EFFECT OF VEGETATION ON NOISE PROPAGATION IN STREETS AND SQUARES

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1 INTRODUCTION

Vegetation as an essential positive sustainable element of urban spaces has recently gathered increased attention from landscape architects and urban planners. Vegetation growing in urban settings can bring environmental benefits that enhance the health and well-being of citizens through, for example, improved air quality, increased thermal insulation for buildings[1,2], reduction of the urban heat-island effect[3], and alleviation of storm water runoff[4]. There are plentiful opportunities for the application of vegetation to urban streets, squares, roofs and roadside courtyards. In the context of urban streets, belts of trees, bushes and seasonal flowers represent the common vegetation usually grown on the edges of roads. In urban squares these can be extended to patches of grass, green spaces or small parks. Green walls[5] are implemented in modern urban design. These include green facades which are made up of climbing plants growing either directly on a wall or, more recently, on specially designed supporting structures. Another type of green wall is the 'living wall' consisting of modular steel containers, geotextiles, irrigation systems, a growing medium and vegetation. Roadside courtyards may accommodate trees and bushes and their facades may be treated with green walls too. The application of modern green roofs, i.e. a system of layers including vegetation covering the top of a building, has also become popular in recent decades.

This paper investigates the effectiveness of vegetation in urban settings in the context of the acoustic impact. It is part of a larger research focusing on noise abatement measures applicable to the propagation path, dealing with greening of buildings and use of vegetation on other urban and rural surfaces, innovative barriers including recycled materials, and treatments of the ground and the road surface. How vegetation affects the sound field in an urban environment highly depends on acoustic properties of the plants and growing media (soil), geometry of the space and distance to the traffic[6]. Data of acoustic properties of the vegetation are however scarce. It has been found that absorption by plants depends on leaf shape, size and thickness and on the height of the plant[7]. Sound-induced vibration of plant elements converts sound energy to heat can play an important role in absorption at mid and high frequencies. Plants and foliage can also produce relatively high scattering (diffuse) reflections[8]. Sound is reflected and scattered by plant elements like trunks, branches, stems and leaves and this affects sound propagation particularly at middle and high frequencies. Absorption of the soil used in green walls has exhibited dependency from the depth of material and its moisture content[9]. Hornikx[10] shows that noise attenuation in street canyons and courtyards increases with larger facade absorption coefficients and decrease with lower frequencies. The effect of façade absorption has been shown to be more efficient for narrower canyons. Kang[11] in a study modelling sound propagation along a narrow street has shown that the extra attenuation provided by placing absorbers on facades increases with greater source-receiver distance.

The aim of this paper is to examine noise mitigation using vegetation in urban streets and squares of geometries typical for European city centres through simulations of sound propagation using a number of established modelling software tools. Simulations of noise propagations have been performed using energy-based CRR (combined ray-tracing and radiosity) and wave-based PSTD (pseudospectral time-domain) methods. The noise abatement schemes included the placement of vegetation on building facades and on low-profile barriers.

The rest of the paper is organized as follows: Section 2 presents the methodology that includes description of the reference geometries, traffic model, applied simulation tools, considered noise abetment schemes, and materials used in the simulations; in Section 3 results are given, Section 4 presents the discussion of the results, while Section 5 presents the conclusions.

2 METHODOLOGY

2.1 Configurations simulated

Typical configurations of European urban centres namely a street and a square are considered as reference configurations, i.e. without treatment. In Figure 1 a single street of dimensions 19.2 m x 76.8 m x 19.2 m (*x* -width, *y* - length, *z* - height) is shown. This reference configuration is denoted as St1. The configuration is computationally treated as being periodic in the y-direction, which creates a long street aligned with building blocks. The height of the street corresponds to 6 story buildings. Figure 2 shows an urban square with a street on a side, denoted as Sq1. The square dimensions are of 38.4 m x 57.6 m x 19.2 m (*x* -width, *y* - length, *z* - height) and the street dimensions are of 19.2 m x 115.5 m x 19.2 m (*x* -width, *y* - length, *z* - height). The façades of both configurations are equal and consist of windows and brickwork parts. The windows are horizontally depressed from the brickwork by 0.16 m to introduce some diffusive effects. Including some diffusivity is considered as essential in the standard configuration. Perfectly flat walls do not correspond to reality, and could also overestimate the effect of abatement solutions. In both configurations road traffic is located in street.

