, Wetland/Habitat Complex and Sports Fields/Courts Project: Final EIS*, Department of Parks and Recreation, Available online at: http://www.seattle.gov/parks/magnuson/EIS.htm [Accessed 12 June 2006]

County of Sacremento (1998), *Noise Element of the County of Sacremento General Plan*, Planning and Community Development Department General and Advanced Planning Section, Available online at: http://www.saccounty.net/general-plan/gp-home.html [Accessed 12 June 2006]

Dunn, H.K. & Farnsworth, D.W. (1939) 'Pressure field around the human head', *Journal of the Acoustical Society of America*, Vol. **10**, pp. 180-198

Evans, J.B. (1990) 'Community annoyance with sports crowd noise: A case study of the facts in a jury decision' in I.J. Busch-Vishniac (ed) *Proceedings of NOISE-CON 9: Reducing the Annoyance of* Noise, The University of Texas, Austin, Texas.

van Heusden, E., Plomp, R. & Pols, L.C.W. (1979), 'Effect of ambient noise on the vocal output and the preferred listening level of conversational speech', *Applied Acoustics*, Vol. **12**, pp. 31-43

Lazarus, H., (1986) 'Prediction of verbal communication in noise – a review: Part 1', *Applied Acoustics*, Vol. **19**, pp. 439-464

Lee, J.S. (2005) *Modelling Sound Power Generated by Groups of People*, School of Information Technology and Electrical Engineering Undergraduate Thesis, The University of Queensland, Australia

Moreno, A. & Pfretzschner, J. (1979) 'Human head directivity in speech emission: a new approach', *Acoustic Letter*, Vol. **1**, pp. 78-84

Ove Arup & Partners Hong Kong Ltd (2005) *Hong Kong Jockey Club Main Arena of the 2008 Olympic Equestrian Event Environmental Impact Assessment Report*, Available online at: http://www.epd.gov.hk/eia/register/report/eiareport/eia_1182005/Reports/final_ES_eng.pdf [Accessed June 2006]

Pearsons, K.S., Bennett, R.L. & Fidell, S. (1977) *Speech Levels in Various Noise Environments*, EPA Report 600/1-77-025

Studebaker, G.A. (1985) 'Directivity of the human vocal source in the horizontal plane', *Ear and Hearing*, Vol. **6**(6), pp. 315-319

Ver, I.L. & Beranek, L.L. (2006) *Noise and Vibration Control Engineering 2nd Edition*, Wiley, New Jersey