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A combined approach for base isolation design

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New buildings in the vicinity of underground railway lines should be protected against noise and vibrations induced by railway traffic.
In the present paper a case study is presented. A 2D FEM model of the Metro station, ground and building was constructed in order to identify the transfer function of vibration from the Metro station to building foundations. A 3D model of the building was constructed, including not only structural elements, but also other non structural walls, in order to identify the transfer function of vibration from foundations to walls and floors. As the acoustic impedance of heavy walls and floors is much higher than that of the air, the numerically assessed vibration fields of walls and floors were used to calculate sound fields in rooms by natural mode analysis. The vibration and sound fields were then compared with comfort criteria in order to design a base isolation system.
With this combined approach, the analysis was performed up to 140 Hz and, if needed, it could have been extended to 170 Hz, which is more than one can usually do with integrated 3D models.

1 Introduction

This paper reports on the characterisation and reduction of the vibration and noise levels expected in a residential 10-storey building with a five-level basement for car-parking to be constructed in the vicinity of an underground railway station, which is part of the presently on-construction Red Line West-Expansion of the Lisbon Metro Network.

The study was divided into the following parts: dynamic characterisation of the source, ground, building, and adjacent buildings; and design of a base isolation system.

2 Characterisation of the source

In order to characterise the vibration induced by the railway traffic on the ground, triaxial acceleration measurements were performed about 1.5 metres away from the railway line in an existing Metro station near the construction site.

Figure 1 shows the lower and higher envelopes of the one-third octave band measured acceleration spectra, which are in good agreement with published measured spectra [1, 2]. An average acceleration spectrum is also shown. In general, the spectra exhibit high energy content in the frequency range 31.5 – 100 Hz.

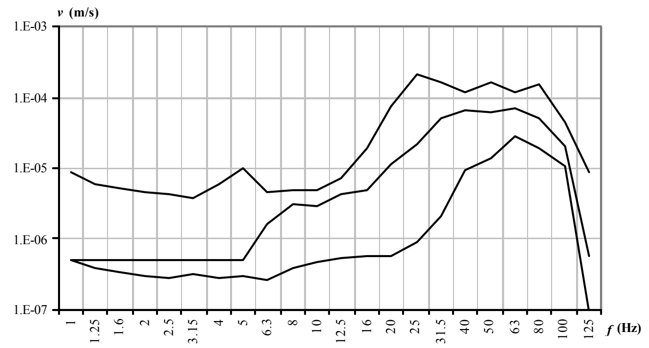

Fig.1 Envelopes and average of the one-third octave band measured acceleration spectra.

As the railway line in the existing Metro station is non-isolated, whereas the line in the on-construction station will be installed on a concrete shell separated from the station structure by a resilient mat, which will reduce the natural frequency of the system of about 60 – 70 % and thus the actual vibration of about 10 – 20 %, the lower envelope of the measured acceleration spectra is assumed to provide an acceptable estimate of the vibration at the source. In spite of this assumption, the three spectra shown in Figure 1 were considered in this study to describe ground excitation.

3 Characterisation of the adjacent existing buildings

A 2D FEM model [3] was used to characterise the transmission of vibration from the underground railway station to the building. The model included also the existing adjacent buildings and therefore measurements had to be performed in order to assess their dynamic properties. In one of the buildings, with a reinforced concrete frame structure, the measurements indicated natural frequencies of 2.0 and 3.3 Hz associated with the first two translational vibration modes and also a natural frequency of 4.3 Hz associated with a torsional vibration mode. In the other building, with a masonry wall-type structural system, acceleration peaks appeared at 2.6 and 3.7 Hz, but the associated vibration modes were not identified.

4 Characterisation of the ground

4.1 Ground profile

Assessment of the ground profile was based on field test data, mainly SPT (Standard Penetration Test), and other published information [4]. The ground profile included 2.0 to 3.0 m superficial backfill, followed by stiff clay with depth increasing strength ($29 \leq N \leq 60$).

For the small displacements induced by railway traffic, the ground exhibits a linear (elastic) behaviour and therefore ground response is mainly controlled by the shear wave velocity, v_S (m/s). Empirical equations, given by Otha and Goto ($v_S = 85\,N^{0.348}$) [5, 6] and Maugeri and Carrubba ($v_S = 48\,N^{0.550}$) [7], were used to obtain 3D profiles of the shear wave velocity such as the one illustrated in Figure 2.

