Probability Approach for Prediction of Construction Site Noise

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Abstract
This paper describes an alternative method of predicting noise from construction sites using a probability approach. The basis of the approach is the separation of the source characteristics from the propagation characteristics. A site area is divided into a number of square patches in which the source can be located at the centre of any patch or node. The approach assumes that the probability that the noise source of certain acoustic power is at a particular node is the same as for all other nodes. The noise level from each patch is obtained and the temporal noise level distribution during the working day period can be constructed. \( L_{Aeq} \) accompanied with standard deviation and noise indices during a working day period can be estimated. The effect of the duty cycle of equipment and number of items of equipment were incorporated in the approach. When validated with the current procedure, the model \( L_{Aeq} \) value has good agreement with those obtained from BS 5228, and thus indicates that the probability approach is capable of predicting the equivalent noise level. The method could be used as the basis of an operational management tool for a noise abatement scheme.

Keywords: prediction of noise; probability; temporal distribution; noise annoyance; equivalent noise level

1. Introduction
Prediction of noise arising from construction sites is considered as early as the planning stage (Carpenter, 1997) to reduce effects which include annoyance, sleep disturbance, speech interference, and increasing risk of hearing impairment (Wilson, 1963; Ng, 2000). Annoyance, however, is the most important effect in terms of the number of affected people (the disruption of human activities) (Large and Ludlow, 1975; Ng, 2000) and is normally expressed in terms of noise complaints. Therefore, the number of construction noise complaints channelled to local authorities in some developed countries exceeds complaints about traffic noise (Berglund, 1999). Hence, in attempting to minimize complaints, local authorities need accurate techniques for predicting the noise emission, that is the total noise from all contributing sources at a given position, arising from construction operations (Waddington et al., 2000).

According to Carpenter et al. (1997) \( L_{Aeq} \) obtained from the current prediction procedure is not accurate because it will result in annoyance to the community not being addressed properly. Research has also revealed that the use of a single \( L_{Aeq} \) prediction may mean that a quality of the sound which has a particular effect on people may be ignored (Madiema and Vos, 1998; Skånberg and Öhrström, 2002; Schomer, 2003; Raimbault and Dubois, 2005). Carpenter (1997) suggested developing alternative prediction methods that can operate on coarse data available in the planning stage and generate results that include quantified error margins. He suggested that a possible method might be a stochastic model that can take into account the fluctuation of noise level generated at the receiver during a real process. This is typically due to conditions when an item of plant may be switched off, idling, operating under light load, or operating under heavy load. Furthermore, many items of plant or operations will move around the site either while working or between phases of operation (Fig.1.). This latter variation not only affects the distance between source and observer but also alters the effect of screening, ground cover, and other factors (Haron and Oldham, 2004; Haron and Yahya, 2009). The current prediction method is deterministic, that is, if one wants to examine the effect of various parameters (acoustic power, distance, duty cycles), it is laborious to apply

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number of items of equipment, and the possibility of operations being concurrent during the course of the working day. The results of this investigation will be applied to the development of a simple predictive model.

2.1 Basic Modelling Approach

The basis of the probabilistic method is the separation of the source characteristics (in particular the duty cycles and associated sound power levels) from the propagation characteristics (determined by the area over which an activity takes place and its position relative to the receiver). By considering first the propagation characteristics, it is assumed that the probability that the noise source is at a particular point within the operational area is the same for all points in that area.

The model considers a site area with width w, depth d, and a receiver located at a distance r, from the sub-site centre. The sub-site is divided into a number of equal patches, as shown in Fig.2. The source (equipment) is assumed to be positioned from patch to patch successively to obtain the effect of variability of noise source. Each patch is identified by a subscript which relates to its position along the x and y directions relative to the origin:

\[
x_i = -w/2 + 0.5
\]
\[
y_j = -d/2 + 0.5
\]

These two values, together with the source height, \( z_s \), define its location. A noise source can be located at a random position in that sub-area with equal probability (Fig.2).

The sound intensity at a receiver from a source position is obtained by assuming hemispherical radiation over a hard surface and is given by:

\[
I_{ij} = \frac{W_s}{2\pi r_{ij}^2}
\]

where \( W_s \) is the acoustic power of the source, and \( r_{ij} \) is the distance from the source position \((x_i,y_j,z_s)\) to the receiver \((x_r,y_r,z_r)\) given by

\[
r_{ij} = ((x_i-x_r)^2 + (y_j-y_r)^2 + (z_s-z_r)^2)^{0.5}
\]

The sound pressure level at the receiver is found by

\[
L_{ij} = 10\log_{10}(I_{ij}/10^{-12})
\]

A statistical analysis on a number of samples of noise level can be carried out to determine the temporal distribution in terms of the probability distribution function, PDF, and cumulative distribution function, (CDF). The mean level can then be obtained as an equivalent intensity level or equivalent sound pressure level, \( L_{eq} \). The standard deviation can also be found.

