Ground, Terrain and Structure Effects on Sound Propagation

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Not Refereed

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Ground and Surface Effects [1,2,3,4]

The surface over which sound propagates can seldom be considered perfectly rigid or totally reflective (with the possible exceptions of open water, ice, or concrete). Typical soil surfaces with or without vegetation tend to absorb energy from incident acoustic waves. Accurate prediction of ground effects requires knowledge of the absorptive and reflective properties (the acoustic impedance denoted as Z) of the surface.

The ground attenuation is mainly the result of sound reflected by the ground surface interfering with the sound propagation direction from source to receiver. The material properties (impedance or wave resistance) of the reflecting medium are decisive for the degree of reflection.

If sound is propagating over ground, attenuation will occur due to acoustic energy losses on reflection. These losses will depend on the surface. Smooth, hard surfaces will produce little absorption whereas thick grass may result in sound energy levels being reduced by up to approximately 10dB per 100 metres at 2000 Hz. The acoustic impedance of a surface or medium is the ratio of the amplitude of the sound pressure r and the amplitude of the particle velocity v of an acoustic wave that impinges on the surface or medium (**$Z = r / v$**). High frequencies are generally attenuated more than low frequencies.

For concrete or water surfaces the incident sound energy is almost completely reflected (acoustically hard surface) whereas at the surface of porous ground and certain snow cover only a minor portion of the incident sound energy is reflected (an acoustically soft surface).

Sound waves that hit an acoustically soft ground (e.g. grass) at a small incidence angle (grazing incidence) partially penetrate into the ground and can leave it with a phase shift. The superposition of the direct and thus reflected wave cancel each other to some degree even though the travel distance is nearly the same. For this reason the noise of a distant street maybe heard much louder on higher elevated levels of a building than on the ground floor provided the ground between source and receiver is acoustically soft.

Acoustically "soft" ground will also affect the total sound attenuation. Soft ground effects can produce additional attenuation of up to approx 3dB over distances of 100m. This can increase with increasing distance up to about 9dB at approx 1,000m.

The excess attenuation is greater the higher the frequency and is influenced by the height of propagation. Hence care has to be taken when assessing sound from sources that are either elevated or in a direct unobstructed line of sight (for example, across a valley) since in these cases the ground attenuation will be minimal.

ISO Standard 9613-2 describes three types of surface namely:

1. Hard
2. Porous
3. Mixed ground

Hard ground may be described as any surface having low porosity such as paving, water, ice and concrete. Porous ground includes ground covered by grass, trees or vegetation and all other surfaces suitable for growth of vegetation. Mixed ground is a mixture of hard and porous surfaces.

ISO9613-2 provides a method for calculating the ground attenuation (referred to as A_{gr}) only for ground surfaces which are approximately flat, either horizontally or with a constant slope.

Three distant regions for ground attenuation are provided by ISO9613-2. These are the source region, middle region and receiver region. According to ISO9613-2 the ground attenuation does not increase with the size in the middle region but is most likely dependent on the properties of source and receiver regions.

All regions are assigned a ground factor G under ISO9613-2 with hard ground G=0, porous ground G=1 and mixed ground G ranges between 0 and 1.

Figure 1 provides the three distinct regions for determining of ground attenuation under ISO9613-2.

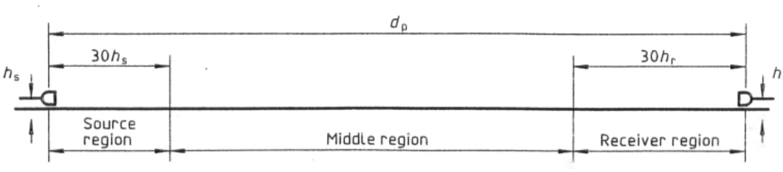


Figure 1: Three distinct regions for determining of ground attenuation under ISO9613-2 [8]

ISO9613-2 provides the total ground attenuation for a specific octave band with the following equation.

$A_{gr} = A_s + A_r + A_m$............Equation 1

A_s is calculated for the source region specified by the ground factor G_S (for that region), A_r is the receiver region specified by the ground factor G_r and A_m for the middle region specified by the ground factor G_m (for the middle region).