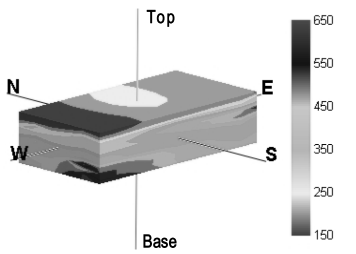

Fig.2 Illustration of a 3D profile of the shear wave velocity, in m/s.

4.2 Vibration transmission through the ground

Figure 3 shows the 2D FEM model used to assess the transmission of vibration from the Metro station to the building foundations and basement walls. The model covers a section of the ground 172.5 m wide and 44.0 m deep with square elements of side length 0.4 m, *i.e.*, the highest significant frequency lies in the range 100 – 150 Hz.

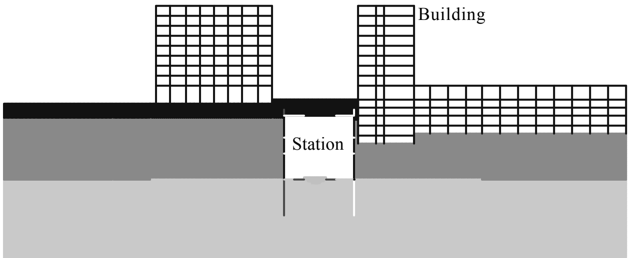

Fig.3 2D FEM transversal model.

The transfer functions between the acceleration close to the rails and the acceleration in the building foundations and basement walls (Figure 4) was calculated by step-by-step time integration for a pulse signal corresponding to a flat Fourier spectrum with amplitude equal to the unity. Amplification is around 15 at 31.5 Hz and 4 at 70 Hz.

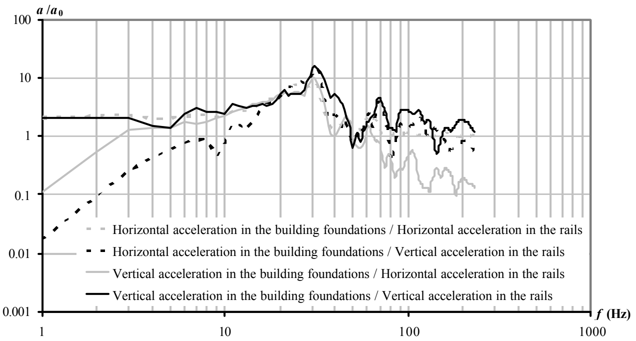

Fig.4 Acceleration transfer functions from the Metro station to the building foundations and basement walls.

As measurements showed that the railway traffic induced vibrations were relevant only when trains were close to the station, there was no need to build a longitudinal 2D model.

5 Characterisation of the building

5.1 FEM models

Figure 5 shows one of the three different 3D FEM models used to assess the vertical transmission of vibration through the building structure. Three different rooms were analysed in floors 1, 3 and 7, and a different model was built for each floor. Rooms 1, 2 and 3 (along the back wall of the building and not visible in Figure 5) are the same for each floor and have a height of 2.80 m and a floor area of 4.90×3.50 m^2, 3.90×3.47 m^2 and 4.50×3.50 m^2, respectively. The room walls were modelled with 15, 20 or 30 cm thick shell elements with a modulus of elasticity (E) of 6.65 GPa [8] and a mass per unit volume (ρ) around 950 kg/m^3. A constant damping ratio (ξ) of 8 % was assumed. In order to accurately assess the dynamic behaviour of the building for small amplitude vibrations, non-structural masonry walls were modelled with pin-jointed equivalent diagonal elements of width $w_{eff} = 0.25d$, where d is the length of the wall panel diagonal [9]. An elasticity modulus of 3.12 GPa was assumed for these diagonal elements which work on the wall plane only. In order to avoid unnecessary consideration of local vibration modes, the mass of these elements was distributed on the slabs and only the floors adjacent to the rooms considered in each case were modelled with shell elements. The other floors were modelled as diaphragms. An elasticity modulus of 30.5 GPa and a constant damping ratio of 5% were assumed for all concrete floors, beams and columns.