2.2 Effect of Duty Cycle of Equipment

An item of machinery might typically generate a number of different sound power levels in the course of a working day.
of a working day depending upon its pattern of use. It might be completely off for A% of the working day, on idle for B% of the working day, and operate at full power for C% of the working day (Waddington and Lewis, 2000; Gilchrist et al., 2003). If an item of machinery operates at full power for 100% of the working day the PDF obtained is called PDF100% on. In order to consider the effect of this operational cycle, two distributions are then derived corresponding to the sound power level of the source for idling power for B% of the day and for full power for C% of the day. For idling mode, it is assumed that an item of machinery operates at idle power for 100% of the working day and the noise level can be obtained by incorporating the idle mode sound power level into Equation 3. The PDF for B% idle mode is expressed using the following:

\[ \text{PDF}_{\text{idle}} = \frac{B}{100} \text{(PDF}_{\text{idle}}) \]  

(6)

The PDF for C% full power mode or PDF_{B\%on} can then be expressed using the following:

\[ \text{PDF}_{\text{on}} = \frac{B}{100} \text{(PDF}_{\text{on}}) \]  

(7)

The probability distribution for equipment with A% off, B% idle, and C% on time is then given by:

\[ \text{PDF} = \frac{A}{100} + \text{PDF}_{\text{idle}} + \text{PDF}_{\text{on}} \]  

(8)

2.3 Effect of a Number of Items of Equipment

Normally a number of noise sources are in operation, and therefore it is possible for an item of equipment to be operating concurrently with any other item of equipment. To obtain the temporal distribution, probability law, that is, intersection, is employed. The combined probability distribution for equipment operating concurrently can be determined using a method first proposed by Nelson (1972, 1973a, 1973b). Noise producing equipments are called events "An" where \( n \) is the number of items of equipment. Consider a simple case of two items of equipment A1 and A2 working concurrently. The total working period is T hours, known as the sample space, whilst PDF(A1) and PDF(A2) are the PDFs for events A1 and A2, respectively.

The combination method was first proposed by Nelson (1972, 1973b) for the combination of noise level distributions in traffic noise prediction. Each PDF is represented by a set of number pairs, one relating to a noise level (the centre of the class interval) and one to the corresponding probability such that:

\[ L_{i} \text{ and } P_{i} \text{ where } i = 1, 2, 5 \ldots m \text{ for PDF(A1)} \]
\[ L_{j} \text{ and } P_{j} \text{ where } j = 1, 2, 5 \ldots m \text{ for PDF(A2)} \]

Subscripts 1 and 2 refer to PDF(A1) and PDF(A2), respectively, as shown in Fig.3. \( L \) refers to the level, \( P \) refers to the probability of that level, and \( i \) and \( j \) refer to particular samples of the first and second distributions respectively. The combined probability that the noise level from PDF(A1) is \( L_{1i} \) when the level from PDF(A2) is \( L_{2j} \) is given by:

\[ P_{gi} = P_{1i} \cdot P_{2j} \]  

(9)

The combined noise level arising from the contributions of both distributions is given by:

\[ L_{g} = 10 \log_{10} \left[ 10^{(L_{1i})/10} + 10^{(L_{2j})/10} \right] \]  

(10)

The combined PDF is obtained by defining a new class of intervals and summing the probabilities associated with the levels that fall within these class intervals. This technique is not limited to the combination of levels from two sources but can be applied to any number of sources.

3. Computation

The simulation of PDF and CDF for an activity or activities can be carried out using MATLAB 7.2. The coding was carried out according to the flow chart shown in Fig.4. The model inputs include the dimensions of the site (d and w), the sound power level and its duty cycle, and the position of a receiver. For
a single item of equipment operating on full power continuously, steps 1 to 2 are repeated to obtain the sound pressure level for the source at all nodes. The noise levels are analysed and the PDF and CDF are obtained.

Fig.5. shows the PDF and CDF of an excavator with a sound power level of 117 dB operating at full power continuously for a working day period. The site area is of width 200 m and depth 100 m and the receiver was positioned 60 m from the site centre. It can be seen that the PDF has unimodal distribution skewed to the left due to the closeness of the receiver to the site boundary. It is noted that as the receiver's position moves further away from the site boundary, the noise level distribution becomes symmetrical. The most vital output is the CDF, which shows the content of the sound during the working day period. The mean level and its standard deviation and indexes such as \( L_{10} \) and \( L_{90} \) can be easily determined. \( L_{10} \) is the noise level which occurred during 90% of the working day, which can be associated with peak noise. \( L_{90} \) is the noise level which occurred during 90% of the working day associated with the background noise, and can be obtained as shown in Fig.5.