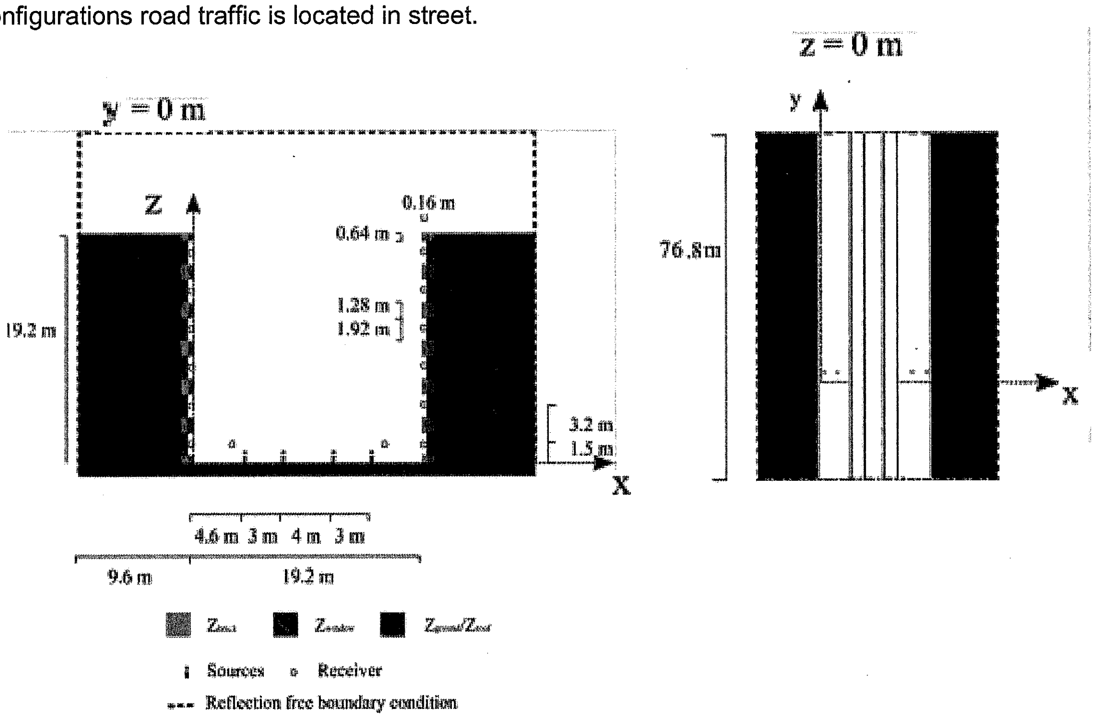
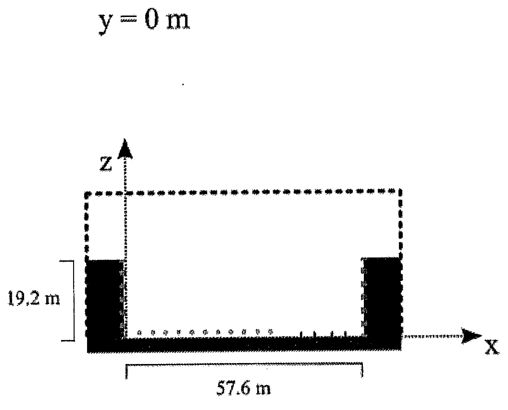


Figure 1. Reference configuration St1: cross section and plan of the street.



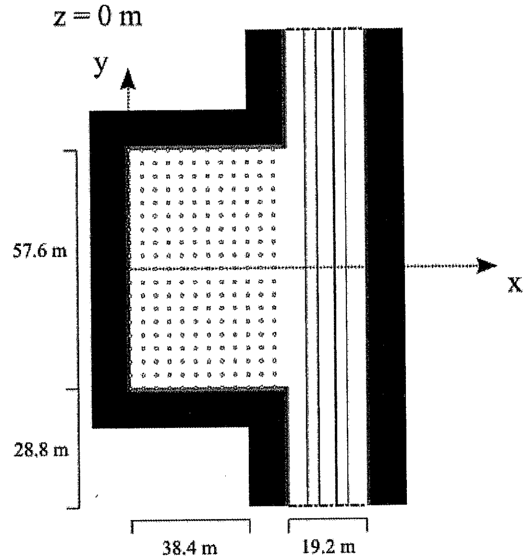


Figure 2. Reference configuration Sq1: cross section and plan of the square with the adjoining street.

