FROM CONCERT HALLS TO NOISE BARRIERS: ATTENUATION FROM INTERFERENCE GRATINGS

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ABSTRACT

The seat dip effect is a low-frequency attenuation affecting sound travelling at grazing incidence over seating in auditoria. It is caused by scattered sound from the seats interfering with sound travelling directly from the source on the stage. In outdoor noise control, the simple single noise barrier gives good attenuation at high frequencies, but is limited by diffraction at low frequencies. This paper presents some results from an attempt to exploit seat dip attenuation as a tool to control outdoor noise propagation. Boundary element calculations are used to explore the effects of multiple low barriers, trenches, scaling and geometry.

1. INTRODUCTION

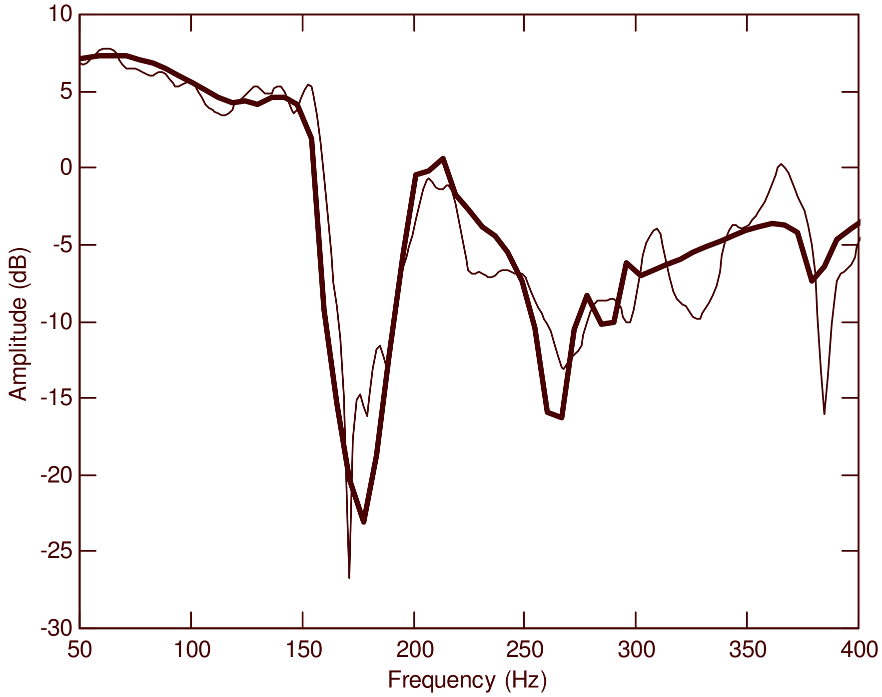
Seat dip attenuation is the anomalous low-frequency attenuation suffered by sound travelling at grazing incidence over rows of seats. The effect was first reported by two teams in 1964 [1, 2] during an investigation of the poor acoustics of the New York Philharmonic Hall. The reports communicated the alarming fact that the attenuation could be as severe as 20 dB around 150 Hz. A larger attenuation will be observed if the angle of incidence approaches closer to grazing, or the sound travels over more rows of seats; a smaller attenuation will be observed if the receiver height is increased. Figure 1 shows a recently measured seat dip attenuation spectrum, for sound passing over eight rows of 1:10 scale model seats [3].

There have been several explorations of the effect and yet complete agreement on the cause of seat dip attenuation does not yet exist. The reports of Sessler and West and of Schultz and Watters concluded that the effect seemed mainly due to a vertical resonance in the gaps between the rows of seats. This frequency domain explanation has been followed by Bradley [4] who argued for both vertical and horizontal resonances. However, frequency domain models do not explain every aspect of the seat dip effect. For example, the attenuation changes over time in the very early sound field [5]. Ishida et al [6] were the first to explain seat dip effect in the time domain: many small reflections from the seats and floor produce a complicated impulse response immediately after the arrival of the direct sound from the stage. The seat dip attenuation is simply what results when this impulse response is Fourier Transformed. More recent measurements have supported this idea [7]. An array of seats can thus be thought of as a diffraction grating for low frequency sound: the seat dip is an interference pattern.

