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GROUND-BORNE NOISE AND VIBRATION TRANSMITTED FROM SUBWAY NETWORKS TO MULTI-STOREY REINFORCED CONCRETE BUILDINGS

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Abstract. During the operation of urban subway rail transit systems, vibrations are generated that transmitted through the soil, induce vibrations in nearby buildings. The transmission of ground-borne vibrations from subway rail transit systems in a building is governed by the soil-foundation interaction, the reduction of vibration level between floors, and the amplification due to resonances of building elements. These are influenced by the type of the building, its construction materials, the foundation soil, and the frequency content of the excitation. A methodology is proposed for the determination of the sound vibration along the height of the building for a specific construction type, demonstrating how the attenuation and amplification parameters can be calculated. For this particular building type, a notable amplification of the vibration due to floor and other structural resonances was found, whereas the vibration and hence the radiated noise levels are similar from the first floor up. An overall building amplification factor is proposed, taking into account all the above mentioned transmission mechanisms.

Keywords: ground-borne noise; vibration; subway; rail transit; multi-story buildings; reinforced concrete.

Introduction

The problem of ground-borne vibration induced by railway traffic as well as the transmission of generated waves along the height of reinforced concrete buildings are investigated. In the prediction of ground-borne vibration and noise from subway rail transit systems, an important factor is the overall coupling of the vibration in the ground to the building foundation, as well as the amplification or attenuation of the vibration as it is transmitted up through the building. The latter is a combination of attenuation going up the building combined with amplification of vibration due to structural resonances, primarily floor slab resonances. Estimates of the decrease in vibration levels with increasing height in heavy masonry buildings are given by Wilson (1971), Ungar and Bender (1975), whereas for lightweight constructions no decrease with height is found. In some cases, vibration levels on the upper floors of lightweight buildings can be amplified due to floor resonances. An attenuation of 1 to 3 dB per floor is typical for vibration as it travels to upper floor levels. The attenuation is due to dissipation in the floor and splitting of vibration energy at each floor-wall joint. Data reported by Ishii and Tachibana (1978) indicate that near the top of a large building, the floor-to-floor attenuation is less than near the ground. The effect of train vehicle characteristics on railway vibration generation is investigated in the literature through of both, numerical analysis, and experimental investigations.

Focus was placed on the evolution and suitability of commonly used numerical techniques to also investigate the effect of train characteristics. A variety of approaches including constant axle loads, randomly varying axle loads, and multi-body loads is available and it was found that multi-body approaches offered the highest accuracy, but required the most computational effort (Kouroussis *et al.* 2014a; Connolly *et al.* 2015a). A common source of vibration and ground-borne noise is local defects (e.g. rail joints, switches and crossings) which cause large amplitude excitations, Relevant studies are validated and comprehensive in time domain, and three-

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dimensional ground vibration prediction models were used to investigate the vibrations generated at the wheel/rail contact due to local rail and wheel surface defects. Different types of rail and wheel defect are mathematically modelled, including rail joints, switches, crossings and wheel flats (Kouroussis *et al.* 2015a, 2015b; Connolly *et al.* 2015b). Regarding the transmission of vibration inside a building, there are several existing methods of determining ground-borne vibrations in buildings due to subway and tramway networks operation, that are essentially based on empirically derived relationships.

Another approach employs the finite element method to model the complicated subway-soil-structure interaction problem (Chua *et al.* 1995; Kouroussis *et al.* 2013). The use of models of infinite length has been proposed (Hunt 1995). A review of the available literature indicates that there is a significant absence of current research in this area, as the existing work is oriented towards solving specific problems (Kliukas *et al.* 2008; Crispino, D'Apuzzo 2001; Vanagas *et al.* 2017). The transmission of vibrations are significantly affected by the type of the load-bearing system of a building, the materials that are used for its construction, the type of the foundation, the existence of a basement and the soil mechanical characteristics. The transfer of the waves between soil and building floor is a function of:

– the coupling between soil and foundation (Kouroussis *et al.* 2014b);
– the reduction between foundation and building floors, interior walls and secondary elements;
– the amplification due to resonances of various building elements.

