Journal of Sound and Vibration (2001) **243**(1), 173–181
doi:10.1006/jsvi.2000.3462, available online at http://www.idealibrary.com on IDEAL®

LETTERS TO THE EDITOR

IMPROVED METHOD FOR SELECTING SCALE FACTORS AND MODEL MATERIALS FOR SCALE MODELLING OF OUTDOOR SOUND PROPAGATION

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(*Received* 12 *February* 1999, *and in final form* 29 *August* 2000)

1. INTRODUCTION

Critical to the development of an acoustical scale model to be used to measure the effectiveness of roadside noise barriers is the selection of both a model scale and materials with which to construct the scale model. Previous work on acoustical scale modelling has typically proceeded by first selecting a scale factor, and then selecting appropriate scale-model materials. This paper reports an improved technique for simultaneously specifying both the optimal scale factor and the optimal modelling materials. The technique was used to specify both a scale factor and model materials to simulate asphalt, hard-packed-earth berms and ground, reflective noise barriers and acoustically hard and soft surface treatments, for use in a subsequent scale-model study of optimal roadside noise-barrier design [1, 2].

Model materials—for example, materials to model the ground and noise barriers — are sought that have the best possible scaled acoustical properties when compared to the real surfaces at the test frequencies of interest. The fundamental acoustical property for these materials is the normal-incidence acoustical impedance of the locally reacting boundary. Real ground materials are not of use in modelling their own acoustical properties at scaled frequencies, since they do not have the same properties after scaling. The accurate choice of model materials is crucial to the accuracy of the scale-model tests.

2. BACKGROUND

A review of the literature on the selection of model materials for outdoor scale modelling revealed a variety of techniques applied to the selection of a variety of model materials.

The material-selection process, involving a comparison of the flow resistivity and porosity of full- and scale-model materials, was discussed qualitatively by Delany, Rennie and Collins [3, 4]. It was concluded that a material denser than its corresponding full-scale counterpart is necessary to model ground successfully. Insulite (11 mm soft board) was used to simulate grassland for scale-model tests. Day [5] noted that a scale-model material that is acoustically analogous to a full-scale material might not be physically analogous in terms of its scaled microstructure, due to physical phenomena that do not scale linearly. As a result, a material that works at one scale factor may not work at another. For the scale modelling of fibrous materials, Voronina [6] discussed the relationship

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between layer thickness and material density, with reference to the non-linear aspects of material scaling.

Jones *et al.* [7, 8] described the development of a scale-modelling facility. Scale-model materials were selected by assuming surfaces of local reaction and by comparing the normal-incidence surface impedance to values associated with outdoor grounds. At 1 : 80 scale, tissue on polystyrene was found to model grass well.

Osman [9] reviewed previous scale-model studies with reference to the materials used to simulate hard or soft ground, building surfaces, barriers, trees and intervening vehicles. Criteria were presented for the selection of scale-model materials that are either ground surfaces or other-than-ground surfaces, at scales of 1 : 16, 1 : 32 and 1 : 64. Model materials for other-than-ground surfaces were chosen after studying their absorption coefficients. Ground surfaces were studied by way of their excess attenuation (*EA*, defined below), without reference to parameters such as effective flow resistivity. Buildings and barriers were simulated using wall, mounting, crescent or illustration boards. Rigid foam was used as an absorptive material to simulate soft ground; hard ground was simulated at all scales by 10 mil vinyl sheet. At 1 : 16 and 1 : 32 scales, soft ground was simulated using fiberboard; at 1 : 64 scale, a felt layer was used. Materials were also proposed for the scale modelling of trees—wood doweling, wire and crumpled paper.