In the case of the street, receiver positions are located along two facades and at a horizontal line at z=1.5m shown in Figure 1. For facade receiver positions, multiple z-coordinates are considered. Receiver positions at façades are considered with regards to the possibility of opening windows or sustainability of the buildings when e.g. windows that are facing too high noise level would need higher sound reduction indices compared to those facing lower noise levels from the traffic. For the receivers at the horizontal line, the sound field is significant for pedestrians passing by at the both sides of the street. In the square, the receivers are located at a height of 1.5m in a 12 x 19 grid with successive receiver points separated by 3.2m in both x and y directions (see Figure 2). Similar to the street, receiver positions are important with respect to pleasantness of the users.

2.2 Traffic model

A lane of traffic has been modelled by three uncorrelated source heights over the ground surface: z = 0.01m denoted by S_1, z = 0.30m denoted by S_2 and z = 0.75m denoted by S_3[12]. Road traffic assumed to have a speed of v = 50 km/h, is composed of 95% light vehicles and 5% heavy vehicles and a flow of Q = 833 vehicles per hour (corresponding to 20,000 vehicles per day) is assumed. The sound power radiated from the line source per unit length can be computed as:

$$L_w = 10\log\left(10^{0.1L_{w,S_1}} + 10^{0.1L_{w,S_2}} + 10^{0.1L_{w,S_3}}\right) + 10\log\left(\frac{Q}{1000v}\right), dB \qquad Eq.1$$

with L_{w,S_1} is the sound power constructed from 80% rolling noise and 20% engine noise (for both heavy and light vehicles), L_{w,S_2} is the sound power constructed from 20% rolling noise and 80% engine noise for the light vehicles and L_{w,S_3} is the sound power constructed from 20% rolling noise and 80% engine noise for the heavy vehicles[12].

Typically, a street of the width as selected in the reference configurations could accommodate four lanes of traffic. However, since the number of calculations is linearly dependent on the number of road traffic lanes, a single lane of road traffic vehicles has been considered. It has been found that the difference introduced by this approach in insertion loss (IL) – the reduction in sound level due to the insertion of an element in the configuration –is reasonably low, below 2dB(A). In the case of the configurations with vegetated walls in the street and square and for the case with a barrier in the street, lane 2 has been considered in the simulations, while calculations for the configuration with a barrier in the square (case Sq5, see Figure 2) have been performed for lane 3. It can be expected that for the latest the first lane will be more shielded by the barrier than lanes 2 and 3, but the last line is less shielded. It can be also expected that difference in effects of lanes 1 and 4 will be cancelled somehow justifying not to compute them.

2.3 Prediction models

To simulate sound propagation in urban spaces, CRR (Combined Ray-tracing and Radiosity) and PSTD (pseudospectral time-domain) models have been applied.

CRR is an energy based model; it combines specular and scattering reflections from the space boundaries[13]. In CRR, a ray-tracing model is used to calculate specular reflections and the radiosity model calculates scattering reflections. CRR makes it possible to perform relatively quick calculations and achieve accurate results of sound propagation in middle and high frequency ranges. CRR model/software was developed at the University of Sheffield and has been verified in simulations of various urban spaces[14]. Computations with CRR methods in this paper are performed at 1/3 octave bands between 100Hz and 4kHz.

PSTD solves the linearized Euler equations on a mesh that discretizes the complete volume of the problem of interest[15]. The method implicitly includes all important wave propagation effects e.g. diffraction and scattering. The drawbacks of the PSTD method are that boundaries can only be modelled either as being rigid or by a second medium with a different density. For urban configurations, where horizontal 'zig-zag' reflections prevail, the different medium approach was found to only lead to small errors compared to modelling with the vertical boundaries media as normally reacting. The method has successfully been applied to previous studies on sound propagation in urban streets and to courtyards[16,17]. For the purpose of this paper computations with the PSTD methods are performed in 1/3 octave bands between 50Hz and 1.6kHz.