ISO9613-2 provides expressions (mathematical terms) to calculate these terms representing the influence of the source to receiver distance d_p and the source or receiver height *h* on the ground attenuation A_{gr} (calculated from equations in ISO9613)

In summary the presence of acoustically *"soft"* ground can lead to a reduction in noise level at the receptor due to absorption of noise energy by the ground, particularly where propagation distances are high. Examples of acoustically *"soft"* ground are grassed areas, areas under crops, and forests with ground covering vegetation. Areas that are concreted or otherwise sealed, and areas of water are acoustically *"hard"*. The proportion of hard and soft ground between the source and the receptor point should be noted. If the effect is seasonal due to variations in ground cover, measurements may need to be taken at a time when ground cover is at a minimum, if this corresponds to a time when public reaction is likely to be highest. Alternatively, measurements could be made close to items of industrial plant and a prediction could be made with no attenuation factor for ground attenuation included. This would indicate the highest likely noise levels that would be experienced at the receptors. Extrapolated levels may be subject to some uncertainty and predicted results are often quoted along with an estimate of accuracy. Ground attenuation has minimal effect on high-level sources, when the receiver has a clear line of sight to the source, although the precise effect depends upon the angle of view. Ground effect is greatly reduced or even eliminated where an acoustic barrier is in place.

Reflection from the ground can result in another mechanism by which sound levels are reduced. When the source and receiver are both close to the ground, the sound wave reflected from the ground may interfere destructively with the direct wave. This effect (called the **ground effect**) is normally noticed over distances of several metres and more, and in the frequency range of 200-600 Hz as illustrated in Figure 2.

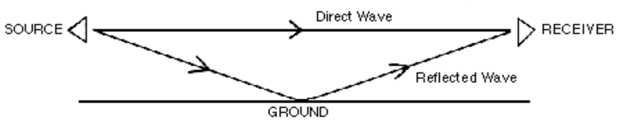


Figure 2: Example of the Ground Effect [3]

Influence of three different ground surfaces at a 100m distance between the source and receiver with the source and receiver height at 2m is illustrated in Figure 3. The graph illustrates that the attenuation due to ground surface increases for soft (porous surfaces) over mixed or hard (non porous) ground. Using 250Hz as a reference Figure 3 illustrates that there is an increase in sound levels of +3dB for "hard ground", a decrease of -3dB for "mixed surface" and a decrease of just over -9dB for "porous surface".

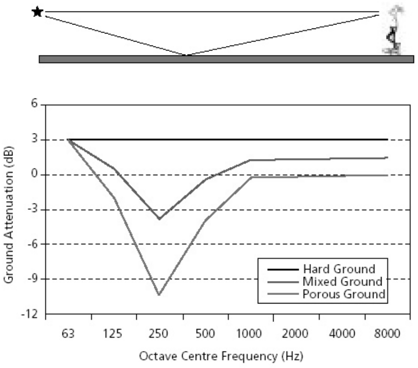


Figure 3: Influence of ground surface at 100m distance between source and receiver (63Hz to 8000Hz). Source and receiver height 2m [4]

Anomalous Excess Attenuation [5]

Anomalous excess attenuation means irregular or uncharacteristic. Large-scale effects of wind speed, wind direction, and thermal gradients in the air can cause large differences in sound transmission over large distances almost all the time, however, there are small-scale influences of these atmospheric factors.

Even under fairly stable conditions for sound propagation through the air, small amounts of diffraction, refraction (bending), and sound interference occur over large distances as a result of small wind, temperature, and humidity differences in the air. These are combined into "anomalous excess attenuation" or "irregular attenuation" which is applied to long-term sound level estimates for average-to-good sound propagation conditions.

Anomalous excess attenuation may help in explaining the fact that measured sound pressure levels at large distances are frequently lower than estimated levels even when sound propagation conditions seem quite good.

Meteorological Correction [1]

ISO9613 provides a metrological correction referred to as C_{met}. ISO9613 states that the attenuation of sound propagation outdoor between a fixed source and receiver fluctuates due to variations in the metrological conditions along the propagation path. Metrological conditions are always favorable or unfavorable, with an important factor being time. In real life there is a variety of meteorolocal conditions which exist over months and years.