Hutchins *et al.* [10] further refined the state of the art in selecting scale-model materials at 1 : 80 scale by using the Delany and Bazley surface-impedance model [11] in conjunction with *EA* predictions for a local-reaction boundary. The Delany and Bazley model was used to generate a least-squares fit between measurements and predictions of *EA*. The best-fit flow resistivity was considered to be the effective flow resistivity. Sanded sheets of expanded polystyrene covered with tissue were found to have an effective flow resistivity of approximately 300 c.g.s. Rayls/cm (as for grass); unsanded sheets of expanded polystyrene covered with tissue were found to have an effective flow resistivity of approximately 600 c.g.s. Rayls/cm (as for gravel).

Almgren [12, 13] studied theoretically and experimentally the effect of the acoustical boundary layer on the scale modelling of sound propagation above a solid surface. It was shown that the non-linear effects of frequency scaling are compounded by this boundary layer which results in a non-zero admittance at the surface of a material that adds to the pre-existing admittance of the material. Furthermore, unlike the case of a local-reaction surface, the acoustical-boundary-layer admittance depends on the angle of incidence of the sound, so that the effective impedance of the surface also displays angular dependencies. The effect is amplified with the proximity of a source and receiver to the surface. Errors of 1–7 dB were observed in studies of *EA* over full-scale frequencies from 100 to 10 000 Hz as compared to predicted *EA*s at a scale of 1 : 100. The error magnitude varied with geometry, scale and frequency; the apparent absorption of a solid surface increased with frequency.

Yamashita and Yamamoto [14] described scale-modelling techniques at 1 : 50 scale. The ground materials used were vinyl-chloride plate for roads, house and buildings, and thin felt for grassy areas. According to the authors, "The absorption coefficients of the materials in the scale model were adjusted to the same absorption in actual cases."

Pirinchievara [15, 16] employed the effective-flow-resisitivity concept to select materials for a 1 : 20 scale model. Polystirol was found to be good for simulating asphalt, velveteen for grass (200 c.g.s. Rayls//cm) and mineral wool for snow-covered ground.

Rasmussen [17] reported for a scale of 1 : 25 that a canvas layer on a hard surface has an effective flow resistivity of 500 c.g.s. Rayls/cm.

Horoshenkov *et al.* [18] reviewed work on the empirical and theoretical selection of scale-model materials. They noted that few researchers have studied the detailed relationship between the microstructural parameters—i.e., layer depth, tortuosity and porosity—of a material and its impedance at scaled frequencies. They developed a theory and methodology for predicting the microstructural parameters required to obtain correct surface impedances at scale frequencies; they claim that comparisons were good between measurements of a material's reflection coefficient and its predicted value. It was concluded that the first criterion for selecting a material is that the flow resistivity of a scale-model material should be n-times higher than that of the full-scale material. The second criterion is that the statistical distributions of tortuosity, porosity, and number of pores per unit volume should remain unchanged.

3. OBJECTIVES, THEORY AND PROCEDURES

The effective-flow-resistivity approach for selecting scale-model materials represents the current state of the art. A scale factor is chosen and model materials, each with an appropriate effective flow resistivity at that model scale, are selected. The objective of the work reported here was to develop an improved procedure for simultaneously determining both the optimal model scale factor and the optimal scale-model materials. The technique utilizes EA curves, comparing the EA measured in a reduced-scale model of an appropriate full-scale configuration at various model scale factors with full-scale curves predicted for various flow resistivities. Useful values of flow resistivity are those giving the best agreement for some scale factor. Materials were sought which had useful flow resistivities close to the target values for the real ground surfaces to be modelled.

3.1. THEORETICAL CONSIDERATIONS

The impedance Z of a ground surface can, with reasonable accuracy, be predicted over a range of frequencies using the Delany and Bazley model [11] involving a single parameter—the specific flow resistivity σ in c.g.s Rayls/cm—a measure of a material's resistance to air flow: $Z = \rho_o c\,[1 + A\,(f/\sigma)^a + jB\,(f/\sigma)^b]$, in which $A = 9{\cdot}08$, $a = -0{\cdot}75$, $B = 11{\cdot}9$ and $b = -0{\cdot}73$.

