Proceedings of the Institute of Acoustics

THE PREDICTION OF CONSTRUCTION SITE NOISE

HOW ACCURATE CAN IT BE ?

Keith Jefferson WSP Environmental, London EC1N 2HS

1. INTRODUCTION

A revised version of BS 5228: "Noise and Vibration Control on Construction and Open Sites"[1] was published in 1997. The new edition contains revisions to the noise prediction methodology, including new procedures for calculating attenuation due to the barrier and ground effects, the intention being to enable more accurate noise predictions to be undertaken without making the method over complicated.

However, there is some evidence that the BS 5228 prediction methodology is not good in certain situations and for propagation over large distances. A series of noise predictions undertaken by the Author[2] revealed that the new BS5228 prediction method still tended to over-predict noise levels for distances of greater than 200m or so. There are also some inconsistencies with other noise prediction methods, and there appears to have been no validation exercise or study into the accuracy of the new BS 5228 method.

This paper details an investigation into the accuracy of the BS 5228 and other noise prediction methods as applied to the propagation of noise from construction sites.

2. THE FREQUENCY SPECTRA OF CONSTRUCTION SITE NOISE

To provide the necessary source data for this study, measurements of the frequency spectra of several different types of construction plant and activity were recorded at a number of busy construction sites. It has been possible to sort the recorded noise spectra into three groups; typical low frequency noise sources, typical high frequency noise sources and impact noise sources that have a fairly flat and broad frequency spectrum. The majority of the noise sources encountered, including excavators, concrete wagons, pumps, generators and most items of plant that are powered by large internal combustion engines, were found to fit the typically low frequency group of sources. From the measured spectra it has been possible to define a "typical" spectrum for each of the low frequency, high frequency and impact sources, obtained from the average values of the recorded spectra in each group. These "typical" spectra are shown in the following tables together with the typical variation in the sound pressure level in each octave band, given as 1x standard deviation.

Typical Source Spectrum - Low Frequency Sources

Frequency	31.5	63	125	250	500	1000	2000	4000	8000	16000
dB re.L_{WA}	-30	-25	-28	-30	-32	-34	-36	-41	-48	-57
±	6.2	5.5	6.1	3.5	1.7	1.6	1.7	2.5	3.6	3.4

Typical Source Spectrum - High Frequency Sources

Frequency	31.5	63	125	250	500	1000	2000	4000	8000	16000
dB re.L_{WA}	-33	-37	-35	-39	-38	-37	-35	-34	-36	-45
±	4.8	3.0	7.1	2.4	2.0	1.8	1.1	0.6	1.3	2.8

Typical Source Spectrum - Impact Noise Sources

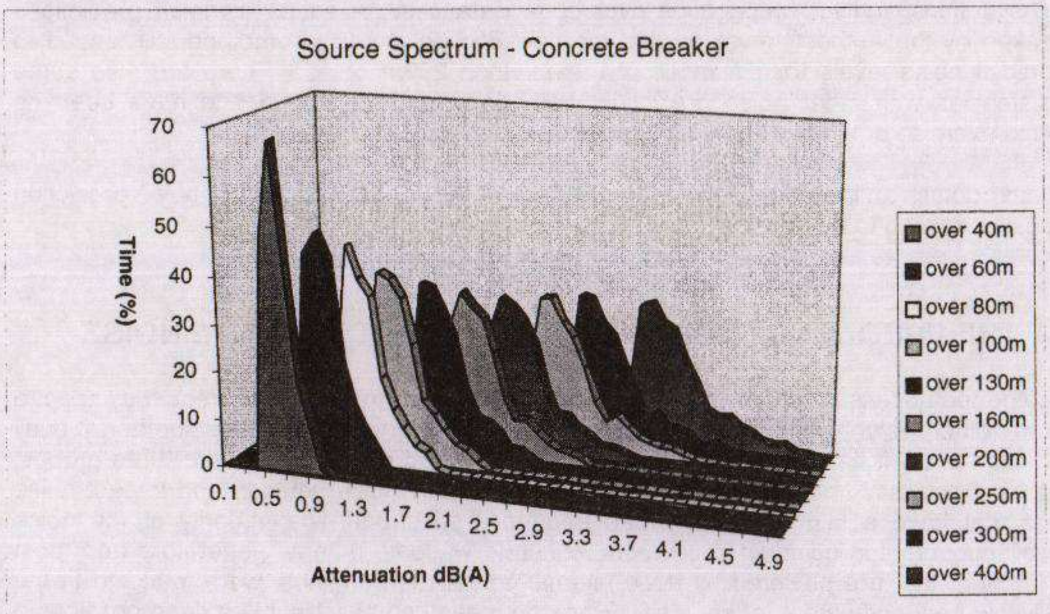
Frequency	31.5	63	125	250	500	1000	2000	4000	8000	16000
dB re.L_{WA}	-35	-35	-31	-34	-34	-34	-34	-38	-41	-52
±	4.1	2.2	3.7	4.0	2.0	2.0	0.8	1.4	3.2	4.3