Because the effect is known to be subjectively perceptible [8], several schemes have been suggested for reducing the attenuation, by modifying the impedance of the floor [9] or its shape [3]. (The attenuation is quite resistant, though: most modifications simply move it to another frequency.) What is a problem in auditoria could become a benefit for environmental noise reduction, however. An array of low barriers will produce the same kind of seat dip attenuation spectrum. This is of interest for several reasons: (1) the source and receiver can be in direct line of sight of each other, (2) the attenuation can be large at low frequencies – this is hard to achieve with a conventional single high barrier and (3) it may be possible to tune the resonant frequency by adjusting the dimensions and / or impedances of the barriers.

There is a previous report in the literature of this sort of scheme for noise reduction [10]. Van der Heijden and Martens found significant attenuation by arrays of parallel walls between 0.11 m and 0.4 m high. They have suggested that such attenuation results from surface wave exclusion. The purpose of this paper is to exploit the author's experience of trying to *reduce* seat dip attenuation in concert halls to the opposite one of trying to maximise the attenuation for outdoor noise control.

Fig. 1. Seat dip attenuation, measured (thin line) and predicted (thick line)



2. METHOD

The scattering from the barriers was predicted using a two dimensional Boundary Element model (BEM) [11]. The boundary element formation was based on the single frequency form of the Helmholtz-Kirchhoff integral equation for completely rigid surfaces. In this case the pressure *P(r)* for one point source was:

$$\int_S P(\underline{r}_s)\nabla G(\underline{r},\underline{r}_s).\underline{n}_s(\underline{r}_s)\,dS + P_i(\underline{r},\underline{r}_0) = \begin{cases} P(\underline{r}) & \underline{r}\in\Omega \\ \tfrac{1}{2}P(\underline{r}) & \underline{r}\in S \\ 0 & \underline{r}\in\Omega_0 \end{cases} \qquad (1)$$

where $P_i(\underline{r},\underline{r}_0)$ was the sound pressure direct from the source; $\underline{n}_s(\underline{r}_s)$ the outward pointing unit vector normal to the surface at $\underline{r}_s$, and $G(\underline{r},\underline{r}_s)$ the Green's function. The Green's function was the standard two-dimensional form:

$$G(\underline{r},\underline{r}_s) = -\frac{i}{4}[\,H_0^{(1)}(k\,|\underline{r}-\underline{r}_s|) + H_0^{(1)}(k\,|\underline{r}-\underline{r}_s'|)\,] \qquad (2)$$

where $H_0^{(1)}(x)$ was the Hankel function of the first kind of order zero. The second term in Eq. (2) was used when dealing with half space and creates image source effects, $\underline{r}_s'$ being the location of the image source. Figure 2 shows definitions of the vectors used.

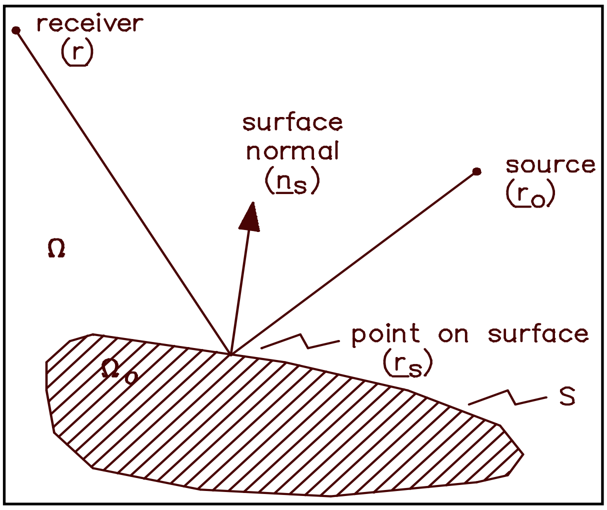


Fig. 2. BEM vectors.