The typical Athenian building is of a different construction to that of other buildings in Europe and North America (Mouzakis, Vogiatzis 2016). The structural elements, through which vibration is transmitted, of the load-bearing system of a typical reinforced concrete multi-storey Athenian building are slabs, beams, columns, shear walls or central core, and staircases. In general, columns form a square grid of 4 to 5 m. All of the aforementioned elements, as well as the surrounding walls of any underground floors, and the foundation, are made of cast-in-place concrete. Usually, foundations consist of rigid footings with a height of approximately 1 m and strap beams. The non-structural elements, such as infill and interior walls, are made of hollow clay brick masonry with cement-lime mortar. In this paper, the results of an extensive experimental campaign within four buildings, close to the Athens under- ground Metro network, are presented: (a) the Public Power Corporation (PPC) multi-storey building consisting of seven floors and a basement, (b) a residential 6-storey and basement, reinforced concrete building at 8 Mourouzi street in proximity to a Turn Out (TO) device, (c) and (d) two 5-storey residential buildings, of which Maroussi 1 has a soft first story and Maroussi 2 has brick masonry infills at all levels. Typical cross-sections of all buildings are shown in Fig. 1.

This paper presents the experimental results of vibration measurements that were recorded at four different reinforced concrete multi storied buildings during the operation of subway rail transit systems of Athens. A methodology is proposed for the determination of the sound vibration along the height of the building for a specific construction type, demonstrating how the attenuation and amplification parameters can be calculated. An overall building amplification factor is proposed.

1. Measurement Setup

In order to derive the typical amplification curve relative to measured train passbys, the following methodology was applied for the PPC building. This building is in proximity to the Athens Metro line 1 in a section where no mitigation measures were implemented at the period of the measurements. A borehole was drilled 2 m from the facade and a triaxial accelerometer was mounted on a down hole tool, which was placed in the borehole. This was done in order to be able to investigate the coupling loss between soil and foundation, as well as to compare the vibration velocity levels in the borehole with those recorded at the soil free surface. Two horizontal and one vertical geophones were mounted on the sidewalk 2.5 m from the building. The building interior measurement locations were at the basement, ground floor, 1st floor, 2nd floor and 4th floor, as shown in Fig. 1, where verti-

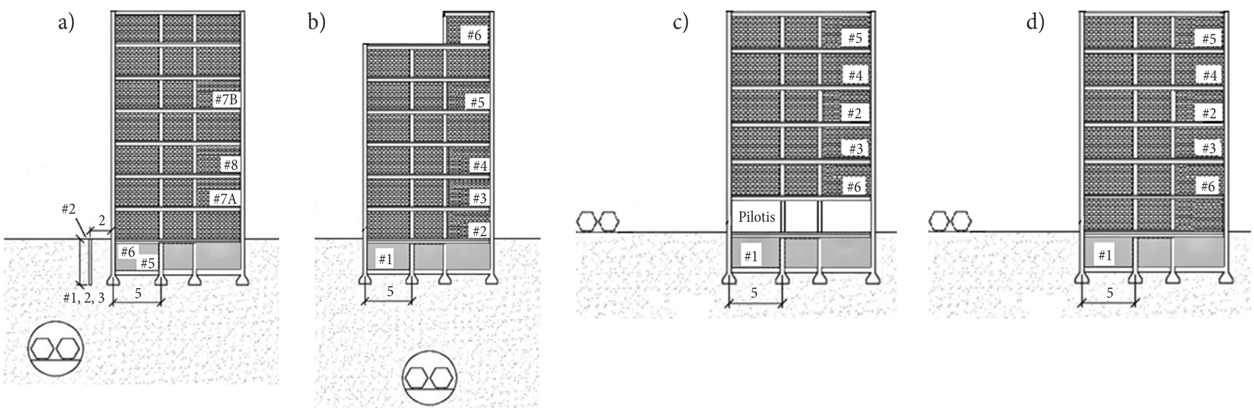

Fig. 1. Cross-section of the: a – PPC building and measurement locations; b – Mourouzi street building; c – Maroussi 1 building; d – Maroussi 2 building

cal geophones were connected to the slabs of the building. For the remaining three buildings, measurements were performed at the basement and at upper floors, where no boreholes were drilled.