A value of C_{met} can be calculated using ISO9613 for the case of a point source with an output which is effectively constant with time i.e. $C_{met} = 0$ if $d_p \leq 10\ (h_s + h_r)$, however it is understood this is usually not the case otherwise C_{met} can be calculated using ISO9613:

$C_{met} = C_o\ [1 - 10\ (h_s + h_r)\ /d_p]$ ....**Equation 2**

If $d_p > 10\ (h_s + h_r)$ ....**Equation 3**

Where:

h_s = the source height (m)

h_r = the receiver height (m)

D_p = the distance between the source and receiver projected to the horizontal ground plane (m)

C_0 = a factor (dB) which depends on local metrological statistic for wind speed and direction and temperature gradients.

ISO9613 states that an elementary analysis may be established from the above two equations from local meteorological statistics. For example, if the meteorological conditions favorable to propagation occur for 50% of the time period of interest the attenuation during the other 50% is higher by 10dB or more then the sound energy which arrives for meteorological conditions unfavorable to propagated may be neglected and C_o will be approximately + 3 dB. The frequency or frequency weighting should be given.

ISO9613 also states that experience indicates a value of C_o in practice is limited to the range from zero to approximately + 5dB and values in excess of 2dB are exceptional, with only elementary statistics being required for local meteorological conditions for a + /- 1 dB accuracy for $C_{0.}$

Terrain and Vegetation [1,5,6,9]

Research on propagation through trees has produced greatly conflicting results. It is clear, though trees appear to be more of a benefit aesthetically than acoustically. Some research says a band of trees 50m+ is required in order to achieve any significant attenuation.

Taller vegetation, where propagation tends to occur through the medium rather than being reflected from it, is of importance if only because the use of natural screens is often advocated as a means of confining the noise from such things as ground-transportation systems.

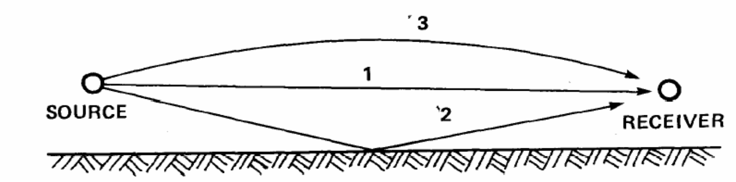


Figure 4: Outdoor sound propagation near the ground [5]

Eyring studied propagation through the Panamanian jungle, Wiener and Keast through dense evergreen forests. Embleton studied propagation through homogeneous deciduous and evergreen woods, whilst Aylor has reported data relating to dense hemlock and red-pine plantations and to hardwood brush.

Typically attenuation rates of 0.2dB/m have been found, so that rather thick belts of trees would be required to achieve effective noise screening i.e 25m or 50m of dense trees for a "theoretical" attenuation value of 5 and 10 dB respectively.

Sound transmission near the earth's surface involves essentially three components of sound paths, shown schematically in Figure 4.

The ground-reflected sound (path 2) may arrive at the receiver either in phase or out of phase with the direct sound (path 1) and may either increase or decrease the received sound level. The ground surface may be hard or soft (reflective or absorbent), and this also affects the phase and magnitude of the reflected path.

Paths 1 and 2 usually determine the sound levels at the receiver, but a solid barrier for example can practically eliminate these paths. In such situations, path 3 may become significant. Path 3 is made up of relatively low level sound that is refracted (bent) or scattered back to Earth by numerous small patches of inhomogeneous air of varying temperatures, speed, direction and density etc. Field studies show that when paths 1 and 2 are virtually eliminated, there remain sound levels that are in the order of 20dB to 25dB below the path 1 and 2 sound levels. These are the sound levels arriving by way of the numerous paths that together make up path 3.

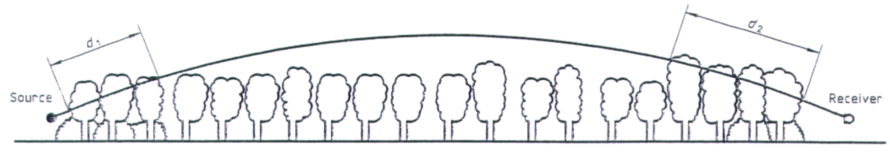
As discussed above certain vegetation and foliage provides a small amount of attenuation (if any), but only if it is sufficiently dense to fully block the view along the propagation path. This attenuation may be due to vegetation close to the source, close to the receiver, or both.