The BEM solution technique involved first subdividing the surface into a set of elements across which the pressure was assumed constant. For this a subdivision of λ/16 or smaller was used. This small subdivision was required because the interference pattern close to the seating array was delicate and sensitive to changing conditions. Once the surface was subdivided the calculation proceeded in two steps: first an evaluation of the surface pressures was made via simultaneous equations, then the pressures at external receiver positions were calculated by a simple surface integral. The CHIEF [12] was used confirm unique solutions. No allowances for corners and edges were made in the application of Eqn. (1). Two-dimensional methods were used for the predictions, with a cross-section through the seating array being defined; this vastly reduced the number of surface elements compared to three-dimensional BEMs and thus greatly decreased calculation times.

To test the validity of the prediction method, the pressure above a simple array of hard seats was compared to scale model measurements. Figure 1 shows a comparison between the experimental results and the BEM predictions. The spectrum is shown at a typical seat, where the sound had passed over eight rows of seats before reaching the microphone. Figure 1 shows that a very good degree of agreement had been achieved, especially considering this was a delicate interference pattern between many reflections, with the source and receiver very close to the seating array.

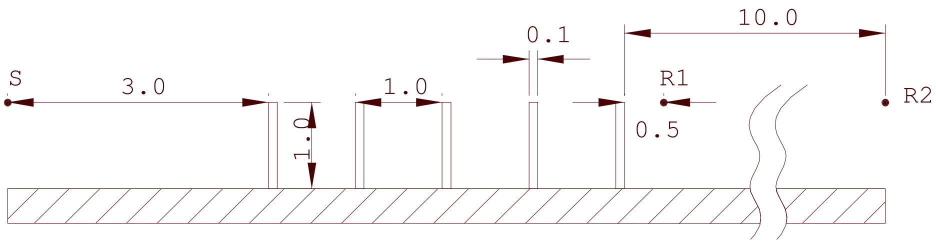


Fig. 3. Basic barrier insertion loss set-up, with source S and two receivers R1, R2.

The advantage of the BEM scheme is that many different configurations can be tested quite quickly. Figure 3 shows the basic barrier set-up. It consists of five barriers, each 1 m high and 0.1 m thick, spaced 1 m apart. The source S is 3 m from the nearest barrier and has a variable height. Two main receiver positions are defined: R1 is 0.5 m away from the barrier array and R2 is 10 m away; both have variable height. In the results presented here, the ground is acoustically soft (absorbent). This is because the effects of the barrier array are clearer when the hard ground reflection is removed. The rest of the paper explores the effects of a few parameters: source and receiver positions, barrier height, using trenches instead of barriers, and combining trenches with a bund for broadband attenuation.

3. RESULTS AND DISCUSSION

3.1 Source and receiver position.

Fig. 4. Effect of source height at R1: 1.0 m (blue), 1.1 m (red), 1.3 m (cyan), 2.0 m (black)

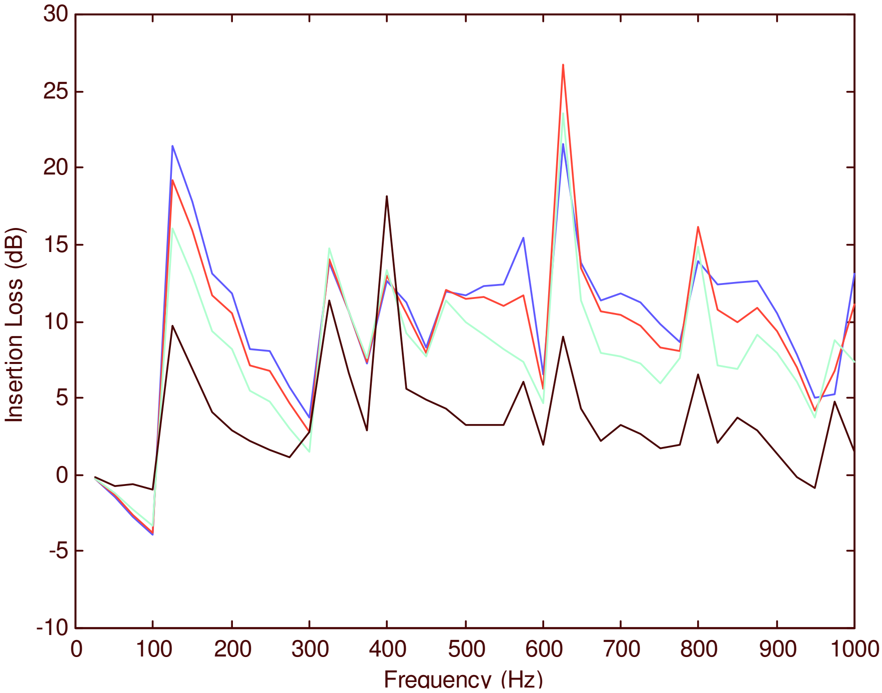


Fig. 5. Effect of receiver height at R1: 0.9 m (blue), 1.1 m (red), 1.3 m (green), 1.5 m (black)