For the vertical vibration velocity, in all buildings, the Nederland BV type SM-7 8 Hz geophones installed in a PE-3 case were used. The sensitivity of the geophones was 0.288 V/cm/sec. The geophones used had long cables without preamplifiers, but higher signal level was provided at the source to overcome some of the effect of the cable length. Two 4-channel digital synchronized recorders were used. In the case of the PPC building, since there were nine measurement locations, it was necessary to make recordings for two sets of train passbys. Ten train passbys were recorded for each building and each set of measurements. The goal of the acoustic measurements was to obtain 1/3 octave band data for deriving a 1/3 octave band amplification curve. The typical averaging time was approximately 4 sec for each pass by, with the analysis covering the frequency range from 10 to 200 Hz. Relevant measurement setups with both accelerometers and geophones are in permanent use in Athens Metro and Tramway networks and have proved a great success (Mouzakis, Vogiatzis 2016; Vogiatzis 2010, 2012; Vogiatzis, Kouroussis 2015). The above measurement set up and the choice of the positions of the sensors made possible to access a transfer function of vibration diffusion from a transit source within typical multi storey reinforced concrete buildings which is quite rare in the existing literature.

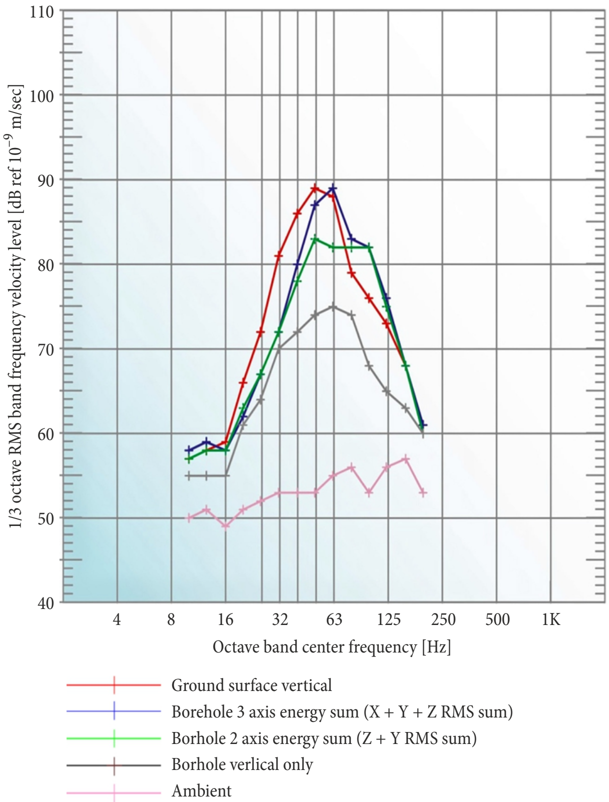

Fig. 2. Borehole and surface averages for sets A and B train vibration in the borehole and at the ground surface

2. Measurement Results

2.1. The Case of the PPC Building

The basic average results from the acoustic measurements and the relevant 1/3 octave band analysis are presented in Figs 2–6. Fig. 2 presents the basic overall results for the vibration measurements in the borehole and at the ground surface. Indicated on the chart is the average surface vertical vibration for the train passbys during the first series of measurements. This figure presents the vibration velocity level:

– for the vertical direction only;
– the vertical direction and the longitudinal one;
– all three directions in the borehole.

Fig. 2 indicates that the surface measurement is of essentially the same amplitude as the energy sum of the three axis measurements in the borehole. However, there is a shift downward by 1/3 octave in the frequency range between about 20 and 125 Hz. The main point of comparison is that it shows that the surface vibration levels are very similar to those measured in the borehole and can be used for derivation of the building amplification factor where data from borehole or other subsurface locations is not available.

The data presented in the graph of Fig. 2 also indicate the typical ambient or background vibration/noise level between trains to show that the vibration level data graphs do in fact represent vibration from the trains over the frequency range covered by the analysis.

2.1.1. Amplification Factors

Figs 3 and 4 present the basic final results for the train pass-by measurements at the PPC building. Fig. 3 indicates the amplification factor from the ground outside the building to inside the building at the various floors, as determined from the comparison of the vibration levels with the building to the vibration level measured in the borehole. Fig. 4 shows a similar result for the average differences relative to the surface measurement outside the PPC building. The geologic strata in Athens is rock, which in some cases extends fairly close to the surface. However, in most areas there is a relatively thick layer of softer material overlaying the rock, resulting in the foundations of the buildings at a nominal 4 m depth not being sunk in relatively solid rock, but in a softer medium. This results in some coupling loss in the transmission of vibration from the ground to the building, as is depicted in Figs 3 and 4. The relevant results from these figures indicates a noteworthy amplification of the ground vibration occurs in the upper floors of the building in the frequency range of 10–20 Hz, with approximately 10–15 dB attenuation for frequencies above 25–31.5 Hz. Finally, the data also shows very consistent results between the 2nd and 4th floor measurements. For the 1st floor, the results are similar except for the high resonance peaks at 16 and 63 Hz.

