Athens Metro Extension Project to Piraeus Ground borne Noise and Vibration Assessment and Control

Konstantinos E. Vogiatzis

***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: HAIDARI-PIRAEUS-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)

K. E. Vogiatzis is with the Department of Civil Engineer in University of Thessaly (tel: 002421074170; fax: 002421074119; e-mail: kvogiatz@uth.gr) and he was the Project Manager of the above project

Fig. 1 Athens Metro extension to Piraeus

Fig. 2 Athens Metro station "Aghios Dimitrios"

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 discredited 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 1. Soil Categories

Soil Category	Min. dynamic soil modulus [GPa]
1	0.1
2	0.4
3	0.9
4	5.5
5	18.0

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 :

Table 2
Soil categories at Attiko Metro Extension to Piraeus

Chainages	Soil category
1+418-2+100	
2+100-3+100	2
3+100-3+600	3(2)
3+600-3+900	2
3+900-4+400	3(2)
4+400-4+650	3
4+650-4+850	3(4)
4+850-5+200	3
5+200-5+450	3(2)
5+450-5+700	4(3)
5+700-6+200	5
6+200-6+400	4
6+400-7+100	2(3)
7+100-7+900	2
7+900-8+240	1
8+240-8+969	3

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:

METRO TUNNEL WALL VIBRATION
↓
PROPAGATION THROUGH SOIL
↓
SOIL VIBRATION
↓
COUPLING TO THE BUILDING VIBRATION
↓
FOUNDATION VIBRATION
↓
PROPAGATION THROUGH TYPICAL ATHENIAN BUILDING STRUCTURE
↓
FLOOR AND WALL VIBRATION
↓
SOUND RADIATION DUE TO VIBRATION
↓
PERCEPTIBLE VIBRATION - NOISE

The prediction of ground borne noise and vibration levels in nearby buildings consisted of the following steps [9]:

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 in all the discrete line sections (as described above) with the following parameters considered per section:

1) Type of tunnel and type of station
2) Real stiffness of ground surrounding the tunnel
3) Soil categorization
4) Maximum train velocity
5) Switch effect (not implemented here)
6) Depth of tunnel and station
7) Distance from foundation to tunnel wall
8) Athenian building amplification transfer function
9) 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].

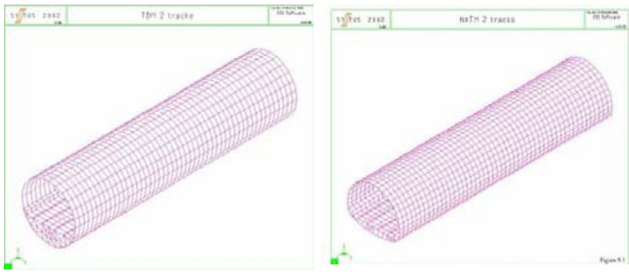

Fig. 3 TBM & NATM (2 tracks tunnel) model

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:

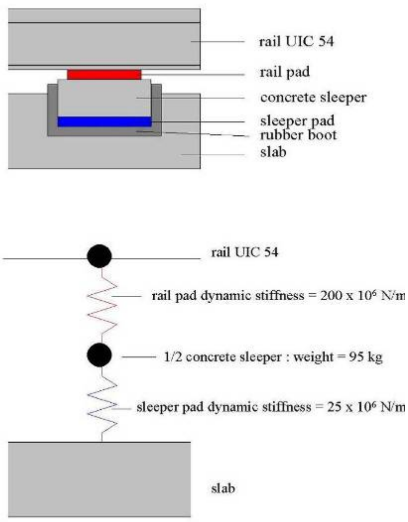

Fig. 4 Standard elastic rail support Stedef, Sleeper, Under sleeper pad & Boot

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.