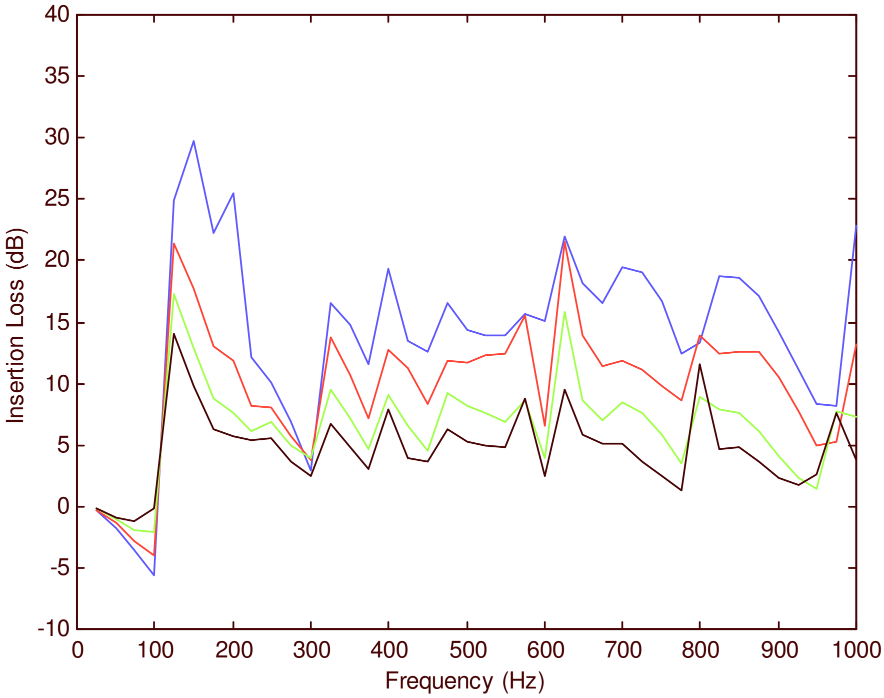
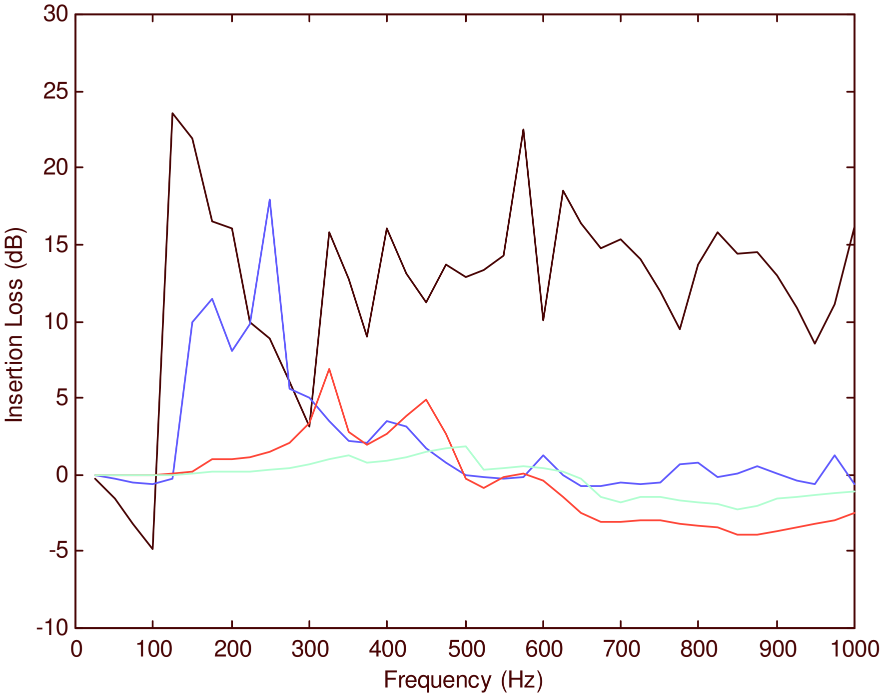