In addition to the potential attenuation loss for thick shelter belts (*dense pine woods*) Figure 5 presents the approximate insertion loss of a 100 foot deep (30m) growth of medium-dense woods made up of a mixture of deciduous and coniferous trees having a height in the range of 20 to 40 feet (6 to 12m). For this density, the visibility penetration is about 70 to 100 feet (20m to 30m).

Although this topic is normally misunderstood or neglected it appears that research results indicate that trees and scrubs used in research can provide only minor attenuation

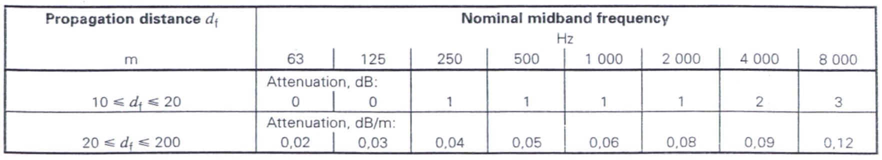
Octave Band (Hz)	Insertion Loss (dB per 100ft (30m) of dense woods)
31	0.0
63	0.5
125	1.0
250	1.5
500	2.0
1000	3.0
2000	4.0
4000	4.5
8000	5.0

Figure 5: Insertion loss of growth of dense woods [5]



NOTE — $d_f = d_1 + d_2$

Figure 7: Attenuation due to propagation through foliage increases linearly with propagation distance d_f through he foliage. Note for calculating d_1 and d_2 the curved radius may be assumed to be 5 Km [10]



Propagation distance d_f	Nominal midband frequency Hz							
m	63	125	250	500	1 000	2 000	4 000	8 000
$10 \leqslant d_f \leqslant 20$	Attenuation, dB: 0	0	1	1	1	1	2	3
$20 \leqslant d_f \leqslant 200$	Attenuation, dB/m: 0,02	0,03	0,04	0,05	0,06	0,08	0,09	0,12

Table 8: Attenuation of an octave band of noise due to propagation through dense foliage [11]

through scattering by the dense trunks and branches.

However hedges and trees provide little to nil attenuation unless extremely dense with branches reaching to the ground, even then the application of sound attenuation is very limited. Unless the hedge or trees are extremely tall sound will propagate over them rather than through it. Generally speaking it is not recommended that vegetation is used or relied on for any form of real life attenuation loss in noise calculations or predictions. Figure 6 gives some possible values for sound attenuation over various grass thickness and tree type.

Trees and other barriers which block line of sight may also have a physiological effect. If a person can not see the sound source (which may be disturbing them) they may not be as anxious.

Annex A of ISO9613 discusses foliage. ISO9613 states that trees and shrubs provide a small amount of attenuation, but only if it is sufficiently dense to completely block the view along the propagation path i.e. when it is impossible to see a short distance through the foliage. Table A.1 of ISO9613 provides additional information regarding the attenuation across the octave band for propagation through foliage given as d_f. The formula for d_f. is given as follows:

$d_f = d_1 + d_2$...........................Equation 4

For calculating d_1 and d_2 the curved radius may be assumed to be 5km.

The attenuation due to propagation through foliage can be calculated using the ISO9613 method as shown in Figure 7 and Figure 8.

Industrial Sites and Urban Areas [1]

Special attention is required for urban situations. The noise source parameters are usually less constant than in open space (speed variations, transient driving). The propagation computation is governed by a large variation of local wind profiles, often defined by building orientations (street canyons).

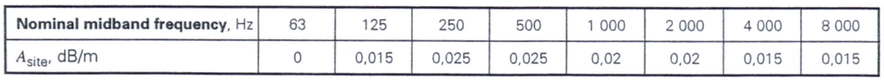
ISO9613 provides information of the effects from miscellaneous objects such as 1) industrial sites and 2) housing. The standard states attenuation can occur due to scattering from installation which is described in ISO9613 as A_{site}. The term installation in ISO9613 is described as pipes, valves, boxes and structural elements. It is noted in ISO9613 that attenuation depends strongly on the site. ISO9613 provides Table A.2, reproduced as Figure 9 below illustrating the attenuation of noise propagation through installations.

