Building and Environment 86 (2015) 81–88

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Scale-model method for measuring noise reduction in residential buildings by vegetation

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ARTICLE INFO

Article history:
Received 30 September 2014
Received in revised form
22 December 2014
Accepted 23 December 2014
Available online 31 December 2014

Keywords:
Scale model
Absorption coefficient
Ground impedance
Vegetation
Noise reduction

ABSTRACT

This paper proposes an evaluation procedure using a scale model to assess the noise reduction effects of vegetated façades for sustainable urban building designs. The absorption coefficients of the scale-model materials were measured to fit the absorption characteristics of real vegetation. The ground impedance of asphalt was also measured to deduce the acoustical properties of ground surfaces and to select the ground material. To assess the reduction of road traffic noise, a line source for a 1:10 scale model was modelled using ribbon tweeters that generated high frequencies ranging from 1 kHz to 40 kHz. Accordingly, the effects of adding vegetated façades were evaluated in the scale model of a street canyon. The noise reduction due to the vegetated façades was less than 2 dB at pedestrian level in a two-lane street canyon. The scale model results were compared with geometric computer simulation results, and both evaluation methods showed similar results. The suggested modelling method can be useful for evaluating the noise reduction in street canyons by vegetation considering realistic features such as the absorption, scattering, and diffraction associated with the materials and sound sources according to the shape of the vegetation.

1. Introduction

Since Spandöck pioneered the application of a three-dimensional acoustic scale model to auditoriums [1], scale models on various scales have been used for auditorium design [2–5] and diffusion studies [6–8] for estimating indoor sound field characteristics such as the reverberation time and clarity. Scale models have also been utilized in outdoor spaces to understand sound propagation phenomena [9,10] and to evaluate noise reduction models [11,12]. In particular, specular multiple reflection due to the rigid reflection surfaces of buildings occurs in street canyons that are flanked by buildings on both sides [13]; diffusion occurs because of the discontinuity and irregularity of windows and walls [14], whereas diffraction occurs at the façade edges and building ceilings [15]. Sound field characteristics such as the reverberation and sound pressure level (SPL) in street canyons have been studied and estimated in scale models [9,10,14]. Ismail and Oldham [14] suggested methods of evaluating the diffusion mechanism in terms of sound propagation in street canyon, and they found that the reverberation time was decreased with increasing surface irregularity. Hornikx and Forssén [10] showed, in a 1:40 scale model of a street canyon, that vertical diffusers on façades can be more effective for noise reduction than horizontal diffusers on façades. Picaut and Simon [9] reported that, in a 1:50 urban scale model, the distance dependences of the reverberation and sound pressure were similar to the measured values; however, because of the scale limitation, their evaluation of the high-frequency characteristics was limited and did not guide the material selection. Urban city models are much larger than auditorium models, so a smaller scale such as 1:50 is necessary. Therefore, using a small scale increases the risk of errors; it is even more important to select the dimensions and materials precisely and accurately after the model is converted to a real scale [16].

Vegetation has potential for noise reduction using sustainable building materials [17–20]. Vegetation has complex shapes and nonlinear characteristics, so its effects on acoustic phenomena can vary in different places in buildings [21]. Owing to the complex configuration of leaves and branches, sound sources can be diffused and absorbed or blocked [22]. In addition, the soil absorption coefficient is high in all frequency bands, which affects noise reduction. To estimate such vegetation-related acoustic phenomena,

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http://dx.doi.org/10.1016/j.buildenv.2014.12.020
0360-1323/

laboratory measurements have been conducted to quantify the material characteristics of vegetation [19,23]. Yang et al. [23] obtained the absorption and scattering coefficients of plants and green walls from a reverberation chamber and found that soil and plants increased the absorption by about 0.6. These results are useful for understanding the absorption and scattering characteristics of vegetation; however, to observe the acoustic characteristics of vegetation in street canyons, it is necessary to derive the quantitative noise reduction by systematically comparing scale-model evaluations in a laboratory on the basis of physical phenomena.

It is useful to investigate the acoustical performance of vegetation in street canyons using scale models. Scale models have the advantages of being unaffected by weather conditions, allowing the reproduction of various types of urban design elements, and reducing the background noise uncertainty that occurs in real field measurements [18,24]. Moreover, given the difficulty of conducting numerical analysis and evaluating the actual sound characteristics while considering the vegetation shape, scale models are appropriate for evaluating the acoustic effects of vegetation. These models can yield results encapsulating the effects of sound reflection, diffraction, and diffusion. Studies of urban city scale models have focused on sound propagation from point sources in terms of the impulsive peak level [9,10,11,14]. The noise reduction obtained in this way would be overestimated owing to the various source-to-receiver distances compared to the results obtained using a line source [25]. Therefore, a line source that emulates continuously moving road traffic noise should be applied to evaluate the noise reduction by vegetation.

