Abstract—ATTIKO METRO S.A., the state company ensuring the development of the Athens Metro network, has recently initiated a new extension of 7.6 Km, has planned for line 3 of Athens Metro from Haidari to Piraeus “Dimotikon Theatre” towards “University of Piraeus” (forestation), connecting the major Greek Port with “ELEFTHERIOS VENIZELOS” International Airport. Piraeus extension is consists of a TBM (Tunnel Boring Machine) 2 tracks & NATM, tunnel sections, as well as 6 stations and a forestation (in NATM tunnel) at the end of the alignment. In order to avoid the degradation of the urban acoustic environment from ground borne noise and vibration during metro operation, the assessment of the required track types & possible noise mitigation measures was executed, and for each section and each sensitive building, the ground borne noise and vibration levels will be numerically predicted. The calculated levels were then compared with ground borne noise and vibration levels criteria. The necessary mitigation measures were defined in order to guarantee, in each location along the extension, the allowable ground borne Noise and Vibration max. levels inside nearby sensitive buildings taking into account alternative Transfer Functions (TF) for ground borne noise diffusion inside the buildings. Ground borne noise levels were proven to be higher than the criterion where special track work is present and also in the case of the sensitive receptor: “Dimotikon Theatre”. In order to reduce the ground borne noise levels to allowable values in these sections, the installation of tracks and special track work on a floating slab (FS) was assessed and recommended.

Keywords—Environmental noise, Floating Slab, Ground borne noise, Metro, Vibration.

I. INTRODUCTION

ATTIKO METRO S.A. the state company implementing the development of the Athens Metro network, has recently undertaken the execution of a 7.6Km new extension, for line 3: from Haidari to Piraeus (existing old ISAP - line 1 station) at Piraeus “Dimotikon Theatre” towards “University of Piraeus” (forestation), connecting the major Greek Port with “ELEFTHERIOS VENIZELOS” International Airport that is anticipated to serve 135,000 passengers on a daily basis [1].

This work was supported from the project “AM LINE 3 EXTENTION: HAIKARI-PIRAUEUS-FORESTATION PIRAEUS UNIVERSITY - Ground borne Noise & Vibration Study” financed by Attiko Metro SA with the collaboration of: TT&E Consultants S.A. (Greece) & D2S Int. (Belgium).

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In particular on November 21st 2008 ATTIKO METRO S.A. (AM) proceeded to the re-procurement of this project - related to Line 3 Metro extension to the western suburbs – which was recently awarded. This extension includes 6 modern stations: Aghia Varvara, Korydallos, Nikaia, Maniatika, Piraeus, Dimotikon Theater and a forestation at NATM tunnel [1].

This new extension also includes TBM & NATM tunnel sections. In particular, a 6,5km part of the tunnel is to be constructed using the Tunnel Boring Machine (TBM), while the remaining parts at the beginning and at the end of the project will be constructed via the NATM method.

Furthermore, 8 ventilation shafts in total are foreseen along the new line as well as two shafts for the TBM’s entering/exiting locations.

LRT networks in urban conditions are considered to be a sustainable means of transportation, due to the substantial reduction of air pollutants emissions by decreasing the number of cars and heavy vehicles (i.e. buses) in the road network. However, an important adverse effect of their operation is the increased level of vibration transmitted to buildings in close proximity. Furthermore the vibration in buildings is the result of the direct transmission of ground borne vibration [2]. There are two ways in which metro traffic can induce vibration in nearby buildings [3]:

- Ground-borne vibration caused by the dynamic impact forces generated in the wheel-rail inter phase due to irregularities of both wheels and tracks that can propagate in the soil and excite the foundation walls of nearby buildings, beneath ground.
- Air-borne noise, caused by low frequency emissions that can excite building structural components (walls etc.) above ground.

Attiko Metro in the last years has implemented a series of Ground Borne Noise and Vibration mitigation measures and monitoring programs in order to achieve the necessary attenuation levels and to ensure the protection of the urban acoustic environment [4], [5].

The aim of the present article is to evaluate the required track types, by means of modeling calculations in order to guarantee, in each location along the extension, allowable ground borne Noise and Vibration study levels in nearby buildings, based also on the preliminary results of the relevant EIA study.

In order to reach this objective, the given extension was indiscriminated into homogeneous sections, i.e. sections along with the tunnel and soil types, depth and distance from nearby buildings and presence or not of a switch can be considered as constant.