The concept of excess attenuation (EA) is used to isolate the contribution of a ground surface to changes in a sound field when that surface is introduced. EA is defined as follows: $EA = L_{p,surface} - L_{p,free\text{-}field} + L_{p,div} + L_{p,air}$. In this expression, sound-pressure levels for a given source/receiver configuration in a free-field ($L_{p,free\text{-}field}$) are subtracted from those in the presence of a surface ($L_{p,surface}$). Additionally, corrections are made to remove the effects of geometrical divergence ($L_{p,div}$), and can be employed to correct for air-absorption losses ($L_{p,air}$) where necessary, particularly in the case of free-field propagation.

The EA of a surface of a given flow resistivity was predicted using methods that assume a locally reacting boundary [19, 20]. The velocity potential of a surface was calculated, including the contributions of the sky wave and the analytical components of the ground wave (reflected plane wave, spherical-wavefront correction and surface wave). The ratio of the predicted velocity potential of the surface (Φ) to the predicted, free-field velocity potential ($\Phi_{free\text{-}field}$) was used to calculate the frequency-dependent changes in the EA:

$$EA = 10\log_{10}\,(\Phi/\Phi_{free\text{-}field}).$$

3.2. EXPERIMENTAL PROCEDURES

Target effective flow resistivities for different outdoor ground materials, as presented by Embleton *et al.* [21], are shown in Table 1. To implement the proposed new method, the EA

TABLE 1

Ranges of effective flow resistivites, σ_{eff}, of common ground surfaces [21]

Ground	σ_{eff} in c.g.s. Rayls/cm
Dry snow	15–30
Sugar snow	25–50
Forest floor	20–80
Grass (e.g., pasture, around public buildings)	150–300
Loose-packed dirt (e.g., roadside)	300–800
Hard-packed sandy silt	800–2500
Limestone chips	1500–4000
Dirt road	2000–4000
Hard-packed, rain-exposed earth	4000–8000
Hard-packed, quarry-dust road	5000–20 000
Asphalt road, sealed by dust and use	~ 30 000

was predicted for an appropriate full-scale geometrical configuration, using scale-model frequencies ranging from 2250 to 88 500 Hz, and for effective flow resistivities varying from a lower limit of 1 to 35 000 c.g.s. Rayls/cm and higher. The following configuration was chosen because it was typical of those involved in subsequent modelling work: flat ground; source height = 0·5 m; receiver height = 1·8 m; and horizontal source/receiver distance = 30 m. Free-field reference levels, required to calculate the *EA*, were calculated from the inferred source sound-power levels using the measured atmospheric conditions. Based on geometrical considerations, the minimum scaling factor of interest was about $n = 25$. Frequency considerations established a maximum scaling factor of about $n = 45$. Scale-model materials were, therefore, evaluated by determining material *EAs* at scales of 1 : 20, 25, 31·5, 40 and 50. The detailed selection procedure was as follows.

(1) For each scale factor, the *EA* of the material was measured in the corresponding reduced-scale version of the chosen full-scale test configuration, over a range of scale-model frequencies corresponding to the full-scale range. To reduce the effects of experimental errors, the results were averaged over three tests at different locations on the material.
(2) For each scale factor, the measured *EA* was compared to the predicted *EA* of the model configuration for various target effective flow resistivities of interest. For each combination of scale factor and flow resistivity, the agreement between prediction and measurement was quantified in terms of the least-squares difference (standard deviation) averaged over the entire frequency range.
(3) The averaged standard deviation results were plotted as contours of equal standard deviation on a two-dimensional grid whose axes were scale factor and effective flow resistivity. On this plotted surface, a material generally revealed regions of relatively low deviation and one or more points of minimum deviation, indicating the useful and optimal combinations of scale factor and flow resistivity for that material respectively. By examining the contour plots for a number of scale-model materials, an optimum scale factor could be chosen, and a set of scale-model materials could be found which act as analogues of real ground materials at that scale factor. Once optimal flow-resistivity and scale-factor combinations were identified, the predicted and measured *EA* curves were plotted together for more detailed evaluation of the agreement.