Therefore, this study proposes an evaluation procedure for the construction of a 1:10 scale model street canyon and derives the noise characteristics in the range 125 Hz–4 kHz frequency band. A scale-model experimental method of evaluating the noise reduction effect of vegetation is described, including the selection process of materials considering their absorption coefficients, the measurement of the ground impedance, and the construction of line sources to reproduce traffic noise characteristics.

2. Materials and methods

2.1. The 1:10 scale model

Data exist for evaluating the absorption and diffusion coefficients of real vegetation [23]. However, if a material's absorption coefficient exceeds 0.5, its scattering coefficient cannot be measured [26]. The absorption coefficient of vegetated façades is greater than 0.5. Thus, in this study the absorption coefficient of the 1:10-scale-model vegetation was used only to select the materials, and the materials were manufactured so that their shape and size was on a 1:10 scale compared to real vegetation.

2.2. Measuring the absorption coefficient

The absorption coefficients of the scale-model materials were measured in a reverberation chamber meeting the ISO 354 standard [27]. The dimensions of the manufactured specimens were 300 mm × 400 mm, and an acryl border was installed on the sides of the specimens to offset the increase in the absorption coefficient on the specimen-exposed sides. For the absorption coefficient measurement, the reverberation time (T20) was analysed by recording the impulse response that occurred through a spark source using a 1/8″ microphone (B&K, Type 4138). Twelve impulse responses were recorded for two sound sources and six microphone locations, and the measurements were conducted three times at the same location to estimate the deviations due to repeated measurements. Measurements performed in an empty reverberation chamber indicated that the standard deviation due to repeated measurements was 0.03 s (averaged over the 1.25–40 kHz band) in the evaluated frequency band, whereas the deviation associated with repeated measurements of the reverberation time with an absorption material was 0.03 s (averaged over the 1.25–40 kHz band).

An urban city scale model was built using medium-density fibre (MDF) and acryl, whereas all the scale-model materials, including the vegetation materials, were selected on the basis of the absorption coefficient measurements to yield the same absorption performance as real vegetation and buildings. The measured values for real systems were extracted from the existing literature and were used for the absorption coefficients of the basic façades (brick, unglazed) and windows (heavy glass, large panes) of buildings and asphalt [28], whereas the measured data for actual green walls (0 L/m^2 water) were used for the absorption coefficient of vegetation [23]. Table 1 shows the absorption coefficients per frequency band, which were converted using digital signal processing according to the law of similarity. The measured absorption coefficient in the scale model showed that the difference between the measured absorption coefficient per frequency band and that of a real material is 0.02 on average and is at most 0.04 for a building structure. In addition, the difference is 0.04 on average and is at most 0.07 for the vegetation materials. When the average absorption coefficients were compared across frequency bands, the differences between them ranged from 0.01 to 0.02. Therefore, the scale-model materials were selected to yield absorption performances similar to those of real materials with a measurement tolerance of ±0.05 on average and ±0.1 for each frequency bands.

2.3. Measuring the ground impedance

ISO 9613-2 [29] considers direct sound occurring in the noise source and ground attenuation due to the ground effect on the reflected sound from the floor surface. Therefore, the effective flow resistivity was measured to estimate the difference due to the ground effect caused by the difference between the properties of asphalts used in road ground materials and those of the 1:10-scale-model material. In Annex B of ANSI/ASA S1.18, the flow resistivity for a one-parameter model is presented, and grass, sandy silt, and asphalt are presented as examples [30]. In this study, the ground impedance was measured for real asphalt and the asphalt scale-model material. The scale-model material properties were measured in an anechoic chamber.

ANSI/ASA S1.18 [30] presents two measurement setups: Geometry A and Geometry B, which correspond to different evaluated frequency bands and use one omni-directional sound source and two omni-directional microphones, respectively. For measuring the properties of hard surfaces such as asphalt (Fig. 1), the Geometry B setup is recommended because it emphasizes the ground effect in high-frequency bands (above 1 kHz). Therefore, the measurements for both real asphalt and the 1:10-scale-model material were performed in Geometry B. A spark source was used as a measurement sound source, and a 1/4″ microphone (GRAS, Type 40BD) and 1/8″ microphone (B&K, Type 4138) were utilized for the real asphalt measurement and scale-model measurement, respectively, considering the response of the real and scale-model floor materials. The real asphalt measurement was conducted at night on open field roads where the background noise was low, whereas the ground impedance measurement of the 1:10 scale model was conducted with 1.6 mm metal plate including MDF structures by scaling down the distances to the source–receiver in Geometry B by a factor of 10.

The ground impedance measurement results for the real asphalt and 1:10-scale-model floor material showed that the level