Figure 4 plots the insertion loss of the five barriers shown in Fig. 3. The parameter in Fig. 4 is the height of the source; the receiver R1 is at a height of 1 m, so source and receiver are always in direct sight of each other. As the source is raised from grazing incidence (1 m), the insertion loss generally decreases. The main peak at around 100 Hz is quite characteristic of seat dip attenuation graphs measured in auditoria. The insertion loss of 15 to 20 dB at 100 Hz is much greater than can usually be achieved by a conventional single barrier.

Figure 5 shows how the insertion loss varies with receiver height, for a fixed source position. A receiver height of 0.9 m is slightly in the shadow zone and this gives the highest attenuation. Increasing the receiver height reduces the insertion loss at almost all frequencies, though the low-frequency peak is still quite strong at the highest receiver. The performance at the far receiver R2 (not shown) is similar, though the differences between receiver heights are less marked. This is because at 10 m away, all are quite close to grazing incidence.

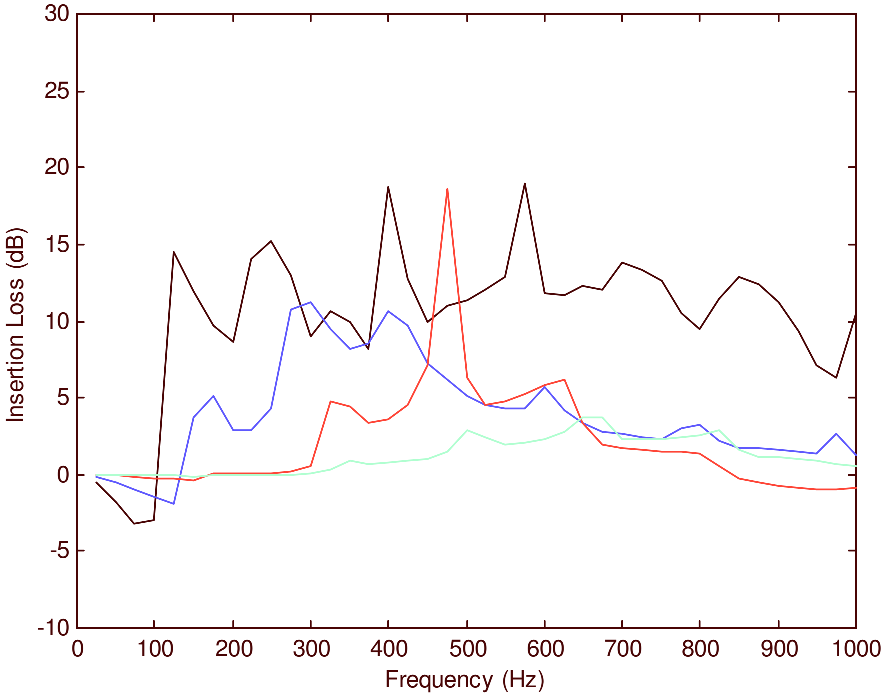
Fig. 6. Effect of barrier height at R1: 1.0 m (black), 0.5 m (blue), 0.2 m (red), 0.1 m (cyan)



3.2 Barrier height.

How small a barrier is needed to produce the interference effects that give rise to the attenuation? Figure 6 shows what happens at the near receiver R1 when the barrier height is reduced in steps from 1 m to 0.1 m. This seems quite as expected: the half-height barriers still produce a strong low-frequency peak in insertion loss, but the even smaller barriers seem to be perhaps too small. However, the story is a little different at other receiver positions, as Fig. 7 shows. Here, the effect of barrier height at the distant receiver R2 is plotted. The overall trend is the same: insertion loss decreases as barrier height is decreased. There is, though, an interesting peak in attenuation at 475 Hz for the 0.2 m barriers. This configuration was subjected to a perturbation analysis, to see how sensitive this peak was to small changes in barrier height and receiver position. It was found that the peak was sensitive to changes in barrier height and to vertical but not horizontal movements in receiver position. This large attenuation could be perhaps be tuned in a specific application where the source and receiver position are known and fixed, so that valuable noise control might be achieved with very low barriers. It might also be possible to reduce the ‘Q’ of the peak by applying some absorption.

