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Prediction of building noise and vibration – 3D finite element and 1D wave propagation models

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Abstract
Construction work or traffic excite nearby buildings, and the perceptible or audible vibration can be a nuisance for the inhabitants. The transfer of the vibration from the free field to the building has been calculated by the finite element method for many models in consultancy and research work. The analysis for all storeys of certain building points such as walls, columns and floors unveiled some rules, some typical modes, and some wave-type responses. A simplified building-soil model has been created, which includes well these effects of building-soil resonance, wall/column resonance, floor resonances, and the high-frequency reduction. The model consists of one wall for a wall-type apartment building or a column for each specific part (mid, side or corner) of a column-type office building. The building response in the high-frequency (acoustic) region is calculated as mean values over all storeys and over wider frequency bands, by wave-type asymptotes of an infinitely tall building, and by the soil to wall ratio of impedances. The secondary noise is predicted by transfer values between the building vibration (center of floors, walls at a room corner) and the sound pressure.

Keywords: building vibration, finite element models, soil-wall floor model, apartment building, office tower

1 Introduction

The literature about building vibrations is quite limited, for example [1-3]. It is often related to railway-induced vibration. Railway excitation, namely from tunnels have typically high-frequency components. Therefore in practice, the prediction of vibration and noise is of importance. The prediction can be done with detailed finite-element models or by simplified models. Both possibilities will be demonstrated in this contribution.

Buildings have been often calculated without the underlying soil or with a very stiff soil. The soft soil, however, yields an amplitude reduction with increasing frequency, modifies the resonance frequencies and mode shapes, and provides a strong radiation damping. Without the soil, many resonance peaks appear in the solution which are not present for the building model with the soil. The building-soil interaction should be included in the building analysis even if the propagation through the soil and the response of the building is calculated separately.

Vibration results are often presented for a single building point (or a few singular points), and a good interpretation is rarely found. The vibration of a building is a complex behaviour which must be studied by many points or the average of many points. This contribution aims at giving an interpretation by looking at many building points or averages of many points.

2 The vibration response for different types of buildings

Some building examples have been analysed by the 3D finite-element method [4], here a wall-type apartment building and a column-type office tower are shown [5]. Results of a simplified 1D model are evaluated for comparison [6].

2.1 A four-storey apartment building

A four-storey apartment building with masonry walls and concrete floors has been analysed on a medium stiff soil. The transfer functions $V(f) = v_B/v_0(f)$ between the free field v_0 and the building components v_B are shown in Fig. 1. These transfer functions show some general characteristics. All freefield-building transfer functions start with $V = 1$ at zero frequency and usually end below $V < 1$ at 50 Hz. That means that the free field is not modified by the building at low frequencies whereas the free field is reduced by the building at high frequencies. In between, amplifications of the free field can occur due to several reasons. At 10 Hz, the resonance of the building on the compliant soil can be found with amplitudes of $V = 5$ to 6. This building-soil resonance frequency is determined by the stiffness k of the soil and the mass m of the building as $f_S = \sqrt{k/m}$. As a consequence, the building-soil resonance frequency should be proportional to the shear wave velocity of the soil $f_S \sim v_S = \sqrt{G/\rho}$ and indirectly proportional to the square root of the number of storeys $f_S = 1/\sqrt{n}$.