The calculation of sound level due to the equipment on idle or on full power can be obtained using the outer 'loop'. Fig.6. shows the PDF and CDF for an excavator with a duty cycle of 10% off, 20% idle, and 70% on. It was found that the effect of duty cycles is to change the PDF into a bimodal shape with two peaks as a result of

\[
\begin{align*}
  x_i &= \frac{w}{2} - 0.5 \\
  y_i &= \frac{d}{2} - 0.5 \\
  r_i &= \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}
\end{align*}
\]

### Stage 3 - Calculation of each node level for idle and full power

\[
P_{\text{idle}, \text{idle}} = \frac{A}{100} + P_{\text{idle}, \text{idle}} + P_{\text{idle}, \text{idle}, \text{idle}, \text{idle}}
\]

### Stage 4 - PDF, CDF, PDF, CDF...

\[
P_{\text{idle}} = P_{\text{idle}, \text{idle}}
\]

### Stage 5 - Combination PDF and Level

\[
L_d = 10 \log_{10} \left( 10^{\frac{L_{10}}{10}} + 10^{\frac{L_{90}}{10}} \right)
\]

### Stage 6 - Plot combination of PDF and CDF

Fig.4. Flowchart for the Computation of Temporal Distribution using the Probability Approach

Fig.5. Temporal Distribution of Noise Level from Excavator Working at Full Power

Fig.6. Temporal Distribution of Noise Level from Excavator Working with Duty Cycle
idle mode, full power mode, and a distance factor.

For multiple sources, Stages 1–4 are repeated for the three items of equipment whose data are shown in Table 1. working concurrently over a period of 12 hours on a site area of 200 m × 100 m. Again, the receiver was positioned 60 m from the site centre. In this case the combination of temporal distribution is nearly unimodal in shape.

Table 1. Acoustic Characteristics

| Equipment (duty cycle)       | Sound power level |
|-----------------------------|------------------|
| Excavator 1 (10% off: 20% idle: 70% on) | 117 dB = full; 111 dB = idle |
| Excavator 2 (20% off: 20% idle: 60% on) | 111 dB = full; 101 dB = idle |
| Loader (10% off: 10% idle: 80% on)    | 109 dB = full; 104 dB = idle |

Fig. 7. shows the individual CDF for each item of equipment, with items having different duty cycles during a working day period. Fig. 8. shows the result of the combination of the PDF and CDF of each item of equipment. From the combined CDF, the content of sound for a working day period can be estimated. The average sound pressure level or equivalent sound level, $L_{Aeq}$ is 71.5 dB with a standard deviation of 4.1.

4. Comparison With Bs5228 Model

Three items of equipment working concurrently on a site considered in Table 1 were used to compare the results obtained from the probability approach and the current procedure, BS 5228. The BS 5228 (1997) model is the prediction method recommended by the DOE (2004). The code predicts noise at receivers in Annex D, Part 1. In this procedure, correction factors were applied to the sound power level to account for factors such as periods of operation of plant or equipment (step 1), distance between the source and receiver (step 2), any screening between source and receiver (step 3), and whether the receiver is in front of a reflecting surface (step 4). Noise levels were collected at the receiver based on the noise generated by the items of equipment using the calculation steps shown in Fig. 7. Data for the first two factors only were available and taken into account in the comparison with the probability approach.

One problem regarding the usage of BS 5228 is that it requires an accurate distance between equipment and receiver. Since all equipment will move around the site, an average distance for each item of equipment was used, namely the distance between the receiver and the equipment positioned at the site centre. The sound level from each item of equipment at the receiver and the combined $L_{Aeq}$ are shown in Table 2. It is well known that the result obtained from BS 5228 is only $L_{Aeq}$.