Candidate scale-model materials that were tested included hard materials such as aluminum sheet (5 mm thick), dense-polystyrene sheet (3 mm thick), varnished particleboard (19 mm thick) and hardboard (3 mm thick, smooth face). Candidate materials for softer surfaces that were tested included expanded polystyrene (Celfort insulation, 25 mm thick), hardboard (3 mm thick, rough face), cotton sheet (one and two layers) and felt (3 mm thick). The cotton sheet and felt tests were conducted by laying the test material on a substrate of varnished particleboard.

4. RESULTS

Detailed results are presented for one material—expanded polystyrene; summary results for all materials tested are presented in Table 2. Figure 1 shows the variation of standard

TABLE 2

Ranges of effective flow resistivities, σ_{eff} in c.g.s. Rayls/cm, of model materials for different scale factors

	Scale factor, n				
Material	20	25	31·5	40	50
Varnished			5900–95 000	2900–24 000	3500–15 000
Dense polystyrene	8600–23 000	7500–39 000	8200–20 000	7400–50 000	3900–27 000
Aluminum sheet		11 250–117 500	6800–37 000	6800–24 000	3700–12 000
Hardboard (smooth)	4500–11 000	3000–28 000	5400–22 000	5200–17 000	2800–5000
Expanded polystyrene	5000–8000	3800–21 000	6600–14 000	3200–8400	4500–8000
Cotton sheet (1-layer)	460–1600	350–1100	320–1000	360–620	400–750
Hardboard (rough)	260–1200	210–880	320–500	130–480	170–270
Cotton sheet (2-layer)	170–480	130–350	82–230	72–220	50–130
Felt	48–150	38–130	47–79	< 44	< 50

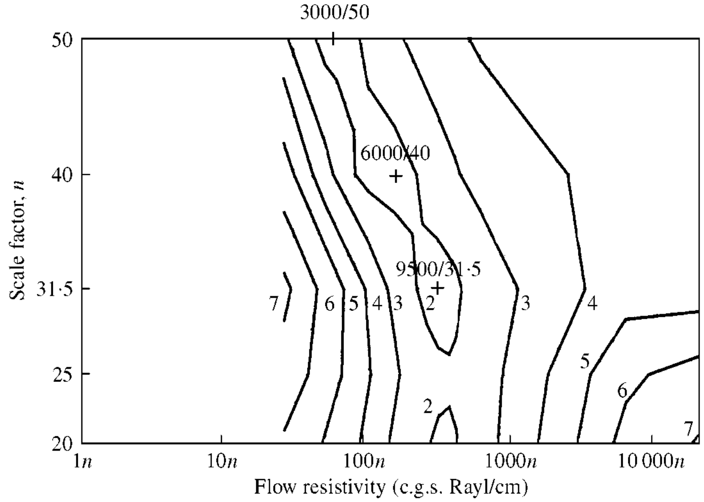

Figure 1. For expanded polystyrene, contour plots of the variation with flow resistivity and scale factor of the frequency-averaged standard deviation between measured and predicted excess-attenuation curves. Several optimal flow-resistivity/scale-factor combinations are indicated. Note that the flow-resistivity scale depends on the scale factor, n.