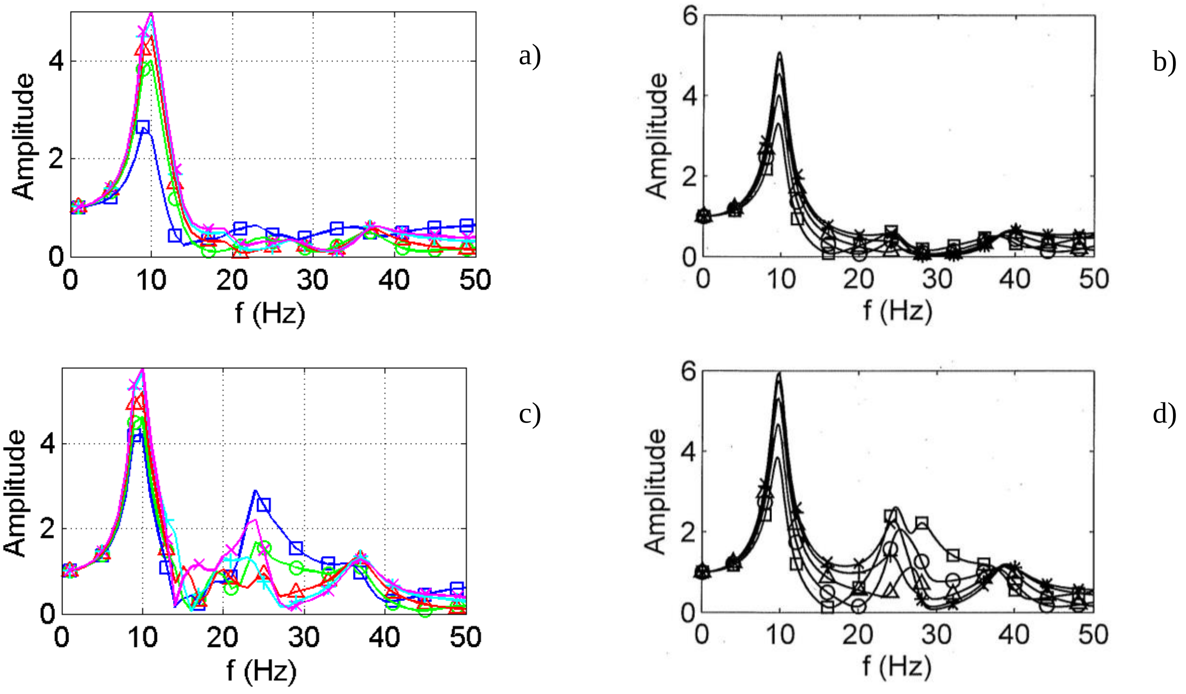

Figure 1 – Soil-building transfer functions of a four-storey apartment building, a,b) walls, c,d) floors, a,c) 3D finite-element model, b,d) 1D prediction model; □ ground floor, ○ 1st, △ 2nd, + 3rd floor, ×roof.

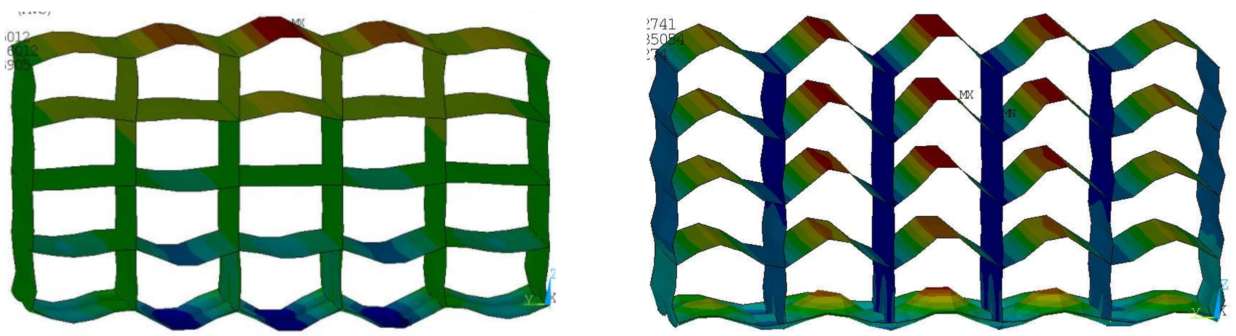

Figure 2 – Vibration modes of the apartment building at a) 24 Hz and b) 37 Hz.

Next at 25 Hz, some smaller amplifications can be found which are due to the floor resonances. The floor resonance frequencies are ruled by the width (5 m x 5 m), the thickness (0.2 m) and the support conditions (clamped-clamped) of the floor (Fig. 2a). Finally, another characteristic behaviour can be observed at 37 Hz where the floors and the walls are vibrating in anti-phase (Fig. 2b). The results for the 1D prediction model are also given in Figures 1c,d. The agreement of the one-dimensional prediction model with the three-dimensional finite-element model is very good.

2.2 A twenty-storey office tower

The twenty-storey office tower presents another characteristic of building vibration. Fig. 4a shows a vibration mode where the amplitudes increase with increasing storey number. This vibration mode is called the column mode because the deformation of the columns is the main reason of this vibration. The column frequency is determined by the wave velocity v_L of the columns (and floors) and the height H of the building $f_C = v_L/4H$.