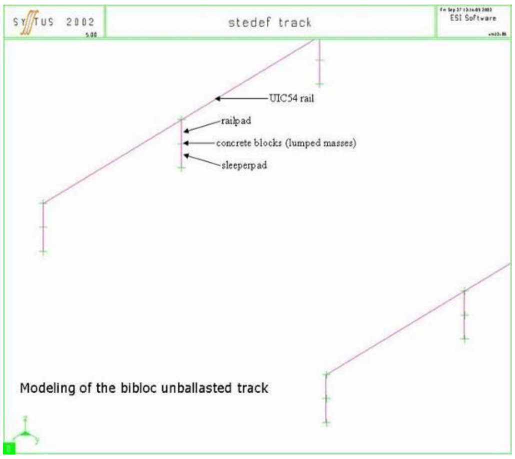

Fig. 5 Bi-bloc unballasted track model

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

1) for concrete:
   Young's modulus: E=3.216x1010N/m^2
   Poisson's coefficient: ν=0.25
   volumic mass: ρ=2500 kg/m
2) for UIC54 rails:
   Young's modulus: E=21x1010N/m2
   Poisson's coefficient: ν=0.3
   volumic mass: ρ=7850kg/m3
   section: A=69.34cm2
   bending inertia: Iy=2346 cm4
3) for rail pads:
   static vertical stiffness: k_z=100x106N/m
   dynamic vertical stiffness: k_z=200x106N/m
4) for sleeper pads :
   static vertical stiffness: k_z=15x106N/m
   dynamic vertical stiffness: k_z=25x106N/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 :

$$V_{CR} = \sqrt{ga\left(1+\frac{M}{m}\right)}\sqrt{1+\frac{m}{\rho l}\frac{\beta}{2}} \tag{1}$$

where :

g is the gravity constant [m/s2]
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
ρl mass per unit length of the rail

$$\beta = \left(\frac{K}{4EI}\right)^{1/4} \tag{2}$$

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 m
- M=6500 kg
- m=911 kg
- ρl=54.43 kg/m
- E=21.1010 N/m2
- I=2346.10-8 m4

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 Im 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].

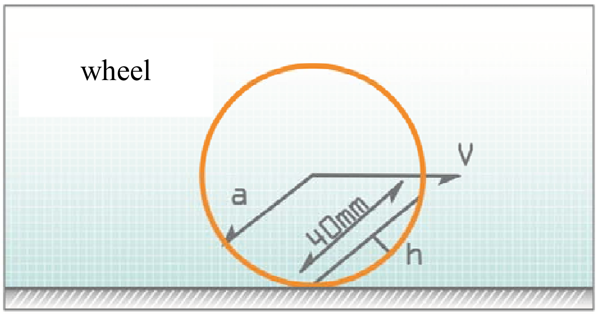

Fig. 6 Equivalent wheelflat

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]:

$$I_m = 2Y_0 m_{eq} \omega_0 \sin\left(\sqrt{\frac{2h}{Y_0}}\right) \tag{3}$$

where :

Y_o the static deflection of the rail under wheel load

ω_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:

$$m_{eq} \approx 0.4 \rho l \tag{4}$$

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

Case	Y_0 [m]	ω_0 [rad/s]	I_m [kgm/s]
“bibloc”	2.5 10^{-3}	456	24.9

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].

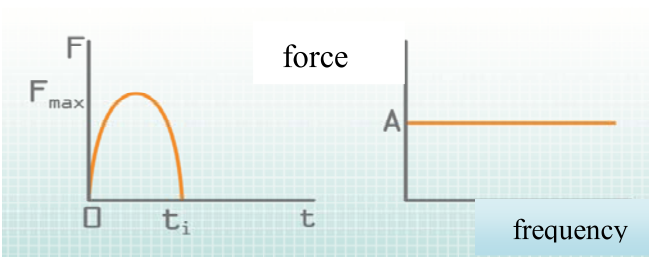

Fig. 7 Impact load variation

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-9m/s, with a graphical presentation in fig. 8.