Moreover, all existing sensitive buildings were particularly investigated. For each section and each sensitive building, the ground borne noise and vibration levels were numerically predicted and the calculated levels were compared with ground borne noise and vibration levels criteria, in order to evaluate the necessary mitigation measures.

The considered standard track type – as per Attiko Metro requirements - was friction free twin-block type sleeper with rubber boot and elastomer pad (dynamic vertical stiffness = 25 kN/mm/pad) under each block on a concrete track bed, with UIC54 rails with a basic sleeper spacing is 700 mm. The typical vehicle was considered to be an unsprung mass of 1822 kg/axle. A worst case scenario of "no coupling loss" between soil and foundation in all buildings was also assessed within this numerical approach with a relevant parametric analysis taking also into account the contribution of the proposed turnouts.

II. MAXIMUM PERMISSIBLE GROUND BORNE NOISE AND VIBRATION LEVELS FROM ATHENS METRO OPERATION

In absence of any relevant Greek legislation, the maximum permissible values of ground borne noise & vibration from train operations [6],[7],[8], as recommended in the respective Environmental Impact Assessment Study are as follows:

1) for Ground Borne Noise:
   - for all residential buildings 40 dB(A),
   - for other sensitive buildings (such as education i.e. Universities, schools, libraries, and also hospitals, churches theatres and archaeological sites and museums: 35 dB(A)
   - for concert halls & TV/Radio studios: 25 dB(A)

2) for Vibration: (max ppv at z direction):
   - 0,5 mm/sec for buildings & relevant sensitive buildings
   - 0,2 mm/sec for archaeological sites and museums

III. GEOTECHNICAL DATA & CONSIDERED ALIGNMENT SECTIONS

Based on all available geotechnical data, the following soil categories have been defined for the dynamic soil modulus for the Piraeus extension of Athens Metro (see table 1). Piraeus extension was divided to homogeneous sections, i.e. sections along which the main parameters were considered as constant [9].

<table>
<thead>
<tr>
<th>Soil Category</th>
<th>Min. dynamic soil modulus [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>5.5</td>
</tr>
<tr>
<td>5</td>
<td>18.0</td>
</tr>
</tbody>
</table>

The different homogeneous sections (more than 150) were considered on the basis of the above soil parameter the tunnel type, as well as according to both min. depth from ground level or basement level to top of rail level [m] and the min. horizontal distance [m] between a nearby building basement and the tunnel centerline.

The relevant soil data provided by Attiko Metro & the relevant geotechnical surveys lead to the following soil types along the considered zone:
IV. NUMERICAL PREDICTION OF GROUND BORNE NOISE AND VIBRATION LEVELS

The transmission path of vibrations to the surrounding community and particularly to a nearby building can be scheduled as follows:

1) Finite element modelling of the tunnel type located in each considered section, including the adequate soil stiffness and the wheel-rail system characteristics, in order to calculate the tunnel wall vibration levels generated by the wheel-rail interphase
2) Propagation of the vibration levels from the tunnel to nearby buildings through the ground
3) Soil-structure coupling at basement levels
4) Amplification of the vibration levels at some frequencies (due to resonances of walls and floors)
5) Calculation of noise generated in the rooms by vibration of walls and floors.

The methodology of vibration velocity calculation in the tunnel invert and transmission to the closest adjacent building has taken into account all the discrete line sections (as described above) with the following parameters considered per section:

- Type of tunnel and type of station
- Real stiffness of ground surrounding the tunnel
- Soil categorization
- Maximum train velocity
- Switch effect (not implemented here)
- Depth of tunnel and station
- Distance from foundation to tunnel wall
- Athenian building amplification transfer function
- Sound radiation in the building

A 35 m length tunnel section was modelled with a finite element method (Systus) as shown in fig. 3 for the respective TBM & NATM tunnel model [9].

In this finite element model the tunnel invert was modelled as 3D elements and the tunnel walls as spatial shell elements.