Fig. 5 presents the average coupling loss in the case where the foundation is on softer material. If the foundation lies on rock, coupling loss can be considered equal to zero.

Fig. 6 presents the overall average amplification factors, considering data for the 1st, 2nd and 4th floors. The averages are shown for both the borehole data and for the surface data as the reference vibration level in the ground, with the average of those two indicated as the average amplification factor measured at the PPC building for ground vibration transmitted to its interior occupied floors. As is evident, the average result shows amplification from 10 to 20 Hz, with net reduction or attenuation from 25 to 200 Hz. Based on the results of ground vibration amplification factors as presented in Fig. 6, an idealized amplification curve for the representative Greek building is indicated on Fig. 7, with selected values given in Table 1 where a notable amplification of the vibration due to floor and other structural resonances is shown. There is an amplification in the frequency range from 10–31 Hz and then gradually decreases by the frequency increment.

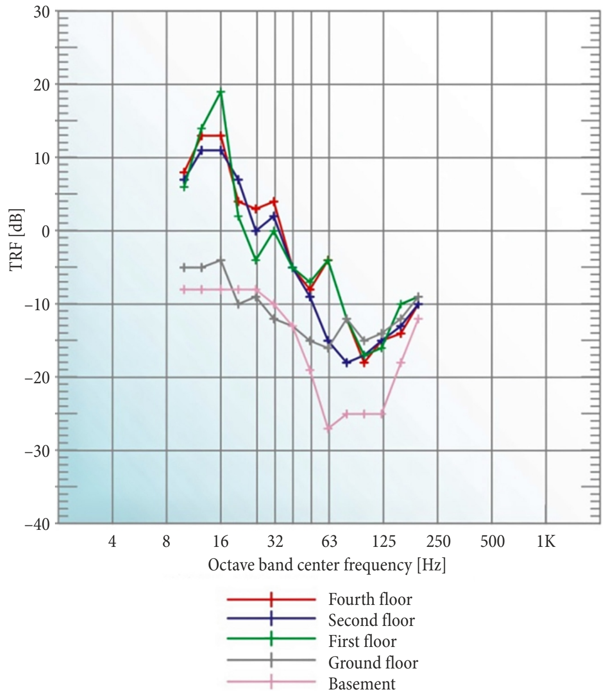

Fig. 3. Average amplification factors relative to borehole Root Mean Square (RMS) sum vibration levels

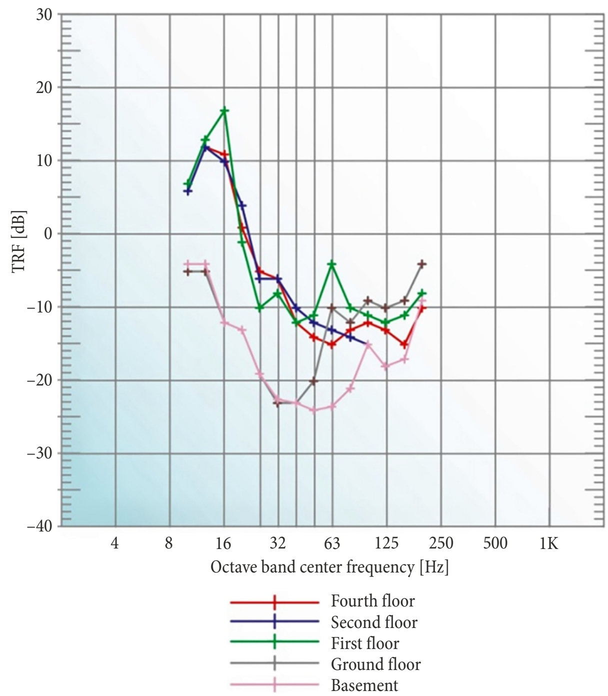

Fig. 4. Average amplification factors relative to surface vertical vibration levels