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

1/3 octave	TBM 2 tracks					NATM	NATM
[Hz]	soil 1	soil 2	soil 3	soil 4	soil 5	soil 3	Soil 2
10	68,1	61,4	56,5	42,5	34,7	57,1	64,1
12.5	74,9	65,6	60,2	45,8	38,0	61,0	68,3
16	86,1	71,7	64,9	49,7	41,9	66,1	74,3
20	78,1	82,2	70,4	53,7	45,8	73,8	83,9
25	74,3	86	79,0	58,4	50,4	74,5	87,8
31.5	80,3	83,3	90,2	66,0	57,9	85,0	79,6
40	88,3	86,1	91,0	76,0	67,8	91,2	97,2
50	84,6	86,3	82,3	74,9	66,6	86,7	89,4
63	73,7	74,2	77,1	72,3	64,9	75,7	78,5
80	67,3	67,5	64,9	70,0	61,9	69,0	73,1
100	67,9	67,1	60,7	61,3	53	65,8	68,9
125	57,9	57	68,9	61,1	53,3	68,3	68,6
160	63,7	64,9	71,8	61,0	58,1	66,4	69,7
200	58,5	61,8	70,1	60,9	57,4	62,1	67,9

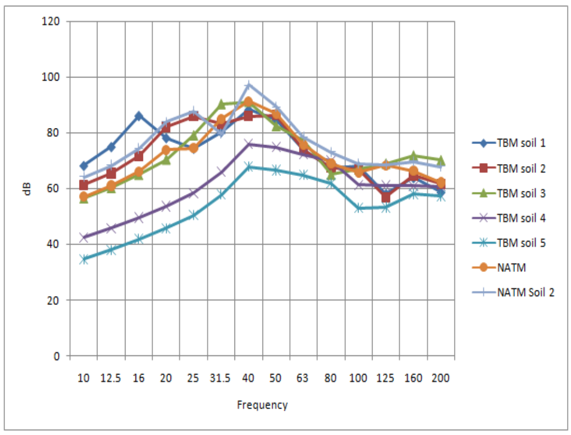

Fig. 8 Vibration levels at tunnel invert for the above tunnel types

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.

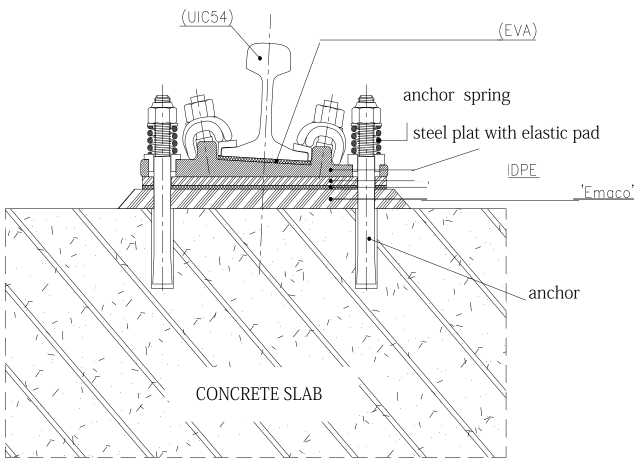

Fig. 9 Installation of the VAE system on a concrete slab

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.

Table 5. Measured ground borne noise levels on tunnel invert for special track work (TO)[dB ref. $^{1e-9}$ m/s]

Ground borne noise & vibration measurement's campaign : 2005 & 2008 at TO's locations			
Frequency band [Hz]	PAPANDREOU shaft 2005	TRUMPET SEPOLIA (Ag. Antonios) 2008	Average [dB]
10	73,7	75,0	74,4
12,5	73,6	72,4	73,0
16	72,8	71,9	72,3
20	72,7	73,5	73,1
25	75,6	77,0	76,3
31,5	83,3	81,4	82,4
40	94,3	87,9	91,1
50	100,6	91,6	96,1
63	96,9	87,9	92,4
80	92,4	92,3	92,3
100	90,1	90,3	90,2
125	88,0	89,4	88,7
160	86,8	92,9	89,9
200	81,6	88,8	85,2

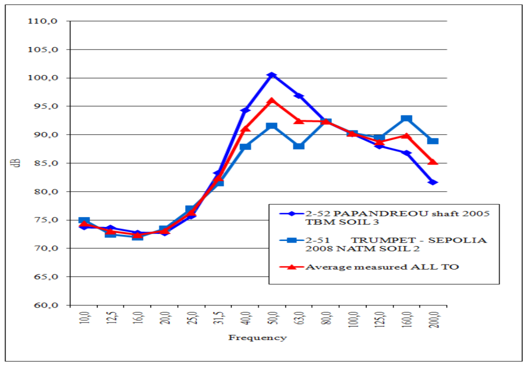

Fig. 10 Measured data at TO's location under normal operation.