The most basic assumption of the N&V assessment was the use of the standard resilient elastic rail support STEDEF which is presented in the fig. 4 hereafter:

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**Table 2**

<table>
<thead>
<tr>
<th>Chainages</th>
<th>Soil category</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+418-2+100</td>
<td>2</td>
</tr>
<tr>
<td>2+100-3+100</td>
<td>2</td>
</tr>
<tr>
<td>3+100-3+600</td>
<td>3(2)</td>
</tr>
<tr>
<td>3+600-3+900</td>
<td>2</td>
</tr>
<tr>
<td>3+900-4+400</td>
<td>3(2)</td>
</tr>
<tr>
<td>4+400-4+650</td>
<td>3</td>
</tr>
<tr>
<td>4+650-4+850</td>
<td>3(4)</td>
</tr>
<tr>
<td>4+850-5+200</td>
<td>3</td>
</tr>
<tr>
<td>5+200-5+450</td>
<td>3(2)</td>
</tr>
<tr>
<td>5+450-5+700</td>
<td>4(3)</td>
</tr>
<tr>
<td>5+700-6+200</td>
<td>5</td>
</tr>
<tr>
<td>6+200-6+400</td>
<td>4</td>
</tr>
<tr>
<td>6+400-7+100</td>
<td>2(3)</td>
</tr>
<tr>
<td>7+100-7+900</td>
<td>2</td>
</tr>
<tr>
<td>7+900-8+240</td>
<td>1</td>
</tr>
<tr>
<td>8+240-8+969</td>
<td>3</td>
</tr>
</tbody>
</table>

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**Fig. 3** TBM & NATM (2 tracks tunnel) model

**Fig. 4** Standard elastic rail support Stedef, Sleeper, Under sleeper pad & Boot
The rails are modelled with beam elements. The rail pads and sleeper pads are modelled with spring elements.

The distance between two sleepers is 0.70 m. Fig. 5 shows the modelling of the track.

The material properties applied in the model are as follows [10]:

1) for concrete:
   - Young's modulus: \( E = 3.216 \times 10^{10} \text{N/m}^2 \)
   - Poisson's coefficient: \( \nu = 0.25 \)
   - Volumic mass: \( \rho = 2500 \text{kg/m}^3 \)

2) for UIC54 rails:
   - Young's modulus: \( E = 21 \times 10^{10} \text{N/m}^2 \)
   - Poisson’s coefficient: \( \nu = 0.3 \)
   - Volumic mass: \( \rho = 7850 \text{kg/m}^3 \)
   - Section: \( A = 69.34 \text{cm}^2 \)
   - Bending inertia: \( I_y = 2346 \text{cm}^4 \)

3) for rail pads:
   - Static vertical stiffness: \( k_z = 100 \times 10^6 \text{N/m} \)
   - Dynamic vertical stiffness: \( k_z = 200 \times 10^6 \text{N/m} \)

4) for sleeper pads:
   - Static vertical stiffness: \( k_z = 15 \times 10^6 \text{N/m} \)
   - Dynamic vertical stiffness: \( k_z = 25 \times 10^6 \text{N/m} \)

As per Attiko Metro relevant technical instructions the considered “unsprung mass” was of 1822 kg/axle with four lumped masses of 911 kg applied on four nodes of the rails, corresponding with a bogie longitudinally centered in the model. All the nodes at both ends of the model are fixed (six degrees of freedom). To eliminate undesirable modes of the rails, nodes of rails and sleepers some degrees of freedom are fixed. To simulate the stiffness of the soil, a spring density is applied radially to all the shell elements in contact with the soil. In order to determine the amplitude of this radial stiffness, a three-dimensional model of the tunnel and the soil has been created. In order to take into account the surrounding soil, some degrees of freedom are fixed on the boundaries of this model.

Four vertical static loads of 1 kN were applied on the invert, in a longitudinally centered section, at the location of the four rails. The static displacements under this load case were calculated. The same static calculation is then carried out on the model described here above, without the track. The radial stiffness on the tunnel walls is then updated in order to reach the same amplitude for static displacements calculated on both models. The dynamic force generated at the wheel-rail contact is calculated for normally maintained wheels and rails [9], [11]. For this approach, the concept of the critical speed VCR which is the forward speed for which there will be a separation between the rail and the wheel. For a resilient rail, the critical speed can be written as:

\[
V_{CR} = \sqrt{ga\left(1 + \frac{M}{m}\right)\left[1 + \frac{m}{\rho_l^2}\right]}
\]

where:
- \( g \) is the gravity constant [m/s^2]
- \( a \) is the wheel radius [m]
- \( M \) is the portion of spring-mounted car mass supported by a wheel
- \( m \) is the wheel unsprung mass
- \( \rho_l \) mass per unit length of the rail

\[
\beta = \left(\frac{K}{4EI}\right)^{\frac{1}{4}}
\]