3. ATMOSPHERIC ABSORPTION

The mechanisms by which sound is attenuated during propagation through the atmosphere by molecular absorption are well understood and are described in the literature (e.g. see EN Bazley[3] for a summary of the literature; for the latest developments in theory and experiments see Bass et. al[4]).

Further experimentation on the role of atmospheric absorption on the attenuation of noise from construction sites would serve little purpose. For this study, the latest theory as described by Bass et. al.[4] has been applied to the measured frequency spectra of construction site noise and measured weather conditions typically encountered in southern England, to determine how significant the role of atmospheric absorption is in the propagation of noise from construction sites. The results provide a statistical time distribution of the overall A-weighted atmospheric attenuation for sound propagation over various distances and for different noise sources. An example of the results for the propagation of noise from a concrete breaker over various distances is shown in figure 1.

Figure 1. Time Distribution of Atmospheric Attenuation over Various Distances



In order to understand the temporal variation of atmospheric attenuation and its effect on the accuracy of noise predictions, it is useful to consider the median values and the 95% confidence limits; i.e. the boundary values between which the atmospheric attenuation will be for 95% of the time. The 95% confidence limits are given by the 2.5 percentile and 97.5 percentile values.

From the above data, it is possible to plot the median dB(A) atmospheric attenuation with distance for the three noise sources, together with the 95% confidence limits, and obtain least squares best fit equations for the average atmospheric attenuation. The equations which reproduce the curves to within 0.1dB and with a correlation coefficient of greater than 0.997, are as follows:

Low frequency spectrum: $\text{Attenuation} = \text{Antilog}_{10}\{-4.845 + 3.236 \text{ Log}_{10} d - 0.513 (\text{Log}_{10} d)^2\}$
High frequency spectrum: $\text{Attenuation} = \text{Antilog}_{10}\{-2.275 + 1.787 \text{ Log}_{10} d - 0.243 (\text{Log}_{10} d)^2\}$
Impact noise spectrum: $\text{Attenuation} = \text{Antilog}_{10}\{-2.821 + 2.155 \text{ Log}_{10} d - 0.332 (\text{Log}_{10} d)^2\}$

where d is the distance in metres from the noise source.

The atmospheric conditions that best fit the average values are standard atmospheric pressure and either 70% relative humidity and 10° Celcius or 85% relative humidity and 5° Celcius. The conditions that best fit the 2.5 percentile value (i.e. close to the minimum expected value of atmospheric attenuation) are standard atmospheric pressure, 90% relative humidity and 15° Celcius.

The potential error in estimating the amount of atmospheric absorption by using these equations, and assuming that the source spectrum is known exactly, is as high as + 1.5dB or - 0.5 dB over a distance of 300m. This error arises purely because of the natural variation in meteorological conditions (mainly temperature and relative humidity) that can occur over time. Further errors are introduced in situations where the source spectrum is not exactly known. An analysis of the data suggests that the potential error introduced by assuming a "typical" spectrum could be as high as + 1.6dB or - 1.9dB.