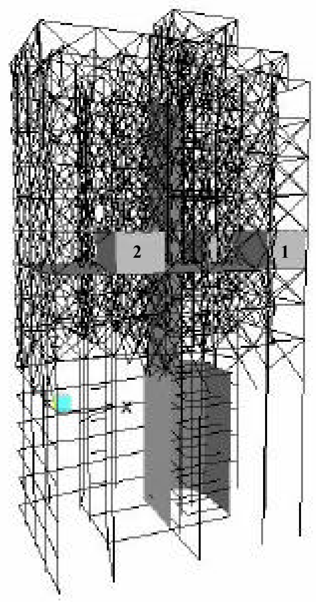

Fig.5 3D FEM model used for assessing vibration in three different rooms of the third floor.

Modal analysis indicated the following natural frequencies:

- First mode (mainly along the x-axis including some torsion): $f = 2.20$ Hz;
- Second mode (mainly along the y-axis): $f = 2.50$ Hz;
- Third mode (mainly torsion): $f = 3.89$ Hz.

5.2 Vibration transmission through the building

Figure 6 shows the envelopes of the acceleration transfer functions between the building foundations/basement walls and the walls and floors of room 1 in the first floor.

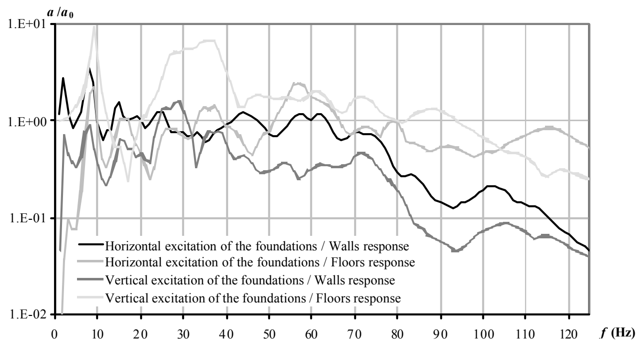

Fig.6 Acceleration transfer functions from the building foundations to the room 1 in the first floor.

Figure 6 indicates that annoyance due to excessive vibration is more likely to be caused by the floors than by the walls. The significant amplification exhibited by the floors at 10 Hz and in the range 25 – 40 Hz could actually be reduced if a damping ratio varying from 15 % at 10 Hz to 5 % at 125 Hz were considered [10, 11]. However, considering the high energy content exhibited around 30 Hz by the acceleration spectra close to the rails (Figure 1) and the significant amplification exhibited, at those same frequencies, by the acceleration transfer functions from the rails to the building foundations (Fig. 4) and then to the room floors and walls (Fig. 6), high levels of vibration are expected at the 31.5 Hz one-third octave band. In order to check the room occupants tolerance to these vibration levels, an annoyance threshold was set according to the standard ISO 2631 [12] and to reference values indicated by Nelson [13]. In Fig. 7, the comfort limit is compared with the envelopes of the one-third octave band acceleration level spectra obtained at the floor and ceiling of room 1 in the first floor for the three levels of rail excitation defined in Fig 1. Although the room occupants are not likely to be annoyed by the lowest level of excitation, a slight increase of the excitation amplitude might be enough to induce significant annoyance at the 31.5 Hz one-third octave band.

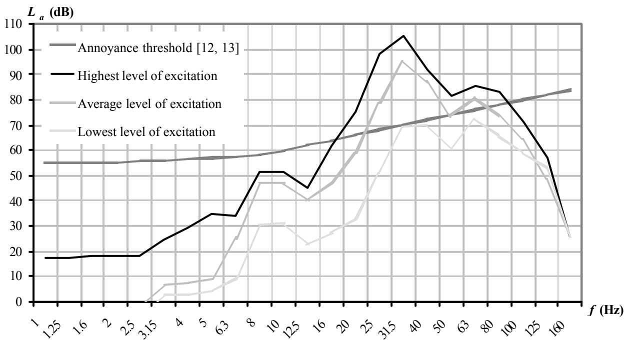

Fig.7 Envelopes of the one-third octave band acceleration level spectra obtained at the floor and ceiling of room 1 in the first floor.