\( K \) static foundation stiffness per unit length of the rail
\( E \) Young’s modulus of the rail
\( I \) moment of inertia of the rail cross section

The following values are used:
- \( a = 0.43 \text{ m} \)
- \( M = 6500 \text{ kg} \)
- \( m = 911 \text{ kg} \)
- \( \rho_l = 54.43 \text{ kg/m} \)
- \( E = 21.10^{10} \text{N/m}^2 \)
- \( I = 2346.10^{-8} \text{m}^4 \)

The foundation stiffness per unit length of the rail was calculated for the considered “bibloc” system. The critical speed was 17.8 m/s or 64 km/h, consisting an important factor since the impulse \( I_m \) of a wheel flat will increase with increasing speed as long as the forward speed is smaller than the critical speed. For speeds above the critical speed, the impulse is constant. The speed considered in this assessment was 80 km/h, therefore a max. impact amplitude in each section was considered. All wheel and rail irregularities giving impact force excitation were integrated in one “equivalent wheelflat”, of 40 mm (fig 6), typical for a normally maintained metro network [9].

![Fig. 6 Equivalent wheelflat](image-url)
For such a wheelflat and for a wheel radius of 0.43 m, the height difference \( h \) can be calculated to be 0.465 mm. Because the wheel impedance is greater than the rail impedance, the impulse is caused by the upward movement of the free rail. The rail is hereby represented as an equivalent mass. The static deflection under wheel load and the resonant frequency of the resiliently supported but not loaded rail are obtained by a finite element calculation.

The rail is hereby represented as an equivalent mass. The impulse for speeds above the critical speed can be written as [9]:

\[
I_m = 2 Y_0 m_{eq} \omega_0 \sin\left(\frac{2 h}{Y_0}\right)
\]

where :
- \( Y_0 \) the static deflection of the rail under wheel load
- \( \omega_0 \) the resonant frequency of the resiliently supported rail (not loaded)
- \( h \) the height difference of the wheel flat
- \( m_{eq} \) the equivalent impact mass of the resiliently supported rail

For typical values of \( K \) and \( EI \), the equivalent mass is very well approximated by:

\[
m_{eq} \approx 0.4 \rho
\]

The static deflection under wheel load and the resonant frequency of the resiliently supported but not loaded rail are obtained by a finite element calculation.

With the considered rail pad stiffness, we arrive at a maximum static rail deflection of 2.5 mm.

The table hereafter summarizes the calculated values and corresponding impulse.

Table 3

<table>
<thead>
<tr>
<th>Case</th>
<th>( Y_0 ) [m]</th>
<th>( \omega_0 ) [rad/s]</th>
<th>( I_m ) [kgm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>“bibloc”</td>
<td>2.5 ( 10^{-3} )</td>
<td>456</td>
<td>24.9</td>
</tr>
</tbody>
</table>

The obtained impulses were converted into an impact force, acting on the rail head, within a time history.

The impact load variation is assumed to be one half of a period of sinusoid, which is shown in fig. 7 [12].

As a conservative approach, four impacts in phase on the four wheels of the bogie, with amplitude of 25 N/Hz each were considered, and furthermore, the vibration levels generated on the invert of the tunnel, just under the four impact excitations, were taken as integrally propagated to the surrounding soil.

In order to calculate the velocity vector of the tunnel invert in the 1/3 octave bands from 10 to 200 Hz, it was necessary to first calculate, for each model, the eigen frequencies and their associated eigenvectors.

The harmonic responses were then calculated for the four nodes located on the tunnel invert just under the four impact excitations. This calculation is done with a modal damping of 5% for each mode, and 10 frequency steps for each 1/3 octave band.

The maximum RMS vibration velocity for each 1/3 octave band was computed and for each 1/3 octave band, the maximum of the calculated values for the four nodes is determined.

The results for both TBM and NATM tunnel typical sections/soils are presented in table 4, in dB ref. 1e-9 m/s, with a graphical presentation in fig. 8.