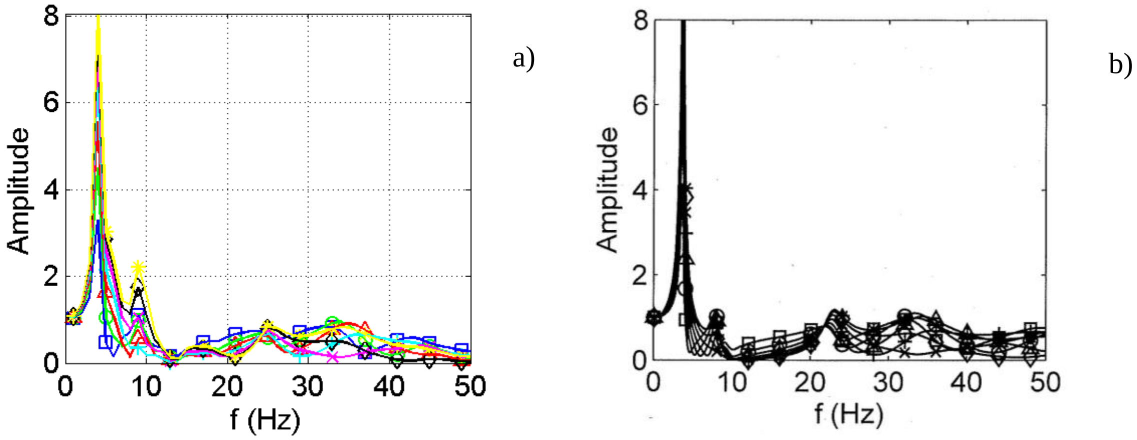

Figure 3 – Soil-building transfer functions of the office tower, a) finite element model, b) prediction model; □ ground, ○ 3rd, △ 6th, + 9th, × 12th , ◇ 15th, ∗ 18th floor.

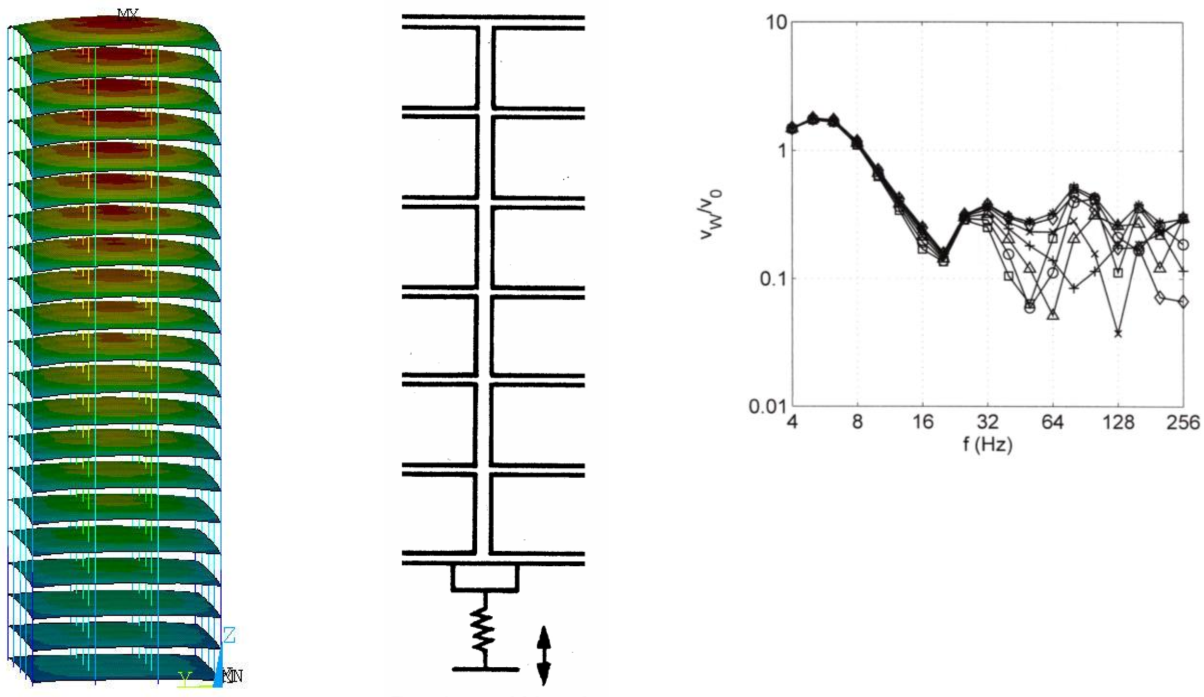

Figure 4 – a) 3D finite-element model of an office tower, vibration mode at 4 Hz; b) 1D soil-wall-floor model of the standard 6-storey apartment building c) soil-building transfer functions of the 1D model (thirds of octaves up to 256 Hz), □ ground floor, ○ 1st, △ 2nd, + 3rd, × 4th, ◇ 5th floor, ∗ roof.

The column frequency indicates an amplification of the amplitudes with height and a resonance in case of a stiff soil. The column frequency of the office tower is f_C = 6 Hz and the soil-building resonance is also at 6 Hz. So, both modes (the soil and the column mode) work together, amplifying each other and resulting in a basic building resonance at 4 Hz which can be found for the finite element as well as for the prediction model (Fig. 3a,b). The office tower has the lowest resonance frequency and the highest resonance amplitudes of all building examples, but at the same time all amplitudes above 10 Hz are quite small, below $V = 1$.

It should be noted that the apartment building of the preceding section has also a relevant column (wall) frequency at f_C = 19 Hz because of the softer masonry material. Due to the soft material, the low-rise apartment building has a low wall frequency and the deformations of the wall have an influence on the basic building resonance shifting it from 12 Hz to 10 Hz (Fig. 1a).