Housing [1]

ISO9613 states that when either the source or receiver or both are situated in a built up region of houses an attenuation will occur due to screening

	Attenuation db/100m			
Frequency (Hz)	Thin Grass (0.1-0.2m) H	Thick Grass (0.4-0.5m) H	Evergreen Trees Height unknown	Deciduous Trees Height unknown
125	0.5	0.5	7	2
250	-	-	11	4
500	-	-	14	6
1000	3	12	17	9
2000	-	-	19	12
4000	-	15	20	16

Figure 6: Commonly used values for sound attenuation [9]



Nominal midband frequency, Hz	63	125	250	500	1 000	2 000	4 000	8 000
A_{site}, dB/m	0	0,015	0,025	0,025	0,02	0,02	0,015	0,015

Figure 9: Attenuation coefficient of an octave band of noise during propagation through installations at industrial plants [16]

by the houses. ISO9613 goes on to state that the effects may largely be compensated by propagation between houses and by reflection from other houses in the vicinity. ISO9613 provides various information for different scenarios.

Barriers [1,2,5,14]

A barrier is a solid structure that intercepts the direct sound path from a source to a receiver. It provides a reduction in sound pressure level within its “shadow zone.”

A wall, a building, a large mound of earth, an earth berm, a hill, or some other form of solid (dense) structure can serve as an acoustic barrier.

When a barrier is installed between the source and receiver some sound energy is transmitted through the barrier, some is reflected and some is diffracted over or around the barrier. These three basic concepts are illustrated in Figure 10.

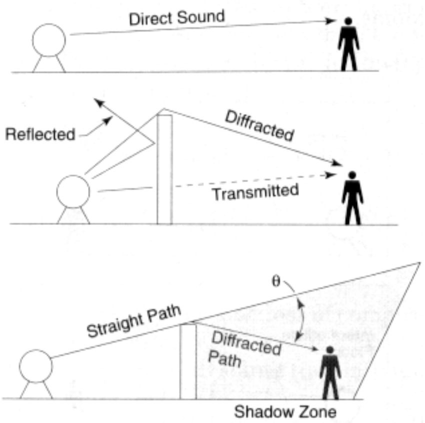


Figure 10: Three basic concepts regarding acoustical barriers [12]

The noise reduction due to the barrier at the receiver’s location is referred to as the insertion loss, which is based on the extension of the path of the diffracted sound wave to the barrier induced insulation in the shadow zone. The sound energy reflected depends upon the absorptive surfaces of the barrier.

The sound transmitted through the barrier depends upon its sound transmission loss of the barrier. Sound diffracted over or around the barrier will be attenuated by increasing the barrier height and length.

A “shadow zone” is created by locating a barrier between the source and receiver. The sound diffraction will depend upon the diffraction angle θ. As θ increases so does the barrier attenuation.

The insertion loss of a barrier at a given point is defined as the difference in sound pressure level (measured at that point) before and after the barrier is constructed.

The insertion loss (D_{IL}) can also be calculated (and measured) using Equation 5 below.

$D_{IL} = L_p(\text{before}) - L_p(\text{after})$ ....Equation 5

Insertion loss can be defined for sound of a single frequency, or a band of frequencies or a broad band source. Insertion loss is of direct practical interest to those considering the construction of a barrier.

The insertion loss of a barrier varies with several parameters, most notably the frequency of the sound (generally the higher frequencies are attenuated more) such that barriers, walls or screens will act to create an acoustic shadow.

The reduction in sound level within this shadow zone is dependant on frequency.

At high frequencies the effect of the barrier is most pronounced whereas at low frequencies diffraction could occur at the edges, so the shadow affect is diminished as illustrated in Figure 11.