Table 4 Calculated maximum vibration velocity levels on tunnel invert [dB ref. 1e-9 m/s]

<table>
<thead>
<tr>
<th>1/3 octave [Hz]</th>
<th>TBM 2 tracks</th>
<th>NATM soil 3</th>
<th>NATM Soil 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>soil 1</td>
<td>68.1</td>
<td>57.1</td>
<td>64.1</td>
</tr>
<tr>
<td>soil 2</td>
<td>61.4</td>
<td>61.0</td>
<td>68.3</td>
</tr>
<tr>
<td>soil 3</td>
<td>56.5</td>
<td>66.1</td>
<td>74.3</td>
</tr>
<tr>
<td>soil 4</td>
<td>42.5</td>
<td>41.9</td>
<td>45.8</td>
</tr>
<tr>
<td>soil 5</td>
<td>34.7</td>
<td>73.8</td>
<td>83.9</td>
</tr>
<tr>
<td>soil 6</td>
<td>61.0</td>
<td>50.4</td>
<td>74.5</td>
</tr>
<tr>
<td>soil 7</td>
<td>64.9</td>
<td>57.9</td>
<td>87.8</td>
</tr>
<tr>
<td>soil 8</td>
<td>45.8</td>
<td>66.0</td>
<td>85.0</td>
</tr>
<tr>
<td>soil 9</td>
<td>41.9</td>
<td>58.4</td>
<td>79.6</td>
</tr>
<tr>
<td>soil 10</td>
<td>76.0</td>
<td>69.0</td>
<td>92.2</td>
</tr>
<tr>
<td>soil 11</td>
<td>67.8</td>
<td>65.8</td>
<td>68.9</td>
</tr>
<tr>
<td>soil 12</td>
<td>70.0</td>
<td>61.9</td>
<td>68.3</td>
</tr>
<tr>
<td>soil 13</td>
<td>69.0</td>
<td>61.1</td>
<td>68.6</td>
</tr>
<tr>
<td>soil 14</td>
<td>73.1</td>
<td>53.3</td>
<td>69.7</td>
</tr>
<tr>
<td>soil 15</td>
<td>61.9</td>
<td>61.0</td>
<td>67.9</td>
</tr>
</tbody>
</table>

Fig. 7 Impact load variation

Fig. 8 Vibration levels at tunnel invert for the above tunnel types
The maximum of response is calculated in the area of 40 to 50 Hz, which corresponds to the frequency range of the first wheel-rail mode for this track.

As per the proposed stations, an assumption was introduced, [13] that the vibration levels on the invert of the station sections can be accepted to be equal to: "calculated vibration levels for the adjacent tunnel section in the same soil type - 3 dB".

Regarding special track work i.e. crossovers or turnouts (TO), the dynamic wheel-rail impact force was considered, originally, to be 10 dB higher than the corresponding force for straight tracks.

However, according to relevant AM vibration studies, it was concluded that the solution of a full TO’s length floating slab implementation (FS) ensures a complete ground borne and vibration attenuation in soil surface.

Alternative solutions involving possible limited slab implementation at frog area, even though presents an acceptable noise levels with the bogie in the middle of the frog area, however in the adjacent full concrete area (bogie on turnout next to slab), the expected noise level are considerably higher [14].

A detailed N&V measurement’s campaign (2005 and 2008) [15], [16], in two distinct TO’s location equipped with a VAE system and "no FS" implementation.

The system by "VAE" (fig. 9) introduces the installation on a concrete slab and already integrates some minimal vibration mitigation in comparison with a very rigid system fixation, including fasteners with integrated elastomer pads.

![Installation of the VAE system on a concrete slab](image)

Acoustic measurements proven that the calculated tunnel invert vibration levels from the model, constitutes a rather conservative approach as per the relative measurements in table 5 and fig. 10.

Following the above measured data a transfer function (TF) for all TO’s locations was proposed in the model (as per table 6 hereafter), resulting by abstracting NATM-Soil2 standard track Stedef spectra from the VAE TO average measured spectra as per table 5 hereafter.