Fig. 7. Effect of barrier height at R2: 1.0 m (black), 0.5 m (blue), 0.2 m (red), 0.1 m (cyan)



3.3 Trenches.

The interference required at the receiver can also be provided by cutting trenches into the ground instead on placing barriers on it. Figure 8 shows a typical result when trenches the same size as the barriers in Fig. 3 are used. A strong peak in low-frequency insertion loss is seen. Over many receiver positions, the attenuation does not vary much with the depth of the trench. Some combinations of receiver position and trench geometry produce larger attenuations, though, as is seen for the 0.1 m case in Fig. 8. For most receiver positions there is a strong single peak in IL. The frequency of this moves around quite a bit with receiver position: it decreases markedly as receiver height increases, and increases (less markedly) as the receiver moves away from the source. One receiver position has a double peak, which hints that the other positions may have more peaks at higher frequencies. The effect of trench width was also examined, but over the range of 0.1 m to 0.5 m this had little effect.

3.4 A bund with trenches.

One possibility offered by these new low-frequency attenuation gratings is that they could be combined with a traditional barrier to give a broadband high insertion loss. One way of doing this would be to take a typical earth bund and dig trenches into the top of it. Figure 9 illustrates a possible profile, with three trenches let into the horizontal top of a bund. The insertion loss of this structure was predicted, with trench depth and receiver height as variables. Three different profiles were tried: a bund with no trenches, one with trenches 0.2 m deep, and one with trenches 0.5 m deep. The results are shown in Fig. 10. It can be seen that the bund with no trenches exhibits the typical insertion loss rising with frequency – at low frequencies its attenuation is limited by diffraction. Once trenches are added, however, a strong low frequency peak is added. The frequency of the peak seems to depend on the depth of the trenches, with the deeper trench giving a lower frequency peak. This suggests possibilities for tuning the peak frequency and also, perhaps, for creating peaks at more than one frequency by using trenches of different depths.

Fig. 8. Effect of trench depth at R1: 0.5 m (blue), 0.2 m (red), 0.1 m (cyan)