Because of the good agreement between 3D finite-element results and the 1D results, the 1D model seems suited for a simple and fast prediction. This model is described in the next section, and corresponding results for more building examples and higher (acoustic) frequencies are presented in the following section 4. As the results for different storeys vary considerably at higher frequencies (Fig. 4c), mean values for all storeys are calculated and presented.

3 The 1D soil-wall-floor model

A wall resting on a foundation and excited by the free-field vibration u_0 (Fig. 4b) is described by the differential equation for the vertical displacements u

$$E_W A_W \frac{\partial^2 u}{\partial x^2} - \rho_W A_W \frac{\partial^2 u}{\partial t^2} = 0 \tag{1}$$

and two boundary conditions, one for the force-free roof

$$F_R = -E_W A_W \frac{\partial u}{\partial x}(x_R) = 0 \tag{2}$$

and the other for the coupling of the foundation to the soil

$$F_S = -E_W A_W \frac{\partial u}{\partial x}(x_S) = k(u(x_S) - u_0) + c\frac{\partial u}{\partial t}(u(x_S) - u_0) \tag{3}$$

E_W is the elasticity modulus, ρ_W the mass density, and A_W the cross section of the wall, k is the stiffness and c the damping of the foundation, see [7].

The solution is found in frequency domain by fitting upward and downward longitudinal waves of the wall to the boundary conditions. The solution can be expressed in the following explicit form

$$\frac{u_W}{u_0} = \frac{\cos\ a\xi}{\cos\ a}\ \frac{1}{1 + iq\ \tan\ a} \qquad \text{resp.} \qquad \frac{u_W}{u_0} = \frac{1}{1+q} \quad \text{for an infinitely high wall} \tag{4}$$

where

$\xi = x/H$ is the position relative to the height H of the building ($\xi = 0$ is the roof),

$a = \omega H/v_L$ is a normalized frequency parameter with v_L the wave speed of the wall.

The parameter

$$q = \frac{i\omega\sqrt{E_W\rho_W}\ A_W}{i\omega c + k} = \frac{K_W}{K_S} \approx \frac{Z_W}{Z_S} = \frac{\sqrt{E_W\rho_W}\ A_W}{1.6\sqrt{G_S\rho_S}\ A_S} \tag{5}$$

describes the support by the foundation stiffness k and damping c. It is the ratio of the dynamic stiffnesses of the wall and the soil (foundation) K_W, K_S. At higher frequencies, it is the ratio of the wall impedance Z_W to the foundation impedance Z_S with the corresponding wall and soil area A_W, A_S. The transfer function (4) consists of 1) a factor for the distribution along the height of the wall and 2) the transfer function of the foundation.

The maximum transfer function of the building is the transfer function of the roof

$$\frac{u_R}{u_0} = \frac{1}{cos\ a + iq\ sin\ a}\ . \tag{6}$$

The mean value of this transfer function is

$$M_2(\frac{u_R}{u_0}) \approx \sqrt{\frac{1}{q}} \tag{7}$$

and the mean value of all storeys compared to the roof can be described as

$$M_2(\frac{u}{u_R}) = \sqrt{\int_0^1 \cos^2 a\xi d\xi} = \sqrt{\frac{1}{2}(1 + \frac{\sin 2a}{2a})} \tag{8}$$

The continuum wall model can be extended to a wall-floor model by including the floor transfer function (force of the floor to the wall due to the displacement of the wall, floor mass m_F, eigenfrequency f_F, and damping D_F)

$$\frac{F_F}{u_W} = (2\pi f)^2 \left(m_F + m'\frac{f^2}{(1+2D_F i)f_F{}^2 - f^2}\right) \tag{9}$$

in the mass density of the wall as

$$m^* = \frac{F_F}{u_W \omega^2} \qquad \text{and} \qquad \rho^* = \rho_W + \frac{m^*}{A_W H} \tag{10}$$

The explicit formula (4) of the continuum wall model still holds, but the parameters ρ^*, v_L^*, a^* are now frequency dependent and complex. More details can be found in [7].

The original parameter q (5) for a wall on the soil is complex but turns to be real and constant for higher frequencies. For a building supported by elastic elements (springs, elastic layers of real stiffness k_I), the parameter

$$q = \frac{i\omega \sqrt{E_W \rho_W}\ A_W}{k_I} \tag{11}$$

is imaginary and linearly increasing with frequency. The inclusion of the floor behaviour makes the parameter complex and strongly frequency dependent around the resonance frequency of the floors. It also leads to a reduced effective building mass at high frequencies.