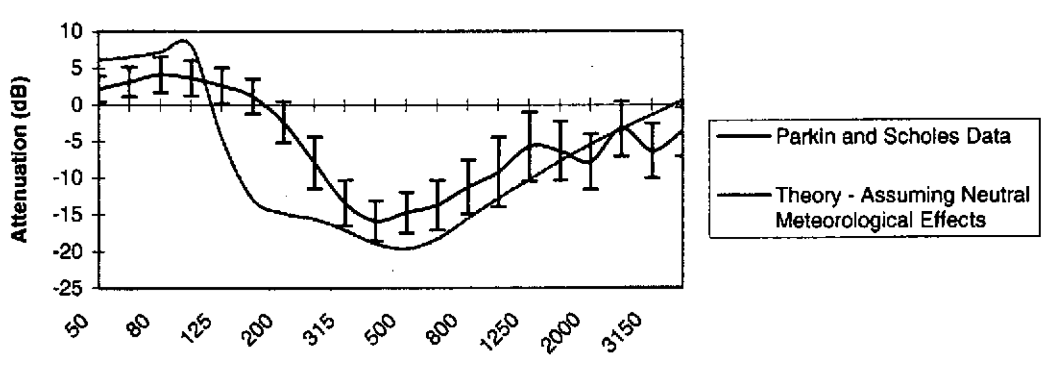
4. GROUND EFFECTS

There are generally two approaches that can be made to the prediction of sound attenuation due to ground effects. The first approach is to consider the theoretical attenuation due to the interaction of the direct and ground-reflected sound paths as they combine at the receiver. The second approach is to consider the results of experiments undertaken to determine the amount of excess attenuation that could be attributed to the ground effect after other factors, such as atmospheric absorption, have been accounted for.

There are both advantages and disadvantages to these two methods. Whilst a theoretical analysis can take into account both the precise source - receiver geometry and the particular characteristics of the ground, such analyses generally cannot account for the meteorological factors, such as wind and temperature gradients, that affect the amount of ground attenuation (although a recent paper by Kuhner[5] , does consider meteorological effects). It should be pointed out that some "theoretical" models of ground attenuation have, in fact, been at least partially developed so as to fit experimental data.

Experimental data, on the other hand, and in particular the results presented by Parkin and Scholes in their two classic papers[6, 7], provides an indication of how ground attenuation is affected by meteorological conditions. Of most interest are the results obtained by Parkin and Scholes for different wind vector and atmospheric conditions. The spread of results for one particular set of measurements is shown in Figure 2.

Figure 2. Ground Attenuation over 347m as Measured by Parkin and Scholes - Averages over All Wind Vectors and Meteorological Conditions

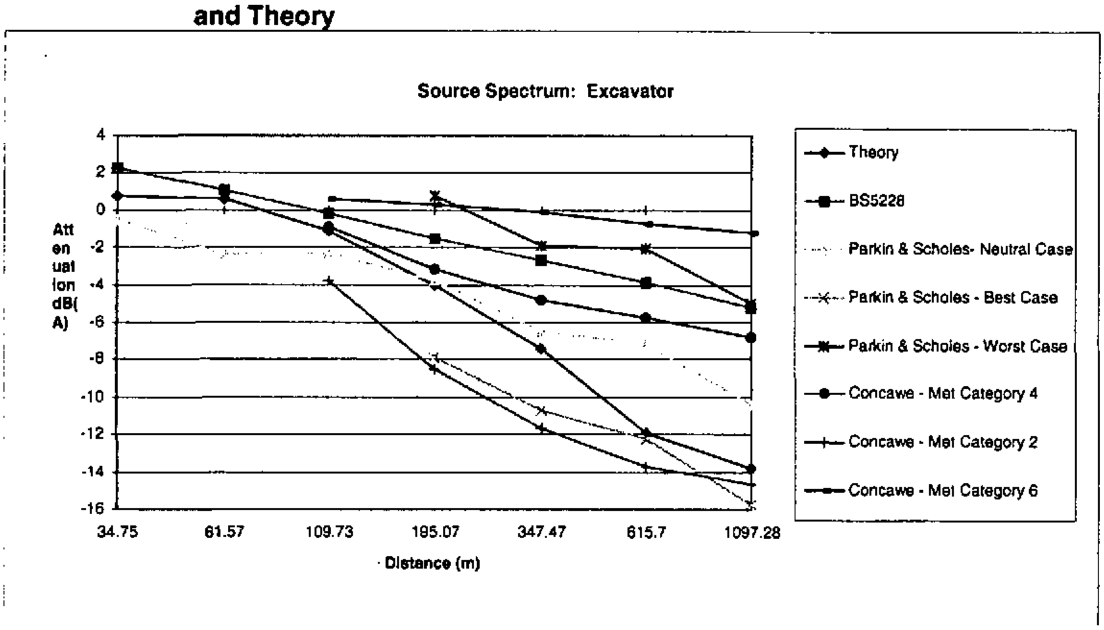


The results presented by Parkin and Scholes show a wide scatter in measured values of ground attenuation which often disagrees with theory by several decibels at most frequencies and up to 10dB at some frequencies. This scatter is in part due to the influence of meteorological conditions (wind vector and temperature gradients), although the results show a large scatter even for measurements undertaken under similar meteorological conditions.