![Measured data at TO’s location under normal operation](image)

<table>
<thead>
<tr>
<th>Frequency band [Hz]</th>
<th>PAPANDREOU shaft 2005</th>
<th>TRUMPET SEPOLIA (Ag. Antonios) 2008</th>
<th>Average [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>75,7</td>
<td>75,0</td>
<td>74,4</td>
</tr>
<tr>
<td>12,5</td>
<td>73,6</td>
<td>72,4</td>
<td>73,0</td>
</tr>
<tr>
<td>16</td>
<td>72,8</td>
<td>71,9</td>
<td>72,3</td>
</tr>
<tr>
<td>20</td>
<td>72,7</td>
<td>73,5</td>
<td>73,1</td>
</tr>
<tr>
<td>25</td>
<td>75,6</td>
<td>77,0</td>
<td>76,3</td>
</tr>
<tr>
<td>31,5</td>
<td>83,3</td>
<td>81,4</td>
<td>82,4</td>
</tr>
<tr>
<td>40</td>
<td>94,3</td>
<td>87,9</td>
<td>91,1</td>
</tr>
<tr>
<td>50</td>
<td>100,6</td>
<td>91,6</td>
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<tr>
<td>63</td>
<td>96,9</td>
<td>87,9</td>
<td>92,4</td>
</tr>
<tr>
<td>80</td>
<td>92,4</td>
<td>92,3</td>
<td>92,3</td>
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<tr>
<td>100</td>
<td>90,1</td>
<td>90,3</td>
<td>90,2</td>
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<tr>
<td>125</td>
<td>88,0</td>
<td>89,4</td>
<td>88,7</td>
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<tr>
<td>160</td>
<td>86,8</td>
<td>92,9</td>
<td>89,9</td>
</tr>
<tr>
<td>200</td>
<td>81,6</td>
<td>88,8</td>
<td>85,2</td>
</tr>
</tbody>
</table>

Table 6. TF for special track work [dB ref. 1e-9 m/s]

Vibration energy is transmitted through the soil as body and surface waves. Body waves consist of compression and shear waves, surface waves consist of Rayleigh and Love waves. Each wave type has a different propagation speed and a
different rate of attenuation with distance.

It was considered that compression waves are the most significant for ground borne noise in buildings near subways [17]. Vibrating tunnel walls can be considered as a cylindrical source, and vibration energy gradually decreases by increasing distance from the source, the energy spreading over an increasing large area.

No recent information about the loss factors and wave propagation speeds of the different soil types along the Piraeus extension were available, therefore the following wave propagation speeds and soil loss factors, in relation as per dynamic Young’s moduli, were taken in to account (table 7).

![Table 7 Estimated wave propagation speeds (m/s) & soil loss factors (η)]

<table>
<thead>
<tr>
<th>Edyn [GPa]</th>
<th>C [m/s]</th>
<th>η</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1100</td>
<td>0.10</td>
</tr>
<tr>
<td>0.4</td>
<td>1900</td>
<td>0.10</td>
</tr>
<tr>
<td>0.9</td>
<td>2500</td>
<td>0.10</td>
</tr>
<tr>
<td>5.5</td>
<td>5100</td>
<td>0.01</td>
</tr>
<tr>
<td>18.0</td>
<td>7000</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Making the assumption that the building basement & foundation are located approx. 5 m under ground level and defining all distances as shown in fig. 11.

The distance \( d \) between the building basement and the tunnel wall is calculated according to:

\[
d = \sqrt{(d_{\text{horiz.}})^2 + \left(\text{depth} - 5 - d_r\right)^2} - r_0
\]

A worst case scenario of “no coupling loss transfer function (TF) soil-basement-upper floors” was taken into account in order to evaluate the most critical locations including crossovers locations. However, this is a very conservative approach for the typical Athenian building that is not reflected in reality and a coupling loss factor should be introduced in the calculations.

Two alternative attenuation curves (as per fig. 12) were considered [18], [19]:

(a) the “original PPC building TF”: according to vibration amplification factor measurements at the PPC building tests at Athens Metro line 1” (ISAP) and

(b) the modified “average TF for the Athenian building” implementing a coupling loss correction as per additional buildings measurements.

Vibrating walls and floors radiate noise which is called ground-borne noise. The relationship between noise level and floor vibration level depends on the room absorption, the room size, the room shape and the oscillations distribution in the room.

The sound pressure level resulting from the vibration is considered as:

\[
L_p = L_v - 22
\]

where:

\( L_p \) = Sound pressure level in dB
\( L_v \) = Vibration velocity level of floor (in dB ref. 1e-9 m/s)

V. GROUND BORNE NOISE AND VIBRATION LEVELS IN NEARBY BUILDINGS

The maximum ground borne noise and vibration levels that can be expected along the Piraeus extension when the metro will be running in the projected tunnels are given by applying all the transfer functions described in the previous paragraphs to all sections and sensitive buildings mentioned above.