4 Behaviour of buildings on the soil or on elastic elements (parameter study with the 1D prediction model)

The starting point is a 6-storey wall-type building on a medium stiff soil (v_S = 200 m/s), see also Table 1. At first, the shear wave velocity of the soil is varied between v_S = 100 and 300 m/s in Figure 5a-c. The softer the soil is, the lower is the building-soil resonance frequency. It is below 4 Hz for the softest soil of v_S = 100 m/s. In the mid-frequency range, there is a strong decrease of amplitudes and at high frequency the reduced levels stay constant. The strongest reduction $V \approx 0.1$ is for the softest soil whereas the stiffest soil yields high-frequency amplitudes close to $V = 1$. The resonance amplitudes of the floors increase strongly with the wave velocity (or stiffness) of the soil.

Buildings with a different number n of storeys show mainly differences at low frequencies (Fig. 5d). High buildings have a lower building-soil eigenfrequency and a stronger reduction in the mid-frequency range. Above the floor resonance frequency, the differences of the buildings are rather small. All buildings behave approximately like an infinitely high building in the high-frequency region.

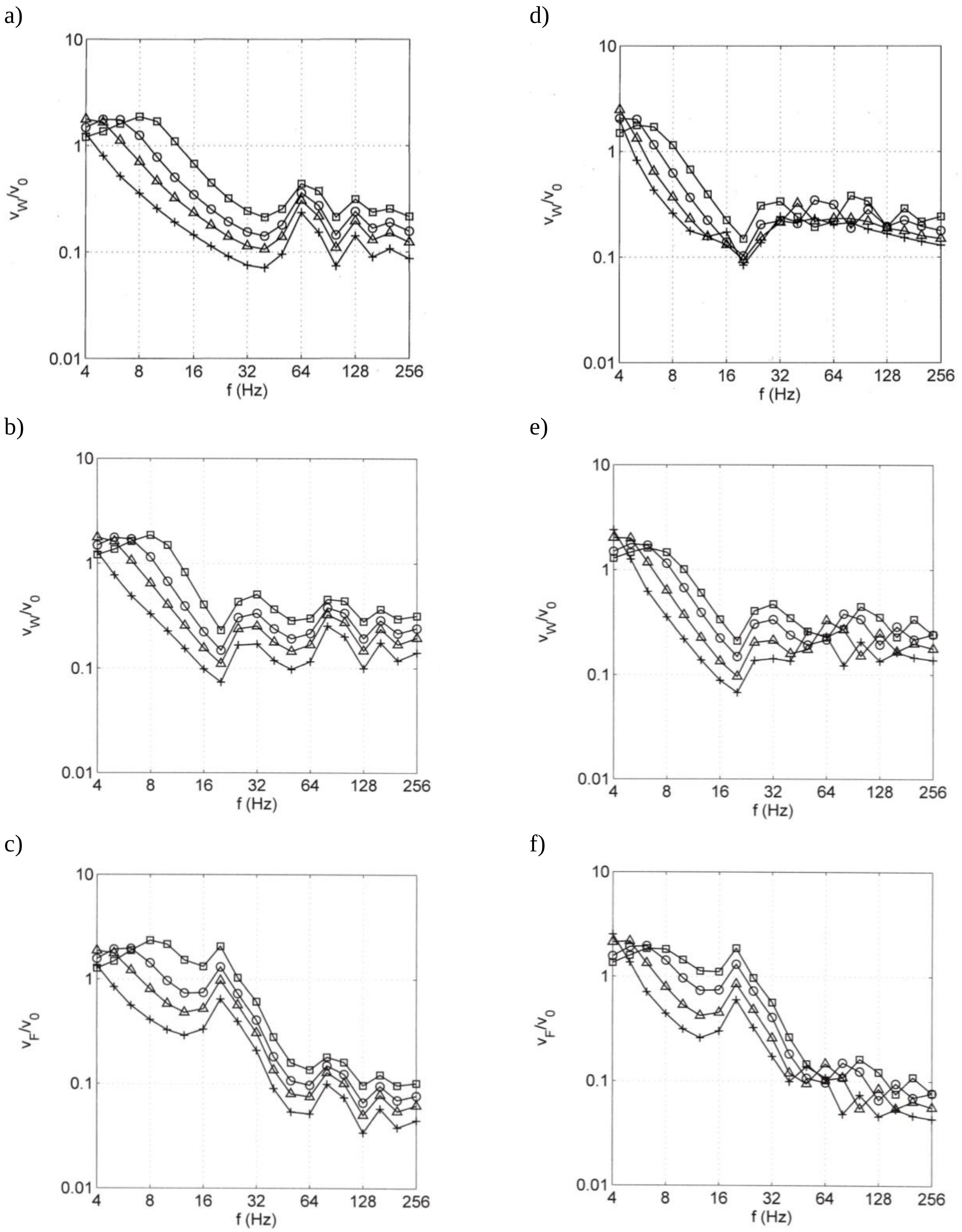

Figure 5 – Average transfer functions of a-c) buildings on different soils, v_S = + 100, △ 150, ○ 200, □ 300 m/s, a) wall-model, b) walls and c) floors of a wall-floor model; d) walls for different numbers of storeys n = □ 6, ○ 10, △ 15, + 20; e) walls and f) floors for different massive buildings ρ_B = □ 200, ○ 300, △ 500, + 800 kg/m^3.