In order to assess how this uncertainty affects the prediction of construction site noise we must consider how the results affect the overall *A-weighted* attenuation of construction site noise. Figure 3 shows the predicted A-weighted attenuation using the results of Parkin and Scholes, the algorithms contained in the CONCAWE[8] report (which are said to be based on the results of Parkin and Scholes), the algorithms contained in BS5228 and the theoretical model of ground attenuation according to Sutherland and Daigle[9] (which is based on the work of, amongst others, Delaney and Bazeley[10], Chessel[11] and Attenborogh[12]). The predicted attenuation relates to the source - receiver geometry used in the experiments of Parkin and Scholes, with a source height of 1.83m, receiver height of 1.52m and source - receiver distances in logarithmic intervals between 34.75m and 1097.28m (distance scales have been converted from the imperial units used by Parkin and Scholes). A flow resistivity of 200kPa.s.m^{-2} is assumed for the theoretical calculations.

The BS5228 algorithm produces very similar results to those of Concawe and Parkin and Scholes for neutral meteorological conditions and for the impact noise source spectrum. For the typical low frequency spectrum, the BS5228 method predicts slightly less attenuation (by 2dB(A)), whilst for the typical high frequency spectrum the BS5228 method predicts slightly more attenuation (by 1dB(A)). There is very little correlation between the theoretical ground attenuation and that calculated using the other methods. The spread of results over different meteorological conditions remains very large, being typically 10dB(A) for propagation over 300m or more with the results for neutral meteorological condition lying in the middle of the range. It must therefore be concluded that the potential error when using the BS5228 algorithm for predicting the amount of ground attenuation could be ±5dB(A) over 300m, although if long term average figures (over a range of meteorological conditions) are required then the potential error could be lower. This is the potential error due to variations in meteorological conditions only. There is also a potential error associated with the variation in the source noise spectrum; analysis shows this to be between 2 and 3dB.

Figure 3 Ground Attenuation according to Parkin and Scholes, Concawe, BS5228 and Theory



5 BARRIERS AND SCREENS

The barrier prediction method due to Maekawa[13] has established itself as the most widely used engineering approximation for the calculation of the attenuation of sound due to the presence of barriers or screens. Variations on the Maekawa method are used in BS5228, ISO 9613[14], CONCAWE and Nordic[15] noise prediction methods. The only difference between the BS5228 method and the Maekawa method is that the BS5228 method is only used on those five octave bands between 125 Hz and 2000 Hz.

Let us consider two important mechanisms that will influence the performance of noise barriers; a modification to the ground effect attenuation and meteorological effects such as the presence of wind speed and temperature gradients and turbulence.

A procedure for combining barrier and ground attenuation is described by Scholes, Salvidge and Sargent[16]. In their paper, Scholes et. al. reported the results of field measurements of the performance of a noise barrier specially erected on a grass covered airfield and under controlled conditions. Octave band measurements were undertaken for various source - barrier - receiver geometries, both with and without the barrier present and under various meteorological conditions. The ground and barrier attenuation effects were separated by assuming the sound field at the top of the barrier is the effective source for receptor points behind the barrier, and then subtracting the measured ground attenuation for this new effective source geometry from the measured overall attenuation (in excess of geometric spreading) at the receptor. Scholes et. al. found that after they had made this correction, the measured values of barrier attenuation were in "reasonable, and in some cases excellent, agreement with the theoretical (Maekawa) values" at mid to high frequencies, but slightly greater attenuation was found at low frequencies. The total noise level spectrum at the receiver locations under zero vector wind conditions clearly showed a combination of barrier and ground attenuation - the total attenuation was close to that predicted by Maekawa but with a reduction in barrier attenuation in the 500 Hz octave band where the ground "dip" occurred (due to the loss of the ground effect which was present with unobstructed propagation) and a corresponding increase in attenuation in the 250Hz octave band (due to the new ground effect at a lower frequency associated with the increased height of the effective secondary source at the top edge of the barrier). Scholes et. al. concluded their paper by stating "Maekawa's method will yield accurate predictions of barrier performance. Even with the ground effect, the received levels with a barrier can be estimated with good accuracy over most of the frequency range by applying the theoretical (Maekawa) attenuations to the calculated received levels without screening".