2.4 Noise abatement schemes

The acoustic treatments in the street and square considered in the simulations were the application of vegetation on either the façades or on a low-height barrier. The abatement schemes with the vegetated wall for the street are cases St2, St3, and St4, while in the square the cases are Sq2-Sq4. Cases St2 and Sq2 represent street and square configurations where the green walls are assumed to be implemented on all facades. St3 and Sq3 represent the abatement considered only on the upper halves of the facades, while in St4 and Sq4 the vegetated walls are modelled at lower halves of the facades. In the case of square, cases Sq2, Sq3 and Sq4 consider the abatement applied on the facades of the actual square and the adjacent street.

Low profile barriers of 0.96m height and 0.96m width (odd dimensions chosen for convenience of the calculations) made from vegetated walls are simulated. The barriers run along the whole length of the street and in the street adjacent to the square. The street case barrier is situated in the middle of the street (case St5) as demonstrated in Figure 5. The square simulations consider a barrier situated between the barrier and the adjacent street (case Sq5) (see Figure 6).

2.5 Material properties

For the brickwork parts, an absorption coefficient for normal sound wave incidence of 0.33 has been assumed according to ISO9613-2 and accounts for surface scattering. This number is high compared to tabulated data that can be found for brickwork[18].

The proposed vegetated wall was produced by Canevaflor[19]. Measured[9] normal incident absorption coefficients of the wall under dry conditions are presented in Table 1.

Table 1. Measured data of absorption coefficient for the vegetation wall considered in the calculations.

Hz	50	63	80	100	125	160	200	250	315	400	500	630	800	1k	1.25k	1.6k
α	0.08	0.11	0.15	0.22	0.3	0.42	0.55	0.7	0.84	0.91	0.9	0.85	0.79	0.78	0.85	0.91

The absorption coefficient of vegetation can drastically depend on the water content. Since these measurements are performed under dry conditions, these can serve as the maximum effects that can be obtained. The absorption coefficient for the frequencies higher than 1.6kHz has been obtained by extrapolation.

3 RESULTS

3.1 Explanation of presented results

The effect of the computed abatement schemes on the urban sound environment is expressed by the insertion loss IL. The equivalent 1/3 octave band dependent sound pressure level at the receiver positions *j* from a road traffic lane can be computed as:

$$L_{eq,j} = 10\log\left(\sum_i 10^{0.1(L'_{w,i}-A_i)}\right),$$
$$L'_{w,i} = L_{w,i} - 10\log(\Delta y), \qquad \textit{Eq. 2}$$

where *i* is the index of the source segment, $L'_{w,i}$ is the sound power per unit of discretization size Δy and A_i is the sum of all attenuation terms due to propagation effects. To compute $L_{eq,j}$ from any of the methods of simulations used in this paper, the following procedure may be followed:

$$L'_{w,i} = \widehat{L}'_{w,i} - \Delta L'_{w,i}, \qquad \textit{Eq. 3}$$

where $\widehat{L}'_{w,i}$ is the apparent sound power that follows from a calculation with a numerical method and $\Delta L'_{w,i}$ is a correction term. For a free field calculation due to a *single* source, the result from a numerical calculation is $\widehat{L}_{eq,j,i}$:

$$\widehat{L}_{eq,j,i} = 10\log\left(\sum_{f_k}\left|p_j(f)\right|^2\right) = \widehat{L}'_{w,i} - A_i, \qquad \textit{Eq. 4}$$

with p_j the computed complex pressure at receiver position *j* and where the sum runs over all frequencies *f* of 1/3 octave band *k*. Since the attenuation term A_i is known analytically in free field, $\Delta L'_{w,i}$ can be derived using Equations 3 and 4. This term is then used to correct the computed results for all configurations such that $L_{eq,j}$ can be computed from $\widehat{L}'_{eq,j}$.

Δy is the spacing between the discrete source positions along the *y*-direction, being 0.32 m in the applied numerical methods, and sources in *y*-direction are uncorrelated. In free field, attenuation term A_i equals to $10log(4\pi R^2)$, where *R* is the distance between source and receiver.
The averaged over receiver position IL calculated in each 1/3 octave of interest can be obtained as follows:

$$\overline{IL_k} = \frac{1}{J}\sum_{j=1}^{J}\left(L_{eq,j,k}^{ref} - L_{eq,j,k}\right), dB \qquad \textit{Eq. 5}$$

with k is the 1/3 octave band number, J the number of receiver positions and *ref* refers to the reference configuration.