If more massive buildings are considered in Figure 5e,f, the same effects as for high buildings are observed at low frequencies, a lower building-soil eigenfrequency and a stronger reduction in the mid-frequency range. At high frequencies, there are clear differences and a shift of characteristic frequencies. The free-free building resonance shifts from 100 to 50 Hz where lower frequencies as well as lower amplitudes are typical for the more massive buildings.

Next, results for a building on elastic support are presented. The stiffness of the support is varied so that resonance frequencies of 8, 10 ,12.5 and 16 Hz are achieved. These resonance frequencies can be clearly seen for the rigid building (Fig. 6a). In Figure 6b,c, a building with rigid walls and elastic floors is considered. The floor masses vibrate with the whole building at low frequencies. Then the floor resonance frequency at 20 Hz is observed as a maximum of the floor response (Fig. 6c) and a minimum of the wall response (Fig. 6b). Above the resonance frequency, the floor masses are decoupled from the building. Therefore, the reduction effect of the elastic support is weaker for the wall (stronger for the floors). Finally, the building with elastic walls and floors is shown in Figure 6e,f. Instead of the strong reduction of the rigid building, the reduction of the elastic building is considerable weaker. This weaker reduction can also be predicted for an infinitely high building (Fig. 7a). This high-building-model does not show the frequency-dependent variations due to the wave reflections at the roof so that the smooth response curves are well suited for a prediction. The infinitely high building model for high frequencies, which is also discussed in [8], is combined with the rigid building model for the low frequencies (Fig. 6a) giving a consistent prediction model (Fig. 7b).

Table 1. The soil and building parameters (the standard parameters are underlined)

Name	Symbol	Value	Remarks
Shear wave velocity	v_S	200 m/s	
Mass density of the soil	ρ_S	2000 kg/m^3	
Area of the foundation	A_S	4 m^2	per column
Area of the foundation	A_S	12 m^2	per wall
Area of the foundation	A_S	60 m^2	per building
Stiffness of the foundation	k	$3.4\, \rho_S\, v_S^2\, A_S^{0.5}$	
Damping of the foundation	c	$1.6\, \rho_S\, v_S\, A_S$	
Number of storeys	n	$\underline{6}$ / 4 / 20	Fig. 1 / 3
Height of a storey		3 m	
Area of the building	A_B	250 m^2	Fig. 5ff
Mass density of the building	ρ_B	300 kg/m^3	Fig. 5ff
Height of the building	H	$\underline{18}$ / 12 / 60 m	Fig. 1 / 3
Mass of the building	m	$H\, A_B\, \rho_B$	
Thickness of the wall		0.25 m	
Area of the wall	A_W	2.5 / $\underline{3}$ m^2	Fig. 1
Thickness of the column		0.6 m	
Area of the column		0.36 m^2	
Thickness of the floor		0.2 m	
Length of the floor		$\underline{6}$ / 5 m	Fig. 1
Young's modulus of the concrete wall	E_W	$3\ 10^{10}$ N/m^2	
Young's modulus of the masonry wall	E_M	$5\ 10^{9}$ N/m^2	Fig. 1
Mass density of the wall	ρ_W	2500 kg/m^3	
Wave velocity of concrete wall	v_L	$(E_W/\rho_W)^{0.5}$	
Column/wall frequency	f_C	$v_L/4H$	
Eigenfrequency of the floor	f_F	$\underline{20}$ / 25 / 13 Hz	Fig. 1 / 3
Damping of the floor	D_F	5 %	
Frequency of the elastic support	f_I	8 / 10 /12.5 / 16 Hz	Fig. 6-7
Damping of the elastic support	D_I	10 %	Fig. 6-7