5.3 Sound transmission through the building

As the acoustic impedance of heavy walls and floors is much higher than that of the air, the numerically assessed vibration fields of walls and floors were used to calculate sound fields in the rooms by natural mode analysis. Using Kihlman's approach [14], the sound field generated in a room with dimensions $a{\cdot}b{\cdot}c$ by a vibrating surface (wall, floor or ceiling) can be given by a Fourier expansion

$$p(x,y,z,t) = -\mathrm{j}\omega\rho_0 \sum_{\mathrm{l,m,n}=1}^{\infty} \frac{8c_0^2\,(-1)^{\mathrm{l}}\, C_{\mathrm{mn}}\, \varphi_{\mathrm{lmn}}(x,y,z)}{abc\left[(\omega_{\mathrm{lmn}} + \mathrm{j}\delta)^2 - \omega^2\right]}\,\mathrm{e}^{\mathrm{j}\omega t}, \quad (1)$$

where the functions describing the acoustic modes (l, m, n) are given by

$$\varphi_{\mathrm{lmn}}(x,y,z) = \cos\left(\frac{\mathrm{l}\pi x}{a}\right)\cos\left(\frac{\mathrm{m}\pi y}{b}\right)\cos\left(\frac{\mathrm{n}\pi z}{c}\right), \quad (2)$$

and the corresponding eigenfrequencies by

$$\omega_{\mathrm{lmn}} = c_0\pi\sqrt{\left(\frac{\mathrm{l}}{a}\right)^2 + \left(\frac{\mathrm{m}}{b}\right)^2 + \left(\frac{\mathrm{n}}{c}\right)^2}. \quad (3)$$

The parameter δ in (1) describes the damping effect caused by sound absorption at the surface of walls and floors. As sound absorption in dwellings is negligible at low frequencies, δ lays around 1.5. The factors C_{mn}, which describe the modal coupling between the vibrating wall or floor and the sound field in the room, are given by

$$C_{\mathrm{mn}} = \int_0^b\int_0^c v_x(y,z)\cos\left(\frac{\mathrm{m}\pi y}{b}\right)\cos\left(\frac{\mathrm{n}\pi z}{c}\right)\mathrm{d}y\,\mathrm{d}z, \quad (4)$$

where $v_x(y, z)$ is the function which describes, on the frequency domain, the velocity field of the construction element. As this velocity field is obtained from the FEM model for each node of the construction elements, the integral in (4) has to be solved numerically.

As a consequence of the modal behaviour of sound fields in dwellings at low frequencies, expression (1) does not have to be calculated for every coordinate (x, y, z) but only for a lower corner position, where the largest number of acoustic modes are excited [15]. The sound pressure spectra in that point can then be computed by adding the sound pressure generated by each vibrating wall or floor in the room.

In Figure 8, the one-third octave band sound pressure level spectra obtained for room 1 in the first floor for the three considered levels of excitation are compared with comfort criteria given by Broner [16] and Inukai [17] and also with the normal equal-loudness-level contours for pure tones corresponding to the hearing threshold and to 30 phon [18].

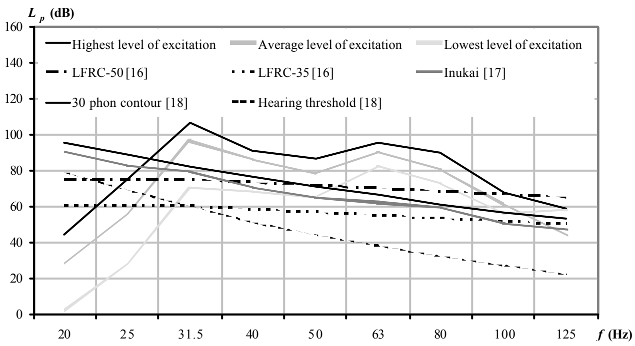

Fig.8 One-third octave band sound pressure level spectra obtained for room 1 in the first floor and comfort criteria.

Figure 8 shows that even for the lowest level of excitation, acting simultaneously at the three directions, x, y and z, high sound levels appear in the range 31.5 - 80 Hz one-third octave bands, *i.e.*, the building must be isolated.

6 Base isolation system

In order to reduce the vibration induced in the building by underground railway traffic, a base isolation system was designed. The system includes isolators located under the column footings and along the peripheral walls of the first level of the basement car-parking. As wall excitation below this level can transmit vibrations to the building through the slabs and columns, all car–parking slabs must be supported on isolators located on short cantilevers along the walls. A schematic representation of the base isolation system is shown in Figures 9 and 10.