The corresponding global values are summarized, for all sections, in the following figures [9]:

1) in fig. 13 (vibration levels) and 14 (ground borne noise levels) for the “original” building TF values as above and
2) in fig. 15 (vibration levels) and 16 (ground borne noise levels) for the relevant “average” building TF values.

In these figures, the sensitive buildings have been allocated as “a”, “b” and/or “c” sections, with the same parameters as the corresponding sections but with a horizontal distance corresponding with the real distance between the considered sensitive building and the tunnel centerline.

For the sections where soil type was not clearly defined, the calculations have been done for the most conservative case.

For the sections where soil type was not clearly defined, the calculations have been done for the most conservative case.
VI. RESULTS AND CONCLUSIONS

All calculated vibration levels are proven to be significantly lower for the modified TF compared to the original (no coupling loss conditions) TF values. This is due to the higher reductions, with the modified values, in frequencies lower than 80 Hz.

Calculated ground borne noise levels are also lower for the modified TF curve compared to the original TF values for all sections, except for where special trackwork is present.

In the sections equipped with special trackwork (TO), the highest ground borne noise levels occur with the modified TF values. This is due to the lower reductions, with the modified values, in frequencies higher than 100 Hz.

The calculated ground borne noise levels comply with the maximum allowable values in all sections except for:

1) sections 59, 60, 137, 143 and 145, which are equipped with special trackwork (TO) and
2) sections 138b, 139 and 140, where the ground borne noise criteria of 25 dB(A) for concert halls apply to the adjacent “Dimotikon Theatre” of Piraeus.

For all these sections, in order to ground borne noise levels to comply with the criteria, appropriate mitigation measures need to be implemented. The calculated ground borne noise and vibration levels (for the standard STEDEF track) have shown ground borne noise levels to be higher than the maximum allowable values in some sections equipped with special trackwork and also in the sections adjacent to Piraeus “Dimotikon Theatre”. In order to limit the ground borne noise levels to allowable values in these sections, it was recommended to install tracks and special trackwork on a floating slab (FS) [20].

The estimated ground borne noise attenuation due to mitigation measures i.e. floating slab (FS) is shown in fig. 17.

![Fig. 13 Piraeus extension ground borne vibration levels](image)

![Fig. 14 Piraeus extension ground borne noise levels](image)

![Fig. 15 Piraeus extension – modified amplification curve: ground borne vibration levels](image)

![Fig. 16 Piraeus extension – modified amplification curve: ground borne noise levels](image)

Fig. 17 Estimated noise attenuation due to Floating Slab implementation

The relevant noise attenuation results by introducing these mitigation values in the calculated levels in the sections described above are presented in table 8 hereafter [21].

These results show that the introduction of an FS leads to allowable ground borne noise and vibration levels in all respected sections [21].
allowable compared to the criterion for all sections equipped with special track work and sections adjacent to the municipal theatre of Piraeus, where the installation of a floating slab, is proven mandatory. FS mitigation measures proven to be a very effective environmental noise protection in Greece - Recent legal framework & action tools", 18th International Congress on Sound and Vibration IC SV 18, 10-14 July 2011, Rio de Janeiro, Brazil.


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Research interests
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Membership & Official Representations
1) IAV (International Institute of Acoustics and Vibration)
2) National Representative : CNOSSOS-EU Technical Committee, Nominated Expert Member of WG 1: Quality Framework for determining: (a) geographical and exposure and risk assessment based scoping of strategic noise mapping; (b) availability of and methods for collecting and checking input data and (c) accuracy of the overall assessment – WG2 Assessment component for Road Traffic Noise & WG 10 : Harmonized strategy for assigning noise levels in buildings
3) Member of Working Group on Road Traffic Noise WG 8, European Commission – Enterprise Directorate-General
4) National Representative Cost Office Action TU 901: Transport and Urban Development- Integrating and Harmonizing Sound Insulation Aspects in Sustainable Urban Housing Constructions. Member of WG2: Subjective evaluation of sound insulation - Laboratory tests and harmonized field surveys
5) National Representative: Invitational Conference on the EU’s Future Noise Policy, Copenhagen, 7-8 September 1998
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