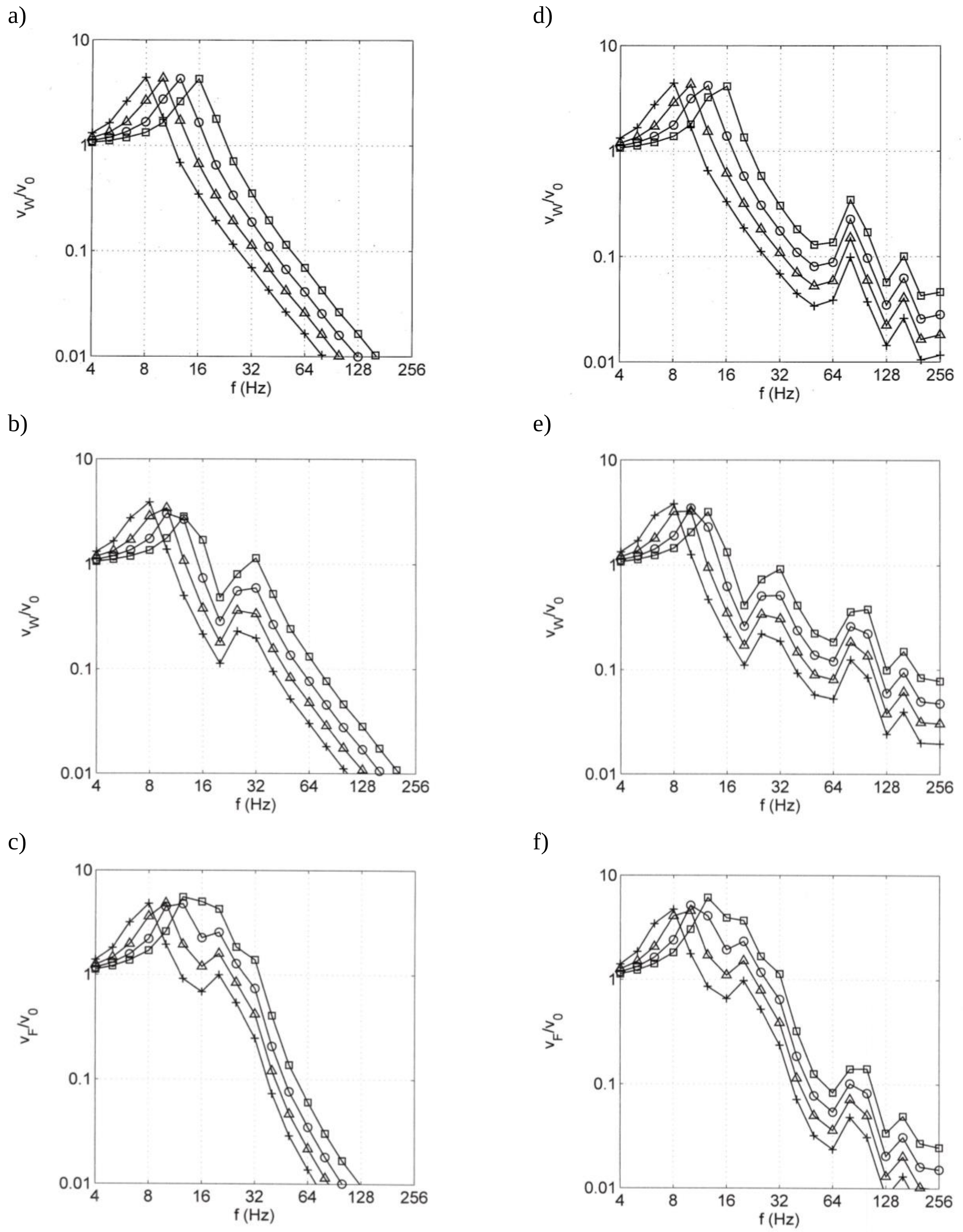

Figure 6 – Average transfer functions of buildings on different elastic supports, f_I = □ 16, ○ 12.5, △ 10, + 8 Hz, a) rigid wall model, b) walls and c) floors of a rigid wall-floor model; d) flexible wall model, e) walls and f) floors of a flexible wall-floor model.

5 Example prediction of vibration and noise

For a prediction, the excitation must be included. Here it is a high-frequency urban train excitation from a tunnel line. The predicted response of the building to this excitation is shown in Figure 7c. The energy of these spectra can be used to evaluate the vibrations according to the standards, for example DIN 4150-2 [9]. The A-weighted response (Fig. 7d) can be used to predict the noise. A simple transfer law

$$L_p = L_v + 6 \text{ dB}. \quad (12)$$

from velocity to pressure can be used to get the spectra of the noise [10]. Once again, the energy of these noise spectra can be used to evaluate the noise level which is compared with the limit values, for example 30 dB at night and 40 dB at day [11]. As in many cases, the elastic support is more effective to reduce the noise than to reduce the vibration.