The field measurements undertaken by Scholes et. al.[16] also considered the effects of wind speed and temperature gradients, and found that at high frequencies and low microphone (receiver) positions (4kHz and 1.5m) there was a difference in barrier attenuation of 16dB between the results obtained with a positive ($+5ms^{-1}$) and negative ($-5ms^{-1}$) vector wind speeds. The results for zero vector wind speed were closer to those with a positive vector wind speed. The difference in results reduced significantly, however, for higher microphone positions.

The only other simple noise barrier prediction method that is currently in use is that contained within the Calculation of Road Traffic Noise (CRTN)[17], although this is strictly only applicable to noise with the road traffic sound spectrum and for a line source. This barrier correction method is unlike the other methods in that it gives the attenuation in dB(A) rather than in dB for a specified wavelength or frequency. This is because the correction has been derived for the typical frequency spectrum for road traffic noise, and so applying this correction method to construction noise will not be valid unless the construction noise has a similar, low frequency spectrum to road traffic.

The CRTN barrier correction method gives a very similar result to the BS5228 and Maekawa methods for the typical low frequency noise sources. For the typical high frequency noise sources the differences between the barrier correction methods become more apparent. Because the BS5228 method does not consider the octaves above 2000Hz, it would be expected that this method would underestimate the barrier performance, and comparison with the Maekawa method shows that it does so by up to 1.7dB, although again this might not be considered to be that significant. Not surprisingly, the CRTN method underestimates the barrier attenuation by a significant amount, although it still might be considered better than the BS5228 "rule of thumb" of assuming 0, 5, or 10 dB.

The error associated with using the BS5228 barrier prediction method over that of the Maekawa method is negligible for the typical low frequency noise sources considered, and still fairly small - at 1.7dB(A) - for the higher frequency sources. Even using the CRTN barrier prediction method gives extremely good results for the low frequency sources. However, very significant errors are associated with meteorological effects and the combined effects of barriers and absorbent ground. The magnitude of these potential errors will be the same as those potential errors associated with the calculation of ground effects and the spread of measured ground attenuation over various meteorological conditions. The potential error when using the BS5228 algorithm for predicting the amount of barrier attenuation could be as high as ±5dB(A) over 300m, although if long term average figures (over a range of meteorological conditions) are required then the potential error could be lower. The new BS5228 barrier prediction method is, though, a welcome addition to the rather crude "rule of thumb" estimation contained within previous versions of the Standard.

6 MOBILE PLANT AND HAUL ROADS

In situations where mobile plant works over a well defined and relatively small area, the BS5228 method is to calculate the sound level at the receiver assuming that the noise source is static and at it's closest proximity to the receiver, and then apply a correction based on the distance ratio, where the distance ratio is defined as the traverse path length of the mobile source divided by the minimum distance to the receiver. There is a tacit assumption in BS5228 that the traverse length is always at right angles to the line of minimum distance between source and receiver. The correction is then applied to the assumed on-time for the plant. A table of correction factors is given in BS5228, the correction being x1 where the distance ratio is 0.5 or lower (small traverse length relative to minimum distance) and falling to x0.06 where the distance ratio is greater than 10 (large traverse length relative to minimum distance).

Although the source of the correction factors is not acknowledged in the Standard, they appear to come from empirical results presented by Clough and Langley[18] which, at least for distance ratios of greater than three, fit well with a theoretical curve which assumes that the sound level at the receiver is calculated from the average sound intensity integrated over time for the traverse path length, but with a suitable stop time at each end of the traverse path. Clough and Langley did emphasise, though, that the data was based on limited measurements and that unrealistically long stop times have to be assumed to make the curve fit the measurement results for small values of the distance ratio.

This prediction method was introduced into the 1985 version of BS5228 because there was evidence that the methods described in the earlier versions of the Standard seriously over-predicted noise levels[19]. However, measurements undertaken by the Author indicate that this revised method also over-predicts noise levels[2]. Tompsett[20] has also pointed out that the method is unable to distinguish between cases where the traverse path is not at right angles to the line of minimum distance to the receiver. A further anomaly with the method is highlighted in "The Control of Noise at Surface Mineral Workings"[21]. This document points out that the method would predict the same noise level from two clearly different situations; one where the minimum distance was to the centre of the traverse length and one where the minimum distance was to the end of the traverse length.