deviation with flow resistivity and scale factor for expanded polystyrene. A long trough is formed by the lowest 2 dB contour, with the material generally becoming “softer” with increasing scale factor beyond $n = 31{\cdot}5$. Ranges corresponding to low deviation are from 5000 to 8000 c.g.s. Rayls/cm for 1 : 20 scale, 3800 to 21 000 c.g.s. Rayls/cm for 1 : 25 scale, 6600 to 14 000 c.g.s. Rayls/cm with an optimum value of about 9500 c.g.s. Rayls/cm for 1 : 31·5 scale, from 3200 to 8400 c.g.s. Rayls/cm with an optimum value of about 6000 c.g.s. Rayls/cm for 1 : 40 scale, and from 2100 to 4400 c.g.s. Rayls/cm with an optimum value of 3000 c.g.s. Rayls/cm for 1 : 50 scale. Figures 2(a) and (b) show the measured and predicted *EA* curves for the optimal values at 1 : 31·5 and 1 : 40 scale respectively. The general agreement is good but, in the second case, precise conclusions cannot be drawn since the interference minimum is not fully evident as the *EA* reaches a minimum at or beyond the equivalent full-scale frequency range at 1 : 40 scale.

The comparisons of measured *EA* to predicted *EA* showed that the effective flow resistivity of a scale-model material varies with the scale factor being employed—the measured *EA* curves are different at each scale factor. These results reinforce the fact that there are acoustically significant phenomena that do not scale linearly with frequency. Acoustically softer materials tended to exhibit a distinct minimum in their *EA* spectra. Acoustically harder materials often exhibited a distinct minimum at or below 1 : 31·5 scale, which was lacking for the corresponding 1 : 40- or 1 : 50-scale spectra. The absence of

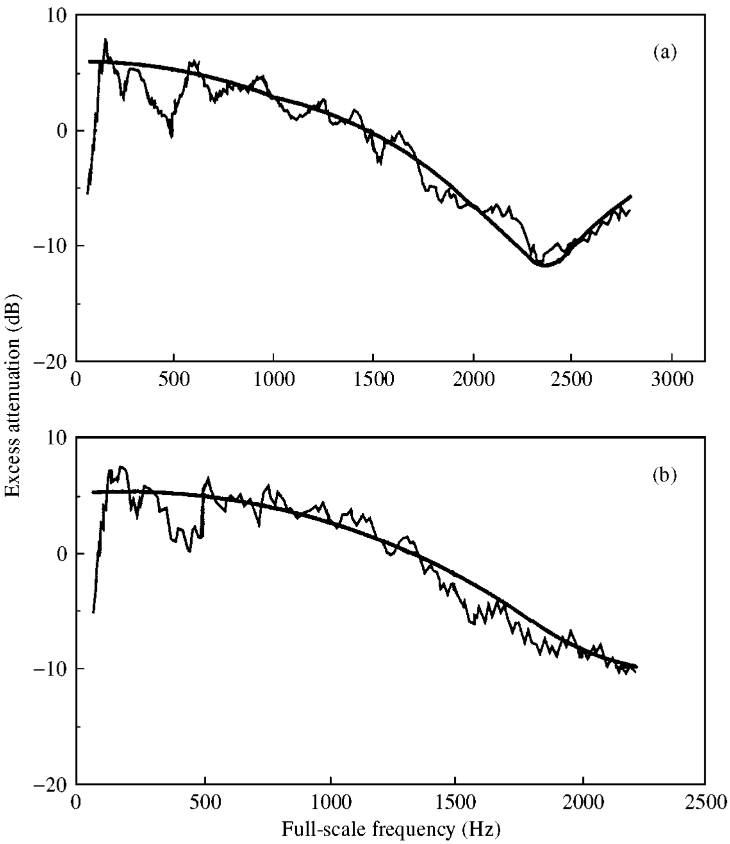

Figure 2. For expanded polystyrene, measured and predicted (smooth line) excess-attenuation curves for two optimal flow-resistivity/scale-factor combinations: (a) 9500 c.g.s. Rayl/cm, 1 : 31·5; (b) 6000 c.g.s. Rayl/cm, 1 : 40.

a distinct trough in the *EA* spectrum limited the ability of an analysis of the averaged least-squares surfaces to differentiate between acoustically harder materials.