The global effect on the noise abatement schemes are expressed by a single number insertion loss in dB(A). This number is computed as:

$$\overline{IL} = \frac{1}{VJ}\sum_{v=1}^{V}\sum_{j=1}^{J} 10\log\left(\frac{\sum_k 10^{0.1\left(L_{eq,j,v,k}^{ref} - Aw_k\right)}}{\sum_k 10^{0.1\left(L_{eq,j,v,k} - Aw_k\right)}}\right), dB(A). \qquad \textit{Eq. 6}$$

Here, the insertion loss is computed in dB(A) per receiver position j, and an arithmetic averaging is done over all receiver positions and various traffic speeds V, ranging from 30 km/h to 70 km/h. *Aw* is the A-weighting. The standard deviation in IL is calculated from the averaging over receiver points. In all figures CRR results are denoted by squares and PSTD results by diamonds.

3.2 Results for vegetated facades

3.2.1 Street

Results of simulations with vegetation absorption on street facades are shown in Figure 3, where the lines represent the values for a 50km/h car speed and the bars are standard deviation covering the results of 30km/h, 40km/h, 50km/h, 60km/h and 70km/h. Further in this paper all discussed in results relate to 50km/h car speed. It can be seen that in case St2 the IL is below 1dB due to direct wave effect and low impact of reflected waves for the line source in the street. The averaged IL is 0.6dBA. This is low in comparison with the case of sound field from a single point source as has been discussed by Kang[20]. Due to low values of absorption coefficient below 160Hz compared to the reference case (absorption coefficient is of 0.33 for all frequencies) the IL is negative for low frequencies. It has been also calculated that for the receiver considered in the street, the IL in case St3 (vegetation covers the lower half part of the facades) is lower than in case St4 (vegetation applied to the upper part of the facades). The average ILs for these cases are of 0.3dB(A) and 0.4dB(A), respectively.

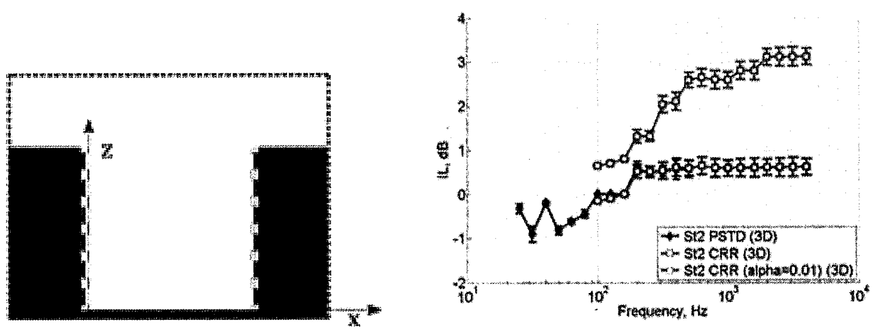


Figure 3. Cross-section and noise mitigation case with vegetated walls in the street (case St2) and insertion loss for case St2.

3.2.2 Square

Results of simulations of absorption on the square facades are shown in Figure 4. When vegetation covers all facades, case Sq2, it results in the IL of 0.7dB(A). In the case of vegetation applied to low part and upper parts of the facades (Sq3 and Sq4, respectively) the averaged over receiver positions ILs are of 0.6dB(A) and 0.35dB(A), respectively.