For haul routes, the BS5228 equation appears to be consistent with the methodology contained within CRTN , except that the distance attenuation in the BS5228 equation appears to be based on the bisector distance from receiver to the haul route rather than the perpendicular distance as defined in CRTN. The correct distance to use when calculating noise from haul routes needs to be clarified, as example calculations undertaken by the

Author[2] showed that the predicted noise levels at the receptor varied by over 4dB(A) depending on how the distance was defined.

More research on the prediction of noise from mobile plant and haul routes clearly needs to be undertaken, given the reported uncertainty and anomalies in the BS5228 prediction methods.

7 THE ACCURACY OF CONSTRUCTION NOISE PREDICTIONS

It can be assumed that at large distances the construction plant or activity behaves as a point source. The distance attenuation term is then determined by simple geometric divergence, and can therefore be calculated exactly; hence there will be no potential error associated with this term. There will, though, be potential errors associated with each of the other attenuation correction terms, and also a potential error in the value of the sound power level of the source. If we denote each of these potential errors with the delta notation, the total potential error in the predicted sound pressure level will be

$$\Delta SPL = \{(\Delta L_W)^2 + (\Delta A_{atmospheric})^2 + (\Delta A_{ground\ and\ barrier})^2\}^{1/2}$$

The errors associated with ground and barrier attenuation are treated as one term, since they both arise from the curved sound paths that occur under wind speed or temperature gradients.

For A-weighted sound pressure levels and for propagation over a distance of 300m, the maximum error in the ground or barrier attenuation term that arises from variations in meteorological conditions is ±5dB(A), and the error that arises from the variation in the assumed source frequency spectrum is ±1.5dB(A). Hence, the total potential error associated with ground and barrier effects is $\Delta A_{ground\ and\ barrier} = \{(5)^2 + (1.5)^2\}^{1/2} =$ 5.2dB(A).
The potential error in estimating the amount of atmospheric absorption, assuming that the source spectrum is known exactly, is ±1.5dB(A) for propagation over a distance of 300m. The potential error in the predicted amount of atmospheric absorption introduced by assuming a "typical" source spectrum can be as high as ±2dB(A). Hence, the total potential error associated with atmospheric absorption is $\Delta A_{atmospheric} = \{(1.5)^2 + (2)^2\}^{1/2} = 2.5$dB(A).

The potential errors in the term for the source sound power level, which can include variations over the operating cycle of the plant, can not be determined from the limited number of source noise level measurements undertaken as part of this study. One could gauge the potential error by looking at the variation in sound power levels quoted for identical or similar items of construction plant listed in BS5228. However, the data presented in BS5228 is over 20 years old and may not be valid for modern construction plant, which in recent years has, at least theoretically if not in practice, had to meet certain noise limits as dictated by various European Directives. However, Wentang and Attenborough[22] have presented a more recent (1989) analysis of the variation in sound power level of construction plant. They found that the variation in values of the L_{Aeq} sound level of similar or identical items of plant obeyed a normal distribution, and that the standard deviation of this distribution was of the order of 5dB(A).

Taking ΔL_W = 5dB(A), the total potential error in predicting the A-weighted sound pressure level at a distance of 300m from construction operations is

$$\begin{aligned} \Delta SPL &= \{(\Delta L_W)^2 + (\Delta A_{atmospheric})^2 + (\Delta A_{ground\ and\ barrier})^2\}^{1/2} \\ &= \{(5)^2 + (2.5)^2 + (5.2)^2\}^{1/2} \\ &= 7.6\text{dB(A)} \end{aligned}$$

It is worthwhile comparing this level of accuracy with the claimed accuracy of other prediction models and the results of comparisons published elsewhere.

ISO9613-2 claims an accuracy of ±3dB(A) for propagation over distances of between 100m and 1000m, although this model is based on given meteorological conditions of downwind propagation only, so the error associated with the ground and barrier attenuation terms would be lower. Furthermore, it assumes that the source sound power level is known exactly. The same comments apply to the Danish method, which claims an accuracy of 1-3dB(A) for propagation distances up to 500m, although Jakobsen[23] has found that this method over-predicted noise levels by some 8dB(A). CONCAWE is more realistic in it's claimed accuracy, being between 4.5 and 6.9dB(A) depending on which meteorological category is assumed, but again the method is applied to one particular set of meteorological conditions. Brown, Cooper and Snow[24] have found that comparisons between measurements and predictions showed that ISO9613, CONCAWE and the ENM (environmental noise modelling software) prediction schemes can over or under predict by 6 to 8dB(A), whilst Rangerlooij, Witte and Ouwerherk[25] have found that even though the various noise prediction models are based on the same principles, the variation in predicted noise levels when using different models can be up to 6dB(A).