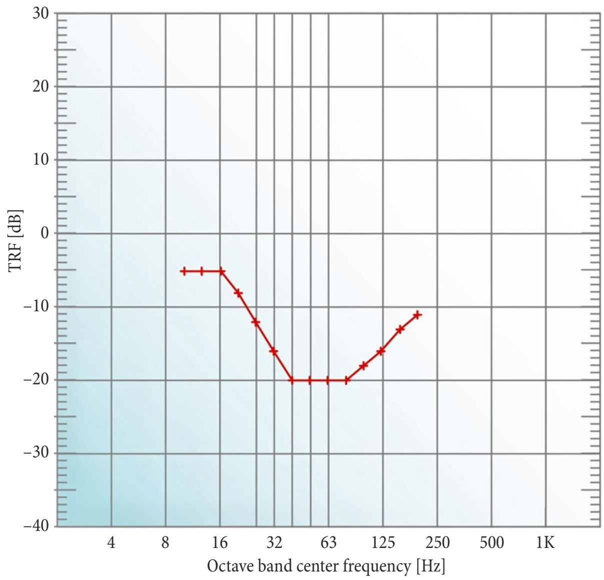

Fig. 5. Recommended coupling loss between soil and basement

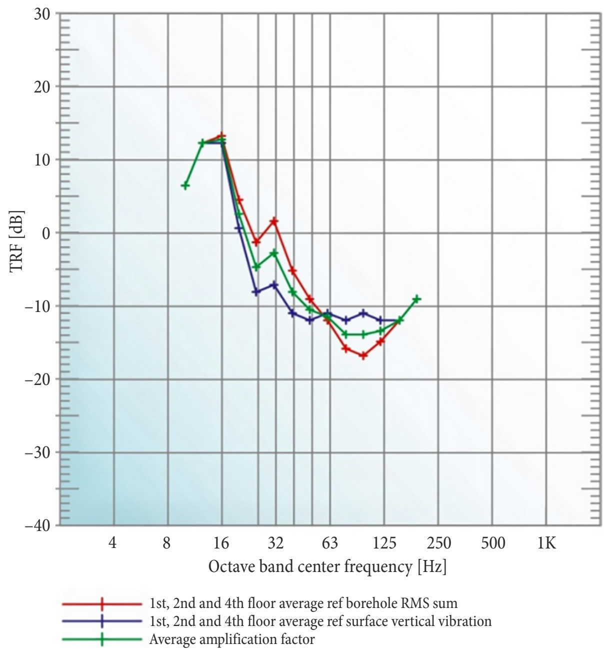

Fig. 6. Average amplification factor at PPC building for 1st, 2nd and 4th floor data

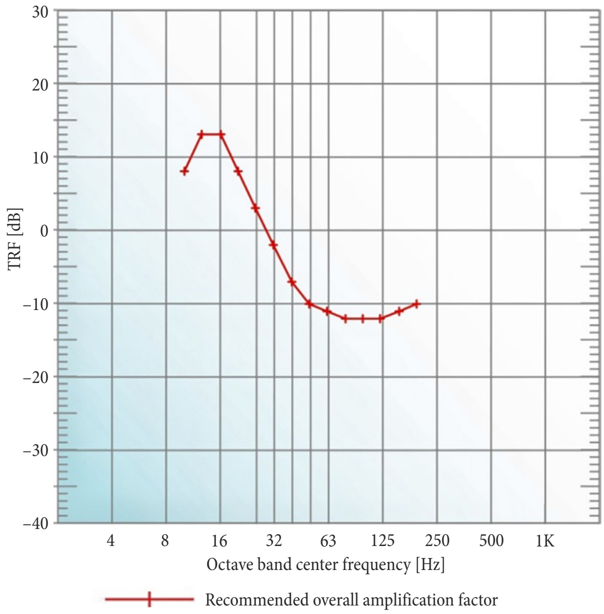

Fig. 7. Recommended amplification for occupied floors of typical buildings in Athens

Table 1. Standard Athens building amplification factor relative to soil surface and to basement for upper occupied floors as determined from the PPC building train vibration measurements

1/3 octave band frequency [Hz]	Amplification factor relative to soil surface [dB]	Amplification factor relative to basement [dB]
10	8	12
12.5	13	16
16	13	21
20	8	17
25	3	15
31.5	2	14
40	–7	13
50	–10	11
63	–11	10
80	–12	8
100	–12	6
125	–12	4
160	–11	2
200	–10	1

2.1.2. Floor-to-Floor Attenuation

The relative floor-to-floor vibration differences are marginal for the PPC building in the frequency range from 10 to 200 Hz. Slight amplification or attenuation was recorded that can be maybe considered equal to 0 dB. Therefore the vibration and hence the radiated noise levels are similar from the first floor up.