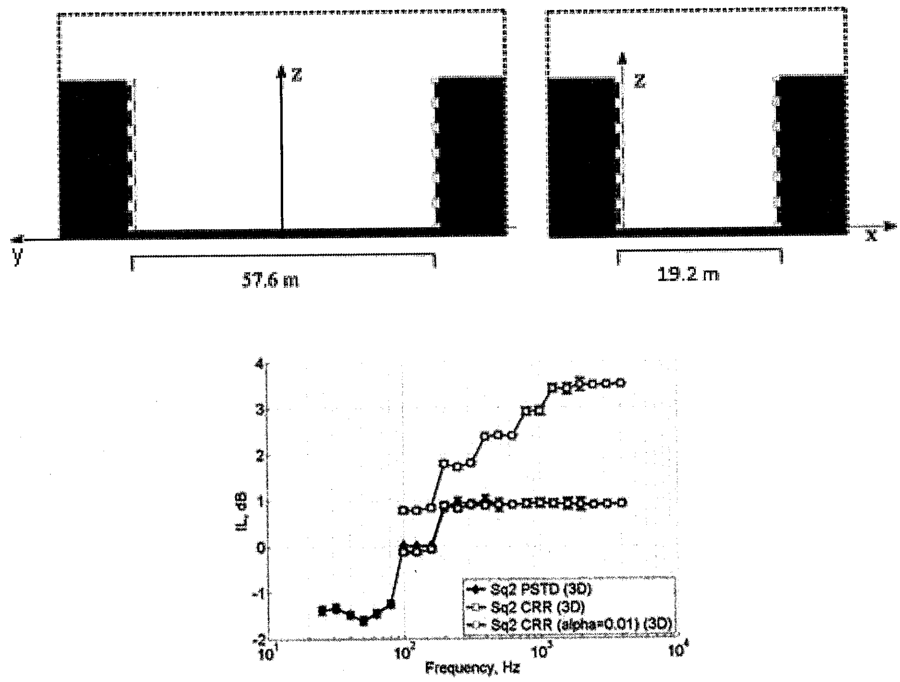


Figure 4. Cross-sections and noise mitigation case with vegetated walls in the square (case Sq2) and insertion loss for case Sq2.

3.3 Results for vegetated barriers

In Figure 5 and Figure 6 the effect of insertion of the barrier in the middle of, respectively, the street and between the street next to the square and square is shown. In the case of the street the IL is of 2.3dB(A). In the square an IL of 4.3dB(A) is achieved.

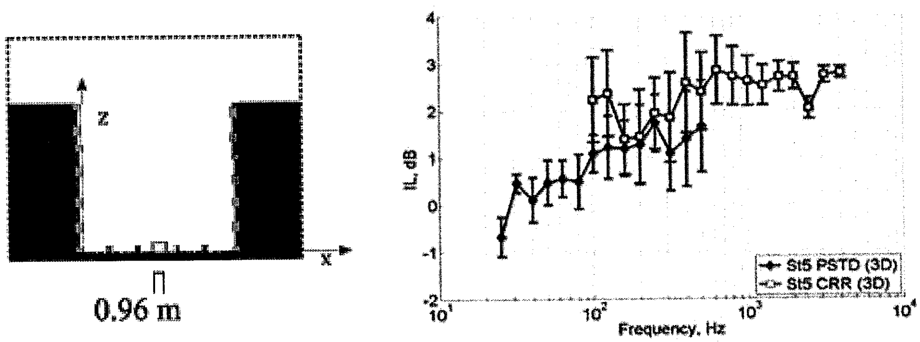


Figure 5. Cross-section and noise mitigation case with the low profile barrier in the street (case St5).

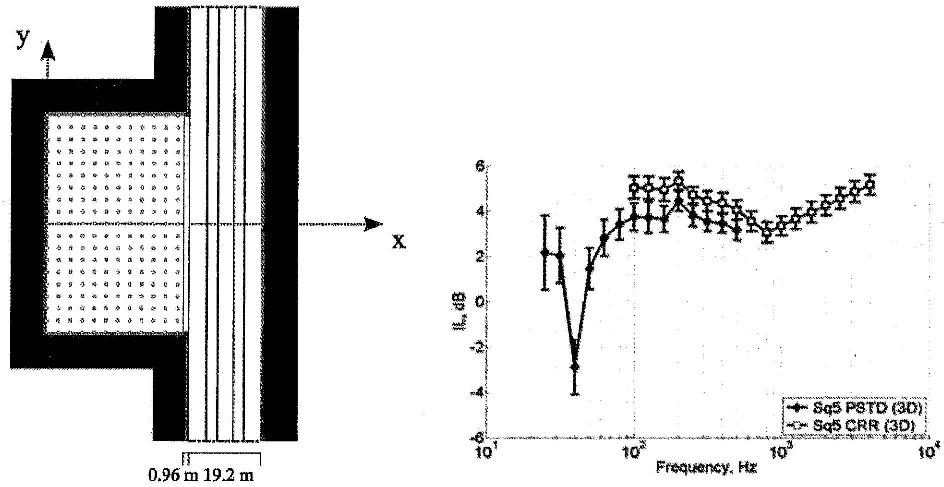


Figure 6. Plan and noise mitigation case with vegetated walls and low profile barrier in the square (case Sq5).