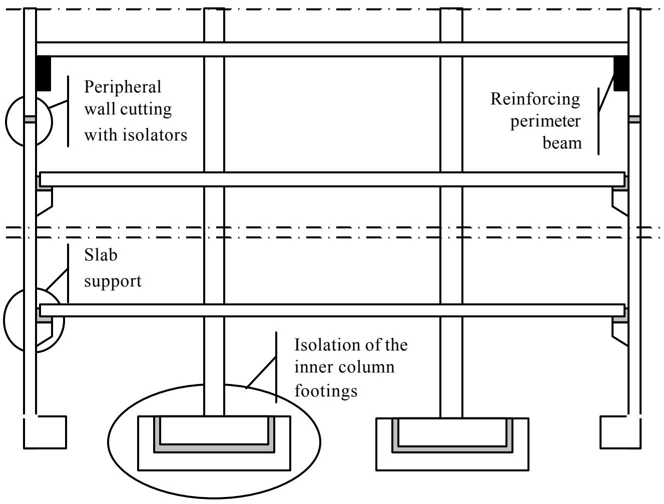

Fig.9 Schematic representation of the base isolation system (isolators in grey).

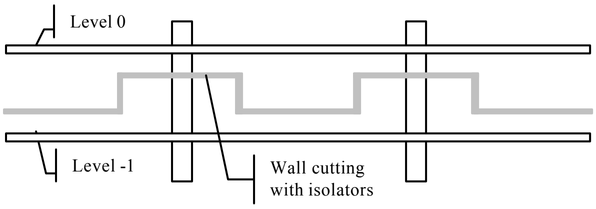

Fig.10 Schematic representation of the isolation along the peripheral walls.

In order to obtain an efficient reduction of the vibration levels at 32 Hz, the natural frequency of the system should be, at least, ¼ of this frequency, *i.e.*, the base isolation system should be designed to have a resonance frequency of 8 Hz in all directions. Although a more efficient isolation system could be obtained with lower resonance frequencies, the building would then exhibit displacements for the seismic action which, taking into account that the building is side by side with other buildings, would be unacceptable.

7 Characterisation of the isolated building

7.1 FEM models

In order to assess the reduction of vibration obtained with the base isolation system, springs with triaxial stiffness given by $(8 \times 2\pi)^2/9.8 \times N_{qp}$, where N_{qp} is the quasi-permanent load value, were inserted into the FEM models described in 5.1.

7.2 Vibration transmission through the isolated building

Figure 11 shows the envelopes of the one-third octave band acceleration level spectra obtained in the construction elements of rooms 1 to 3 in the first and seventh floors for the lowest excitation level. The behaviour of the walls and floors does not change much from room to room and there is no evidence of energy dissipation from the first to the seventh floor.

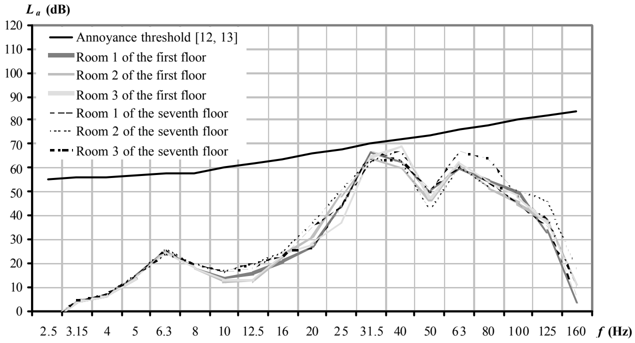

Fig.11 Envelopes of the one-third octave band acceleration level spectra obtained, for the lowest excitation level, in the isolated building.

A significant reduction of the acceleration level was obtained for room 1 in the first floor at the 63 Hz one-third octave band (Figures 7 and 11). At the 40 Hz band the improvement is still significant but lower than 10 dB. At the 31.5 Hz one-third octave band the acceleration level decreased only 3 dB. This slight improvement was expected because the resonance frequency of the isolation system (8.0 Hz) is only slightly lower than the natural frequency associated to the first vertical vibration mode of the non-isolated building (9.1 Hz). This conclusion is confirmed in Figure 12, where the one-third octave band acceleration level spectra of room 1 in the first floor are shown, separately for floors and walls, for the building without and with the base isolation system installed. Figure 12 shows that walls are more effectively isolated than floors.

