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.](image)

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 ≤ N ≤ 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, vS (m/s). Empirical equations, given by Otha and Goto (vS = 85N0.348) [5, 6] and Maugeri and Carrubba (vS = 48N0.550) [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.](image)
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.

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.

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 m², 3.90 × 3.47 m² and 4.50 × 3.50 m², 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/m³. 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.

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.
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 occupant’s 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 in the excitation amplitude might be enough to induce significant annoyance at the 31.5 Hz one-third octave band.

\[ p(x,y,z,t) = j\omega \rho_0 \sum_{l,m,n=1}^{\infty} R_\delta (-\alpha)^l C_{lmn} \varphi_{lmn}(x,y,z) e^{j\omega t}, \]  

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

\[ \varphi_{lmn}(x,y,z) = \cos \left( \frac{\pi x}{a} \right) \cos \left( \frac{m \pi y}{b} \right) \cos \left( \frac{n \pi z}{c} \right), \]  

and the corresponding eigenfrequencies by

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

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].

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.
is no evidence of energy dissipation from the first to the seventh floor.

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.

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
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.

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 63 and 80 Hz one-third octave bands. For the isolated building, the chosen comfort limits are not exceeded at the 63 and 80 Hz one-third octave bands. For the isolated building, the chosen comfort limits are not exceeded at the 63 and 80 Hz one-third octave bands. For the isolated building, the chosen comfort limits are not exceeded at the 63 and 80 Hz one-third octave bands.

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.

References