Considering the results presented above, it can be noted that greening the façades of street and square mostly affects the highest frequencies. This is mainly due to a high value of the absorption coefficient of 0.33 for brickwork considered in the reference cases. The vegetated walls that replace the brickwork have a low absorption coefficient (high impedance) for the low frequencies, causing negative IL values (for low frequencies) and a rather low IL for the higher frequencies. Therefore, CRR computations for the reference cases St1 and Sq1 have been also performed with an absorption coefficient for normal sound incidence of 0.1. The results are included in Figure 3 and Figure 4 and show an average increase in the IL for about 2.0dB(A) for the street case (St2) and of 2.5dB(A) for the square case (Sq2).
Generally, vegetated facades in the street are less efficient than in the square, however the differences are smaller than 1dB. Vegetating all façades in the street is most effective for higher receiver positions (higher level of the street) on the both sides of the street. For case St2 the highest IL is of 1.2-1.3dB for the middle and high frequencies (400Hz-4kHz). In the square, the highest IL is obtained for the receiver positions in the far field (for larger distances to the source) and for the middle frequencies (2dB at 500Hz for PSTD and 3.5dB for 1kHz for CRR). It can be explained by the fact that in the near field the sound field is mainly dominated by the direct waves from the source while in the far field the effect of the direct wave is lower and the reflections from the facades contribute more.

A vegetated barrier in the street is less efficient than in the square for the receiver considered, although no direct comparison can be made. Indeed in the street configuration the receivers are located on both sides of the barrier while all the receivers in the case of the square are placed behind the barrier. In the street the highest IL is obtained for the lowest receiver position (1.5m height) on the site of the street that is of 1.5-6.7dB (PSTD) for 100-500Hz. For the case with the barrier in the square the highest IL of 9.4dB is obtained for the receiver positions that are closed to the barrier that is due to the shielding effect.

The effect of diffraction at low-to-mid frequencies resulted in slight disagreement between results obtained using CRR and PSTD for cases with the barrier (St5 and Sq5). The CRR results are higher than PSTD results by about 1dB between 100-125Hz for St5 case and by 0.5-1dB between 100-500Hz for Sq5 case.

Noise mitigation schemes using vegetation as considered in this study are generally beneficial for the acoustic performance of urban spaces. However, a holistic approach to the built environment should take into account other aspects of urban design e.g. thermal and lighting aspects. To achieve a balanced solution these aspects combined with costs of application and maintenance of greenery elements should be considered and carefully designed.

4 CONCLUSIONS

In the geometries of an urban street and square, energy based (CRR) and wave-based (PSTD) methods have been applied to simulate the effect of vegetation on noise propagation from road traffic. In the street case good agreement between the simulation methods has been achieved for the cases with vegetated facades. For the cases with barriers, the effect of diffraction causes a disagreement between results obtained using CRR and PSTD methods for the lower and middle frequencies.

In the street case, a decrease of the SPL of 0.6dB(A) can be achieved when vegetation is applied to all facades. When vegetation covers the lower half part of the facades the average IL is of 0.3dB(A), while in the case of vegetation in the upper part of the facades, the IL is 0.4dB(A). When vegetation covers all facades in the case of the square, an average IL of 0.7dB(A) is noted. When the vegetation is applied to the lower and upper parts of the facades, the averaged ILs are of 0.6dB(A) and 0.35dB(A), respectively. It has also been demonstrated that decreasing a frequency independent absorption coefficient from 0.33 to 0.1 for the reference cases results in increase of the broadband IL for 2dB(A) in the street with vegetated facades and for 2.5dB(A) in the square with vegetated facades.

Insertion of a low height vegetated barrier between two sides of the roads in the street results in a decrease in SPL of 2.3dB(A). In the case of the square, when barrier is applied between the square and the adjacent street, an IL of 4.3dB(A) is achieved.

It is important to note that in the very low frequency range, the vegetation gives a more limited absorption coefficient than the modelled brick work.

Acknowledgment

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