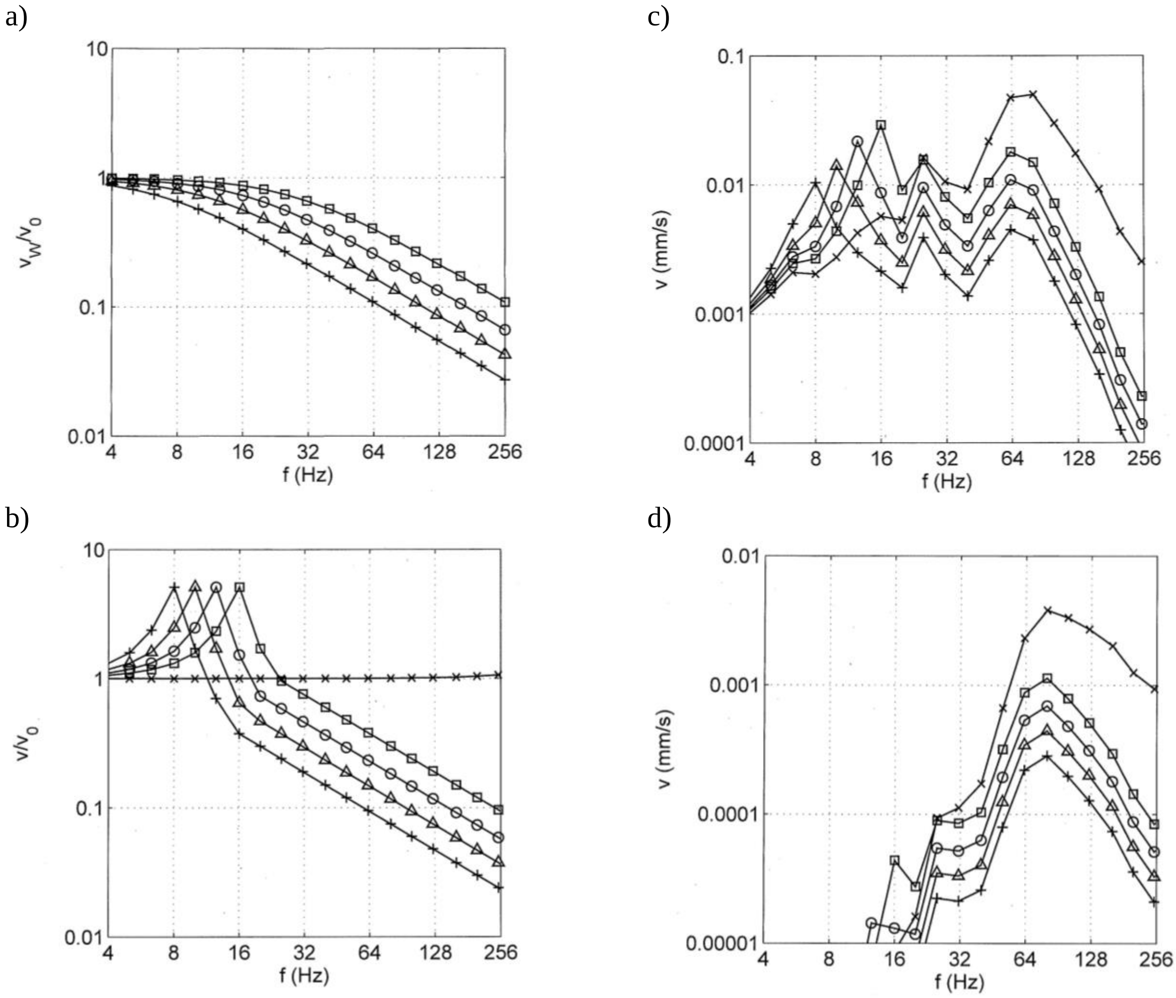

Figure 7 – Average transfer functions of buildings on different elastic supports, f_I = □ 16, ○ 12.5, △ 10, + 8 Hz, a) building of infinite height, b) prediction model (rigid and infinite height); c) building response to a train excitation ×, d) A-weighted vibrations (from c).

6 Conclusion

The vibration of buildings has been analysed by 3D finite-element models and by 1D prediction models. The agreement between the 1D and 3D models is very good what has been demonstrated for an apartment building and an office tower. Soil, wall and floor resonances have been identified at low frequencies. These modes can interact if the corresponding frequencies are close together and can result in lower resonance frequencies especially for column-type office buildings. At higher frequencies, the amplitudes of different storeys vary considerably, so that the high frequencies have been analysed by mean values of all storeys. The high-frequency reduction from the free field to the building has been quantified with different models, rigid or elastic walls, with or without floors, and finally with an infinitely high wall model. The reduction is constant for the buildings on the soil whereas a building on an elastic support has linearly decreasing amplitudes with frequency. The variations of the soil, the mass of the building, and the number of storeys result in a shift of amplitudes, a shift of frequencies or in very similar high-frequency amplitudes. The infinitely high wall seems to be acceptable for high frequencies, more realistic than the strong reduction of a rigid building. At low frequencies however, a rigid model yields good results. The combined rigid and high-building prediction curves and a simple transfer formula from velocity to sound pressure allow a simple and fast prediction of vibration and noise.

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