Surfaces were assessed for their suitability for modelling a real-world surface when their reported ranges of useful effective flow resistivites overlapped the relevant range of values listed in Table 1. To model acoustically hard surfaces—such as asphalt roads with an effective flow resistivity of about 30 000 c.g.s. Rayls/cm (assumed range 25 000–35 000 c.g.s. Rayls/cm and above)—candidate materials are dense polystyrene at 1 : 25, 1 : 40 or 1 : 50 scale, aluminum sheet at 1 : 25 or 1 : 31·5 scale, and varnished particleboard at a scale of 1 : 31·5. Acoustically soft surfaces, such as forest floors with an effective flow resistivity of 20–80 c.g.s. Rayls/cm, can be modelled using double cotton sheet at 1 : 50 scale, or with felt at scales of 1 : 20, 1 : 25, 1 : 31·5, 1 : 40 or 1 : 50.

Considering an effective flow resistivity of 4000–8000 c.g.s. Rayls/cm as the benchmark for hard-packed earth, several materials might be adequate—aluminum sheet at scales of 1 : 31·5, 1 : 40 or 1 : 50, dense polystyrene at a scale of 1 : 40 or 1 : 50, expanded polystyrene or smooth hardboard at scales of 1 : 20, 1 : 25, 1 : 31·5, 1 : 40 or 1 : 50, and varnished particleboard at scales of 1 : 31·5, 1 : 40 or 1 : 50. For modelling grass surfaces, with an effective flow resistivity of 150–300 c.g.s. Rayls/cm, candidate model materials include rough hardboard at 1 : 20, 1 : 25, 1 : 40 and 1 : 50 scale and double cotton sheet at 1 : 20, 1 : 25, 1 : 31·5 or 1 : 40 scale.

An optimal scale of 1 : 31·5 was selected for subsequent modelling work [1, 2] in conjunction with four model materials—expanded polystyrene to simulate hard-packed-earth berms and ground, dense polystyrene for vertical walls and acoustically hard berms, varnished particleboard for asphalt roadways, and felt for acoustically soft berms. The selected scale-model materials allowed the testing of outdoor sound propagation over a wide range of expected surface impedance and the testing of the associated range of berm insertion losses expected in real-world highway conditions. Additional testing to simulate other ground surfaces would be possible using double layers of cotton sheet to model grass surfaces for the berm and surrounding terrain.

5. CONCLUSION

A procedure for selecting both an optimal scale factor and optimal model materials has been developed. Materials to be used to model acoustically hard and soft grounds and noise barriers in subsequent work have been tested. The technique identified an optimal scale factor of 1 : 31·5, and suitable associated model materials.

Clearly, one important question concerns the invariability of results obtained using the proposed method; that is, whether they are independent of the geometrical configuration—in particular, the source/receiver distance—involved in the full-scale *EA* configuration. The likely answer is that they are not; while the method is generally applicable, its results are probably only applicable to configurations similar to those tested. Thus, the optimal combinations of scale factor and effective flow resistivity reported in Table 2 may not always be accurate, and the model materials may not be good choices to model real grounds, if significantly different geometrical configurations are used. Several papers have discussed the optimal measurement configuration for estimating the acoustical properties of grounds, but none has addressed the specific issue of the possible variation of the effective ground impedance with test configuration [22, 23].

In further work, it would therefore be useful to measure the broadband *EA* over a set of distances, and to perform a broadband least-squares minimization at all required source/receiver distances simultaneously. The *EA* of the scale-model materials, as represented by the effective flow resistivity, would be even more accurately determined by such an approach. Great accuracy in differentiating between scale-model materials would result, allowing for the modelling of a greater variety of surfaces and propagation phenomena.

ACKNOWLEDGMENTS

The authors would like to acknowledge the collaboration of Michael Kent, British Columbia Ministry of Transportation and Highways, and of Clair Wakefield, Wakefield Acoustics Ltd., in the scale-modelling project. The investigation was supported with funding by the British Columbia Ministry of Transportation and Highways.

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