8 REFERENCES

1. British Standard BS5228:Part1: Noise and Vibration Control on Construction and Open Sites. British Standards Institute. 1997
2. K. Jefferson and R.N. Vasudevan. The Prediction of Construction Site Noise - An Example of the Old and New BS5228 Methods. Proc. I.O.A. Vol. 19. Part 8. 1997
3. E.N. Bazely. NPL Acoustics Report Ac74. Sound Absorption in Air at Frequencies up to 100kHz. 1976
4. H.E. Bass, L.C. Sutherland, A.J. Zuckerwar, D.T. Blackstock and D.M. Hester. Atmospheric Absorption of Sound: Further Developments. J. Acoust. Soc. Am. 97 (1) pp680-683. Jan 1995 and erratum J. Acoust. Soc. Am.99 (2) p1259. Feb 1996
5. Kuhner. Excess Attenuation due to Meteorological Influences and Ground Impedance. Acustica - Acta Acustica Vol. 84 pp870-883. 1998
6. P.H. Parkin and W.E. Scholes. The Horizontal propagation of Sound from a Jet Engine Close to the Ground at Radlett. J. Sound Vib. 1 pp1-13. 1964
7. P.H. Parkin and W.E. Scholes. The Horizontal propagation of Sound from a Jet Engine Close to the Ground at Hatfield. J. Sound Vib. 2 pp353-374. 1965
8. C.J. Manning. The Propagation of Noise from Petroleum and Petrochemical Complexes to Neighbouring Communities. CONCAWE. 1981
9. L.C. Sutherland and G.A. Daigle. Atmospheric Sound Propagation. Encyclopedia of Acoustics, edited by M.J. Crocker. John Wiley & Sons. 1997
10. M.E. Delaney and E.N. Bazley. Acoustical Properties of Fibrous Absorbent Materials. Applied Acoustics. Vol. 3. 1970
11. C.I. Chessel. Propagation of Noise along a Finite Impedance Boundary. J. Acoust. Soc. Am. Vol. 62 pp825-834. 1977
12. K. Attenborough. Review of Ground Effects on Outdoor Sound Propagation for Continuous Broadband Sources. Applied Acoustics 24 pp289-319. 1988
13. Z. Maekawa. Noise Reduction by Screens. Applied Acoustics 1. 1968
14. ISO 9613 - Part 2: 1996. Acoustics - Attenuation of Sound during Propagation Outdoors - Part 2: General Method of Calculation. International Organisation for Standardisation. 1996
15. I.A. Moerkerken. The Netherlands Prediction Model for Outdoor Noise Propagation. Directoraat Generaal voor de Milieuhygiene. 1986
16. W.E. Scholes, A.C. Salvidge and J.W. Sargent. Field Performance of a Noise Barrier. J. Sound. Vib. Vol. 16 No. 4 pp627-642. 1971
17. The Calculation of Road Traffic Noise. The Department of Transport and The Welsh Office. 1988
18. M. R. H. Clough and M. S. Langley. Moving Noise Sources – A Comparison of Theory with Practical Measurements. Proc. Acoustics 82 – Proc. I.O.A
19. R.D. Jones. The New Code of Practice for Noise Control on Construction and Open Site. Proc. IOA Vol 7 Part 1. 1985
20. K.R. Tompsett. Site Noise - An Improved Method of Predicting Noise from Open Sites. EuroNoise '92 – Proc. I.O.A. Vol. 14 part 4. 1992
21. The Control of Noise at Surface Mineral Workings. WS Atkins and the Department of the Environment. HMSO. 1990
22. R Wentang and K Attenborough. The Prediction of Noise from Construction Sites. Proc. I.O.A. Vol. 11 Part 5. 1989
23. J Jakobsen. Testing the Joint Nordic System for Prediction and Measurement of Environmental Noise from Industry. Proc. Internoise '83. 1983
24. K. Brown, D. Cooper and D.J. Snow. The Variability of Simple Noise Propagation Models. Proc. Internoise '96 pp3165-3168. 1996.
25. P. van Rangelrooij, J. Witte and M.A. Ouwerherk. Comparison of Noise Calculation Models. In Computational Acoustics and it's Environmental Applications, edited by G.A. Brebbia. Computational Mechanics Publications. 1995