There are a number of computationally intensive methods for calculating the shadow effect

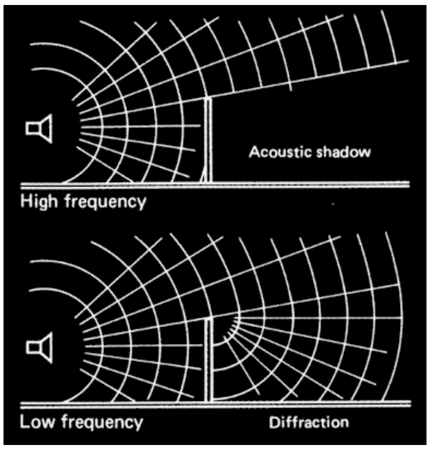


Figure 11: Concept of shadow affects for a barrier in relation to high and low frequency sound waves [2]

reduction; however, a simple desk top method is set out as follows;

R=10*log(3+((40fd) /c))....**Equation 6**

Where

R is the reduction (dB) over the inverse square law

f is the frequency (Hz), d the path length difference (Refer to Figure 12 below)

c is the speed of sound.

A further method known as the Maekawa Method may be used to work out the approx attenuation of a thin rigid barrier between the source and receiver. The following formulae may be used:

Eb = 10*log (3 + 40 x/λ) dB....... ....**Equation 7**

Where

λ = Wave length of the sound (m)

x = Path Length Difference (a+b-c). The difference in path length between the direct path and the path over the barrier can be calculated using Figure 12.

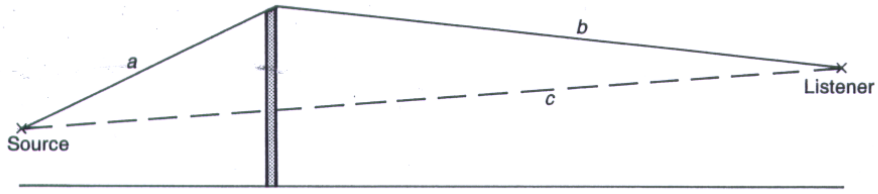


Figure 12: Diagram of the Path Length Difference (PLD) for a simple thin acoustic barrier [17]

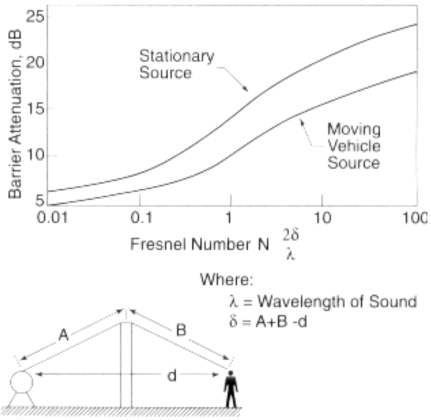


Figure 13: Attenuation and given frequency by means of the *Fresnel Number* for stationary and moving vehicle [12]

Note 1: In Figure 12 the source and receiver locations are on the same relative ground level.

Note 2: A "thin" barrier is described as having only one edge where as a thick barrier has two edges.

Mathematically the geometric relationship between the source, barrier and receiver can be related to barrier attenuation and given frequency by means of the **Fresnel Number (N)** as shown in Figure 13 below for stationery and moving vehicle sources.

A thin barrier is one in which diffraction occurs at a single edge, as shown in Figure 14 (a). A solid fence, of the type usually constructed to be a noise barrier fence, and a free standing wall are two examples of a thin barrier. A thick barrier is a barrier in which diffraction occurs at two edges, i.e. another diffraction point is provided as shown in Figure 14 (b).

A building or an earth berm with a wide flat top are examples of a thick barrier. Generally, if the barrier thickness is greater than 3m, a barrier is regarded as thick for sound components of all frequencies. If the thickness t is less than 3m, the barrier is still regarded as thick for sound components of wavelength less than t/5.