2.1.3. Upper Floors Relative to Basement

Fig. 8 indicates the average differences found for the various floors measured in the PPC building compared to the basement. As is evident from the chart, except for the resonance at 63 Hz, the ground floor vibration is essentially the same as the basement. However, at the upper floors, namely the 1st, 2nd and 4th floors, the vibration levels are of substantially higher level, indicating the amplification relative to the basement, with the maximum amplification occurring at 16 Hz with gradually decreasing amplification from 25 to 200 Hz, except for the 63 Hz resonance at the 1st floor.

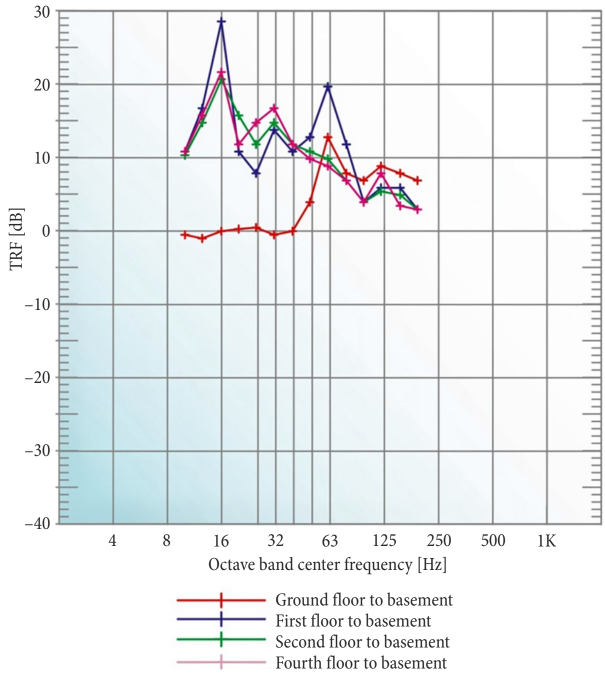

Fig. 8. Average amplification factors relative to PPC building basement

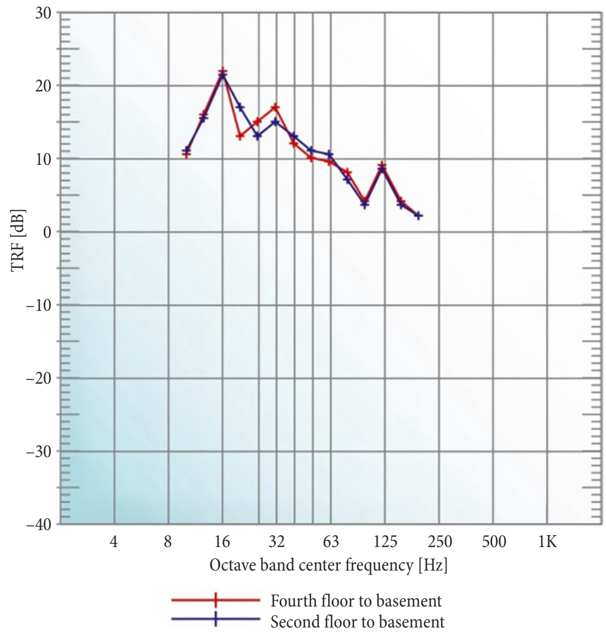

Fig. 9. Average amplification factors from basement to upper floors in PPC building

Fig. 9 shows the average transfer function as measured from the basement to the upper floors. The results in Fig. 9 indicate the amplification factor, which should