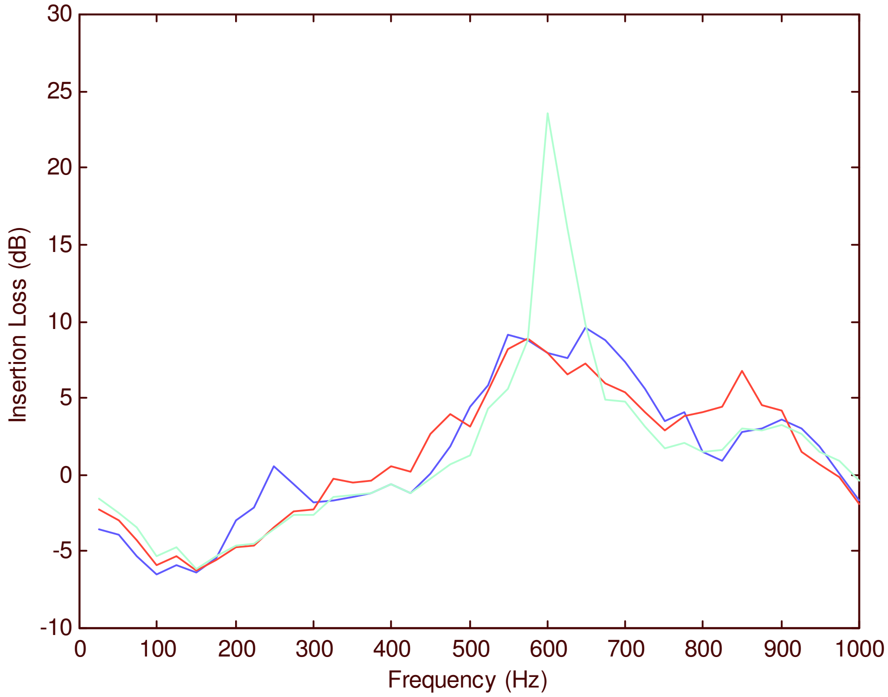
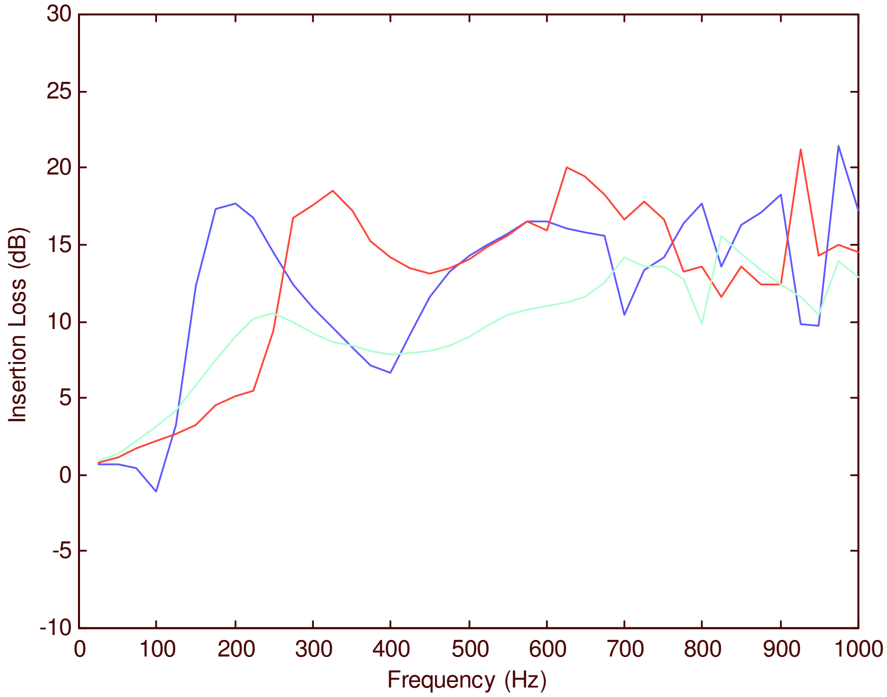


Fig. 10. Effect of trench on bund at R1 (1 m high): 0.5 m (blue), 0.2 m (red), 0 (cyan)



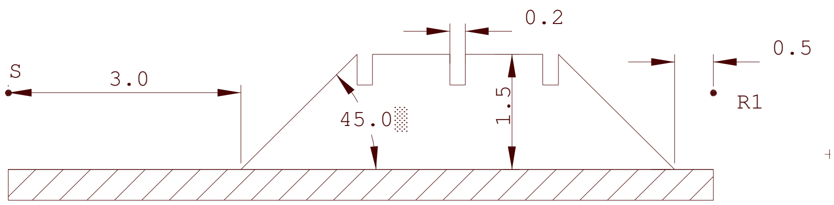


Figure 9. Set-up for prediction of bund insertion loss.

4. CONCLUSIONS

An initial study has been made to exploit the seat dip effect to provide designs for low frequency noise barriers. Attenuation is achieved by destructive interference from multiple diffracted waves arriving at the receiver. It has been shown that substantial low frequency insertion losses can be achieved by using a few low barriers or trenches with the source and receiver in direct sight of each other. The frequency and size of the insertion loss peaks depend on source and receiver position, the height of the barriers or (partially) the depth of the trenches. Combining the trenches with a traditional earth bund produces a possible prototype for a broadband barrier, one which gives a high insertion loss across a wide frequency range.

There is much which could be investigated to explore and improve this effect further. A fractal array of different-sized barriers or trenches might be used to give multiple insertion loss peaks at many frequencies. The effects of surface roughness and absorption have also yet to be investigated. With a quicker, perhaps less accurate prediction technique, one might attempt to optimise the barrier profile numerically to give a desired graph of insertion loss versus frequency.

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