Table 2. BS5228 Procedures

| Equipment   | Distance correction | % on time correction | Sound pressure level at receiver |
|-------------|---------------------|----------------------|----------------------------------|
| Excavator 1 | -43.5 dB            | -1.5 dB              | 72.1                             |
| Excavator 2 | -43.5 dB            | -2 dB                | 65.5                             |
| Loader      | -43.5 dB            | -0.4 dB              | 64.6                             |
| Combined    |                     |                      | 73 dB                            |

The results of the combined $L_{Aeq}$ obtained from BS 5228 and the probability approach have a disparity of 1.5 dB; however the results of the probability approach are accompanied by a standard deviation of 4.2. Also the indices which show the content of sound during the working day period are weighted by their probabilities. Based on the $L_{Aeq}$ results it can be seen that the probability approach has good agreement with the BS 5228 procedure.
5. Conclusion

This paper has described the basis of a probability approach to predict the temporal noise level distribution arising from construction site operations due to either individual noise sources or a combination of noise sources. The method has advantages over the procedure currently used as it enables the determination of any indices required in evaluating the environmental quality. This can facilitate decision-making processes where noise is a potential problem.

The method could be used as the basis of an operational management tool. The construction project manager could rapidly establish the probability of a specified limited noise level being exceeded. The CDF can also be related or could then be used to predict the $L_{Aeq}$ experienced over a short time period as usually measured by local authority staff when checking for conformity with a specified level during the construction process (DOE, 2004).

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References

1) Berglund, B., Lindvall, T., and Schwela, D.H. (1999) Guidelines for community noise, World Health Organisation, Geneva.
2) BS 5228, Part 1. (1997) Noise and vibration control on construction and open sites.
3) Carpenter, F. (1997) Construction noise prediction at the planning stage of new developments, Building Acoustics, 3(4): 239-249.
4) Carpenter, F., Gibbs, B.M., and Lewis, J. (1997) BS 5228: The prediction of noise from construction sites. In: Proceedings of the Institute of Acoustics.
5) Department of Environment (DOE), Malaysia, (2004) The planning guidelines for environmental noise limits and control.
6) Gilchrist, A., Allouche, E.N., and Cowan, D. (2003) Prediction and mitigation of construction noise in an urban environment. Canadian Journal of Civil Engineering, 30: 659-672.
7) Haron, Z., and Oldham, D.J. (2004) Stochastic modeling in environmental and building acoustics, Journal of Recent Research Development, Sound and Vibration, 2: 213-234.
8) Haron, Z., and Yahya, K. (2009) Monte Carlo analysis for prediction of noise from construction sites, International Journal of Construction for Developing Countries, 14(1).
9) Kurze, U.J. (1971) Statistics of road traffic noise, Journal of Sound and Vibration, 18: 171-195.
10) Large, J.B., and Ludlow, J.E. (1975) Community reaction to construction noise. In: Proceedings of the Inter-Noise, Sendai.
11) Madiema, H.M.E., and Vos, H. (1998) Exposure–response relationships for transportation noise. The Journal of the Acoustical Society of America, 104(6): 3432-3445.
12) MATLAB, version 7.2, The MathWorks, Inc.
13) Nelson, P.M. (1972). The combination of noise from separate time varying sources. TRRL Report LR 526.
14) Nelson, P.M. (1973a). A computer model for determining the temporal distribution of noise from road traffic. TRRL Laboratory Report 611.
15) Nelson, P.M. (1973b). The combination of noise from separate time varying sources. Applied Acoustics, 6(1): 1-21.
16) Ng, C.F. (2000) Effects of building construction noise on residents: A quasi-experiment, Journal of Environmental Psychology, 20(4): 375-385.
17) Raimbault, M., and Dubios, D. (2005) Urban soundscape: Experiences and knowledge. Cities, 22(5): 339-350.
18) Schomer, P.D. (2003) Does the soundscape concept have real utility. In: Proceedings of Inter-noise 2003:2825-2826.
19) Skånberg, A., and Öhrström, E. (2002) Adverse health effect in relation to urban residential soundscapes. Journal of Sound and Vibration, 250(1): 151-155.

20) Wentang, R., and Attenborough, K. (1989) The prediction of noise from construction sites. In: Proceedings of the Institute of Acoustics, St Albans, UK.

21) Waddington, D.C., and Lewis, J. (2000) The preliminary estimation of noise from construction sites. In: Proceedings of the Institute of Acoustics, Liverpool.

22) Waddington, D.C., Lewis, J., Oldham, D.J., and Gibbs, B.M. (2000) Acoustic emissions from construction equipment, Building Acoustics, 3(4): 239-249.

23) Wilson, A. (1963) Final report of the committee on the problem of noise. Final Report, Cmnd. 2056, HMSO, London.

24) Wong, C.Y., Lam, K.C., and Hui, W.C. (2004). Soundscape of urban parks in Hong Kong. In: Proceedings of Inter-Noise, Prague.

25) Yang, W., and Kang, J. (2005) Acoustic comfort evaluation in urban open public spaces. Applied Acoustics, 66: 211-229.