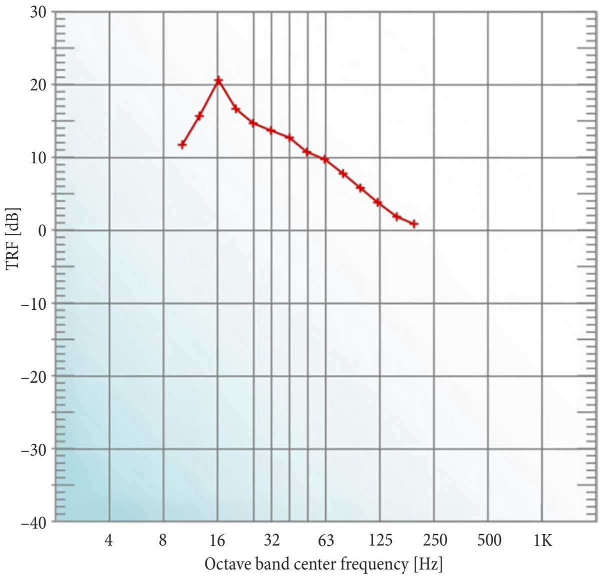

Fig. 10. Recommended amplification factors from basement to upper floors in PPC building

Basement (#1) 1st floor (#3)

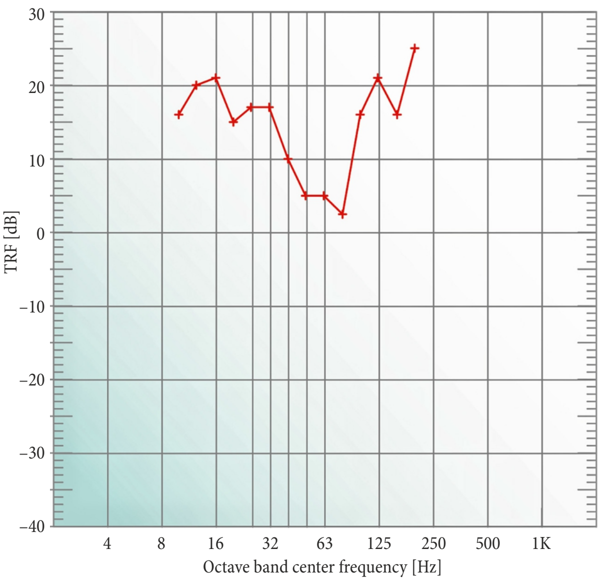

Fig. 11. Mourouzi street building: transfer function from the basement to the 1st floor

be used for all cases where the building foundation is in contact with a lower elevation high stiffness rock to develop the projected noise and vibration levels in the upper floors of such buildings. An idealized curve for this special case amplification factor is indicated by Fig. 10 and Table 1. The table shows that there is a notable amplification of the vibration due to floor and other structural resonances at 16 Hz.

2.2. The Case of the Mourouzi Street Building

Six measurement points were selected inside the building to measure the vibration velocity level. These points were located at: the basement, the ground floor, the 1st, the 2nd, the 4th and the 6th one, as shown in Fig. 1b.

The results of the transfer function for the Mourouzi street building from the basement to the 1st floor presented in Fig. 11, indicate the similarity with the PPC transfer friction with an even more significant amplification in the upper frequencies. As for the PPC building, also in this case, the respective measurements indicate that there is no attenuation from floor-to-floor in the upper levels in the building. An additional complete set of airborne noise measurements were run simultaneously with the above geophone vibration measurements and were introduced at one of the locations (1st floor bedroom). According to the relevant acoustic measurements, the worst case of ground-borne noise annoyance is reported at the 1st floor (location #3), with an average L_{max} from train operation, varying from 39.2 to 41.3 dB(A) or, simply, 40±1 dB(A) with relevant background noise from 34 to 35 dB(A). For the rest of the building the relevant values of L_{max} from train operation are presented in Table 2.

In order to understand the magnitude of the above airborne noise measurements, it should be emphasized that during normal life conditions (elevator, walking, talking etc.) within the building (during day and evening) the relevant ground-borne L_{max} recordings (with no train operation) varies from 30 (basement) to 53.5 dB(A) in the first floor, which indicates that the noise from the train operation is not distinct during day but becomes quite audible during the night and early morning hours creating significant annoyance.