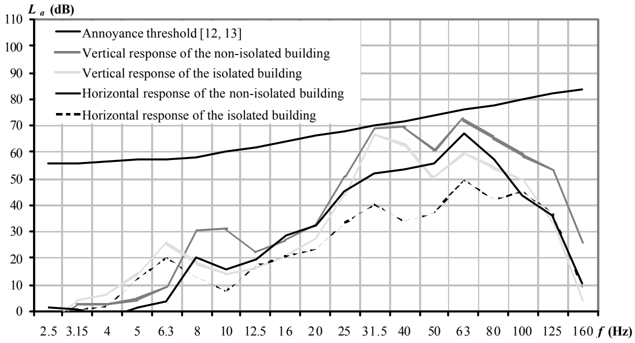

Fig.12 Envelopes of the one-third octave band acceleration level spectra obtained at the floors and walls of room 1 in the first floor for the isolated and non-isolated building.

Theoretically, further improvement could be obtained by increasing the mass of the building, which would then reduce its natural frequencies. In order to test this solution, the thickness of the slabs was increased of 3 cm and, consequently, the first natural frequencies of the room floors increased (from 39.5 to 45.4 Hz in the case of room 1), thus making the base isolation system potentially more efficient. However, as shown in Figure 13, only a slight improvement of 1 dB was obtained at the 31.5 Hz one-third octave band and, surprisingly, the highest acceleration level obtained at the 63 Hz band in room 1 in the seventh floor actually increased about 3 dB.

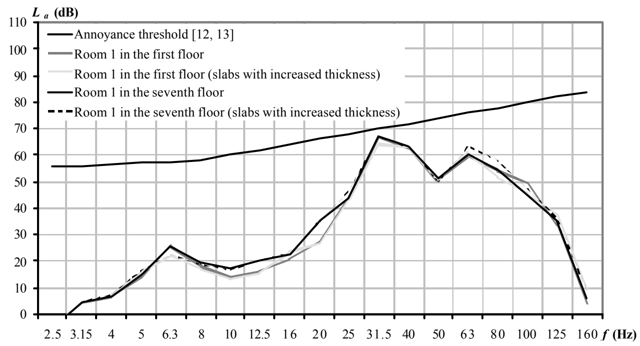

Fig.13 Envelopes of the one-third octave band acceleration level spectra obtained for the isolated and non-isolated building.

7.3 Sound transmission through the isolated building

Figure 14 shows the one-third octave band sound pressure level spectra predicted, for the lowest level of excitation, in a corner 40 cm away from the walls and floor of rooms 1 and 3 in the first floor. The sound pressure level spectra for room 1 are shown for the non-isolated and isolated building and also for the latter with slabs of increased thickness.

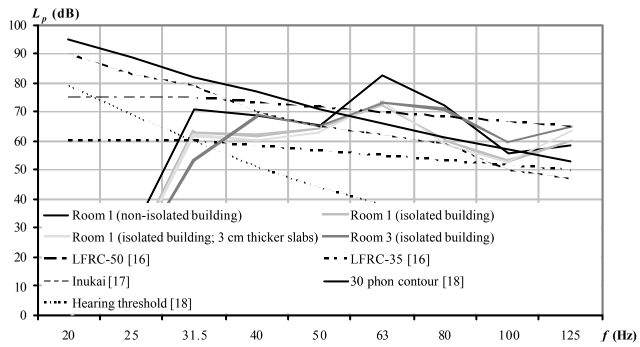

Fig.14 One-third octave band sound pressure level spectra obtained for rooms 1 and 3 in the first floor of the isolated building and comfort criteria.

Figure 14 shows a sound pressure level reduction in room 1 at the 63 and 80 Hz one-third octave bands. For the isolated building, the chosen comfort limits are not exceeded at the 80 Hz band, *i.e.*, annoyance due to low frequency noise is unlikely. At the 63 Hz one-third octave band, even the rating LFRC-50 [16] is slightly exceeded, which, in addition to the tonal content of the noise in that frequency band, may indicate that discomfort still remains.

8 Summary and conclusions

In this paper, FEM and natural mode analysis were used to assess vibration and sound levels in a building to be constructed near an underground railway station. The models indicated that although vibration levels are acceptable, annoyance due to low frequency noise is likely to occur. Base isolators were then designed in order to control vibration transmission and thus noise generation. However, as the building is located in an important seismic zone, the resonance frequency of the base isolation system is limited to 8 Hz, which is still too high. Thus, further studies are required in order to identify the main vibration transmission paths in the building and the optimal isolation systems for controlling local vibration of floors and walls.

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