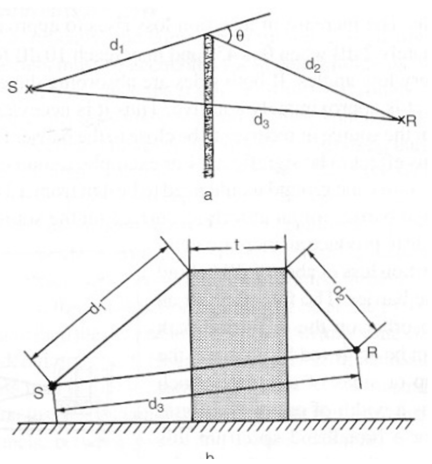


Figure 14: (A) Top: Diffraction at a single edge. (b) Bottom: Diffraction of a thick barrier. Note diffraction occurs at two edges with a thick barrier [17]

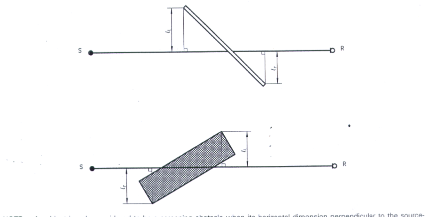


Figure 15: Plan view of two obstacles between the source (S) and the receiver (R) [13]

Insertion loss can be determined by means of calculation or measurement. The approximate insertion loss of an outdoor barrier can also be estimated.

Figure 15 represents a plan view of two obstacles between the source (S) and the receiver (R) which can be used to calculate if the object will act as an effective barrier. An object is only considered to be a screening obstacle when its horizontal dimension perpendicular to the source-receiver line SR is larger that the wavelength i.e. $L_1 + L_r > \lambda$.

One method of calculating the attenuation of a barrier with simple geometry (single barrier edge) is given below. Figure 16 illustrates the

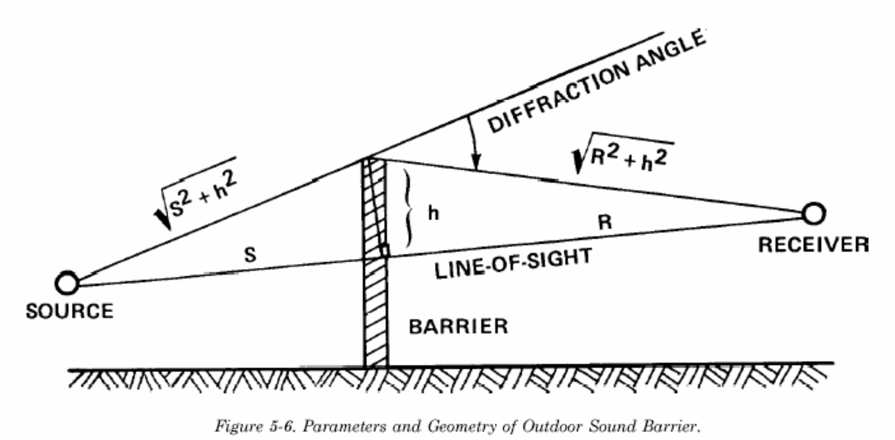


Figure 5-6. Parameters and Geometry of Outdoor Sound Barrier.

Figure 16: Geometrical aspects of an outdoor barrier [5]

geometrical aspects of an outdoor barrier where no extraneous surfaces reflect sound into the protected area. The insertion loss provided by the barrier to the receiver position is a function of the path length difference between the actual path traveled and the line-of-sight direct path.

Large values of barrier height "h" above the line-of-sight path produce large values of the diffraction angle and large values of path length difference, which in turn provide strong shadow zones and hence large values of insertion loss.

Note In Figure 17, the direct line-of-sight path length is S+R, and the actual distance traveled is:

$(\sqrt{s^2 + h^2} + \sqrt{R^2 + h^2})$ ....**Equation 8**

Then the path length difference (PLD) is given by:

$PLD = (\sqrt{s^2 + h^2} - S + \sqrt{R^2 + h^2} - R)$ ....**Equation 9**

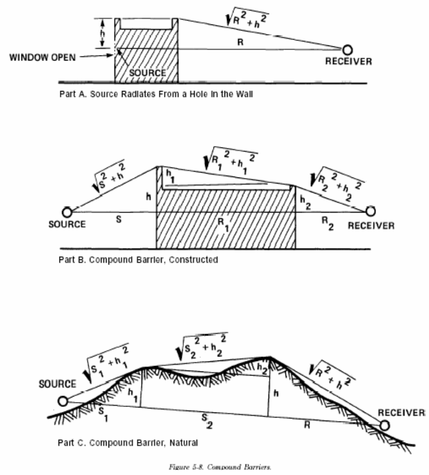


Figure 17 A,B,C: Example of three complex compound barriers [5]

Figure 17 below illustrates three common situations that do not fall into what may be deemed simple geometry as shown in Figure 16. The procedure suggested here is to estimate the path length difference and use relevant tables (not provided) to obtain the insertion loss.