Table 2. Relevant values of $L_{\max}$ from train operation

Level/Roof	$L_{\max}$ from train operation
Basement (#1)	29.3±1 dB(A)
Ground level (#2)	33.2±1 dB(A)
2nd floor (#4)	30.7±1 dB(A)
3rd floor (#5)	39.5±1 dB(A)
6th floor (#6)	37.8±1 dB(A)

2.3. The Case of the Maroussi 1 and 2 Buildings

Two five-storey reinforced concrete buildings with basement were selected at Maroussi, facing the Athens Metro line 1. Maroussi 1 building has a soft first story, whereas the Maroussi 2 building has brick masonry infills at all levels. Measurement points are depicted in Fig. 1c and

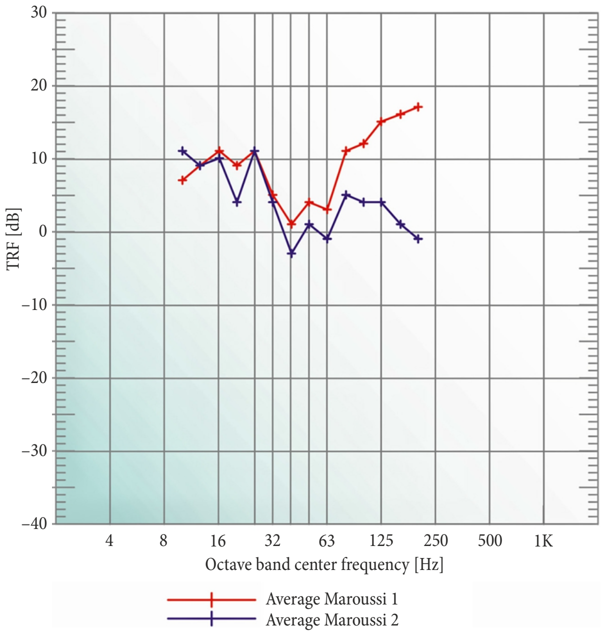

Fig. 12. Average 1st floor to basement relative vertical vibration levels for Maroussi 1 and Maroussi 2 buildings

1d. Fig. 12 presents the average differences between the basement measurements and the first floor measurements. This graph shows the basic amplification factor from the excitation level at the basement floor level to the upper structure of the building. This is the factor, which must be used when transferring the ground-borne vibration calculated to be transmitted from the train to the building foundations. Taking into account the average levels for the floor-to-floor vertical vibration transmission as determined for each of the two buildings from the vertical vibration levels measured at each floor, it shown no change from floor-to-floor for these buildings. The overall average of these results then indicates that a zero attenuation factor should be used for prediction of expected noise levels from floor-to-floor within the building. The measurements indicate that the radiated noise levels are similar from the first floor up.

3. Discussion of the Results and Concluding Remarks

Based on the given analysis for all buildings the findings in this paper consists a solid base for the accurate projection of transmission of ground-borne vibration and noise in multi-storey reinforced concrete buildings. Specifically, the following conclusions are underlined:

- for the typical multi-storey reinforced concrete building with a basement on foundation in an overall depth of 4 to 5 m, a significant reduction of vibration level between the ground surface and the building is established in a relatively thick layer of softer material overlaying the rock. For foundation laying on rock the coupling loss can be considered equal to zero;
- the vibration measurements on all upper floors for the PPC building indicates that there is notable vibration amplification from the basement to the floors due to structural resonances. This amplification relative to basement vibration occurs mainly in the frequency range from 10 to 31.5 Hz and then gradually decreasing to 0 dB at approximately 200 Hz. Especially, in the case of Mourouzi street building, a similar response was recorded in the frequency range from 10 Hz to 100 Hz. However, regarding the higher frequencies, the relevant vibration levels tend to increase. For Maroussi 1 and Maroussi 2, there is reduced amplification for the lower frequencies, while for higher frequencies, lower values than Mourouzi street building were measured.
- the analysis for all buildings, indicates a minor or even no attenuation from floor-to-floor in the upper levels' introducing vibration and radiated noise levels quite similar from all levels above first floor;
- for the PPC building, in particular, it was observed by combining the coupling loss factor at the foundation with the amplification factors occurred as transmitted to upper level with an overall building amplification factor, with increase of the vibration levels in the range from 10 to 25 Hz and a decrease from 31.5 Hz up. The maximum increase was defined equal to 13 dB in the range 12–16 Hz, while the relevant reduction, in the 50–200 Hz range, is 10 to 12 dB;
- the generated rail excitation due to the TO influence in the case of the Mourouzi street building is clear in both lower and higher frequencies, indicating the need for adequate mitigation measures such as floating slabs.

Is finally noted that in cases where the subway tunnels are practically adjacent to other type of buildings, the above conclusions may be not applicable and similar experimental campaigns should be engaged for each different building type.

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