In Part a of Figure 17, the source could be a wall-mounted exhaust fan, an inlet to a ventilating fan, or a louvered opening permitting air into (and noise out of) a mechanical equipment room. The conventional source distance S is zero and the slant distance becomes h. Thus, the total path length difference:

$(h + \sqrt{R^2 + H^2} - R)$ ....**Equation 10**

In Part B of Figure 17, the path length difference is calculated from three triangles, as follows:

$PLD = [(\sqrt{s^2 + h^2} - S + (\sqrt{R_1^2 + h_1^2} - R_1) + (\sqrt{R_2^2 + h_2^2} - R_2)]$ ....**Equation 11**

Part C is solved with similar mathematical methods to Parts A and B,

Figure 18 illustrates a side elevation of a cooling tower regarding two alternative positions and path length difference calculations.

The noise reduction caused by a barrier depends on two factors namely the path length difference of the sound wave as it travels over or around the barrier compared with direct transmission to the receiver (a + b - c)

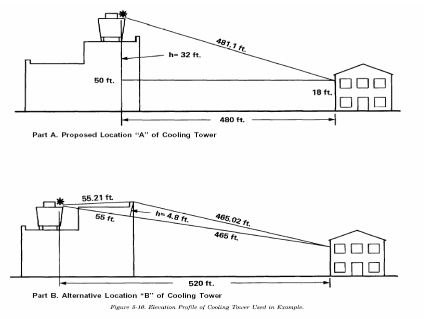


Figure 18: Example of side elevation of a cooling tower in two alternative positions regarding path length difference calculations [5]

and the frequency content of the noise.

It is impossible to define an optimal barrier in absolute terms. Generally for any barrier to work it must meet the following requires (reproduced from ISO9613):

- The surface density is at least 10 kg/m2 or greater depending upon sound level and frequency components (e.g. lots of sound energy present in the low frequency region);
- The object has a closed surface without any cracks or gaps;
- The horizontal dimension of the object normal to the source receiver line is larger than the acoustic wavelength at the nominal frequency for the octave band of interest in other words $L_1 + L_r > \lambda$.

The acoustic performance of any barrier is determined by its position, height, length, absorbing and reflective characteristics. A barrier is most effective when placed very close to the source.

It should be remembered that a barrier performance can be reduced by temperature and wind gradients.

The reduction of propagated noise depends on the extent of the sound shadow which in turn depends on the total effective height of the obstruction.

The sound shadow can be increased either by increasing the effective height of the obstruction or by moving it closer to the source.

The sound shadow cast by a barrier is much less clearly defined than the light shadow cast by an opaque body, and some sound will be diffracted over the top and round the ends of any practical noise barrier.

This indicates that a practical barrier need only attenuate transmitted sound sufficiently to reduce it to a level less than the level of diffracted sound.

The contribution from diffracted sound increases as the receiver moves away from the barrier.

It is also extremely important to consider the reflective and absorbent properties of any barrier. When the sound hits the barrier (a solid object) the energy is predominantly reflected.

It is important to note that the sound energy when reflected is simple being "moved around" and it does not just substantial dissipate.

If the energy is attenuated from reaching the receiver on the other side of the barrier it may simply end up being "dumped" some where else in the immediate environment.

To help solve the problem the noise barrier reflecting can be designed to specifically absorb sound energy over the entire frequency or a specific range.

The absorptive characteristics of any material are a function of the frequency of the sound wave. Noise barriers may therefore be designed to either insulate the noise striking it by reflecting it back or prevent its transmission through the barrier, hence insulating the adjacent shadow zone.

References

The above article has been complied from previous research carried out by other authors, and anything referenced in this paper has been directly reproduced from the original authors work as referenced below.

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