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

Frequency band	Average measured data at TO's locations	NATM Standard track STEDEF soil 2	Proposed TF values for the sections equipped with special track work
[Hz]	[dB]	[dB]	[dB]
10	74,4	64,1	10,3
12,5	73,0	68,3	4,7
16	72,3	74,3	-2,0
20	73,1	83,9	-10,8
25	76,3	87,8	-11,5
31,5	82,4	79,6	2,8
40	91,1	97,2	-6,1
50	96,1	89,4	6,7
63	92,4	78,5	13,9
80	92,3	73,1	19,2
100	90,2	68,9	21,3
125	88,7	68,6	20,1
160	89,9	69,7	20,2
200	85,2	67,9	17,3

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)

Edyn [GPa]	C [m/s]	η
0.1	1100	0.10
0.4	1900	0.10
0.9	2500	0.10
5.5	5100	0.01
18.0	7000	0.01

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 :

$$d = \sqrt{(d_{horiz.})^2 + (depth - 5 - d_r)^2} - r_0 \qquad (5)$$

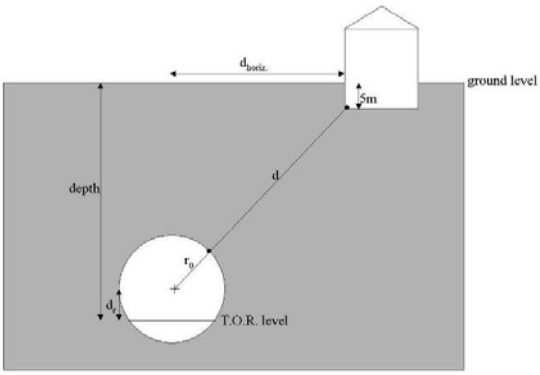

Fig. 11 Distance from TOR (top of rail) to basement level

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

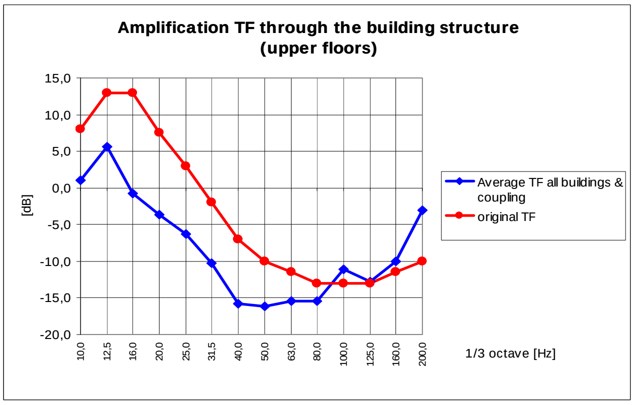

Fig. 12 TF for the typical Athenian building

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.

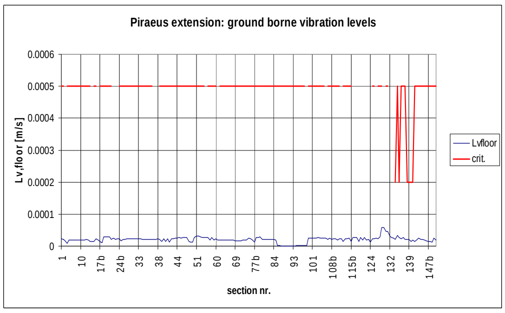

Fig. 13 Piraeus extension ground borne vibration levels

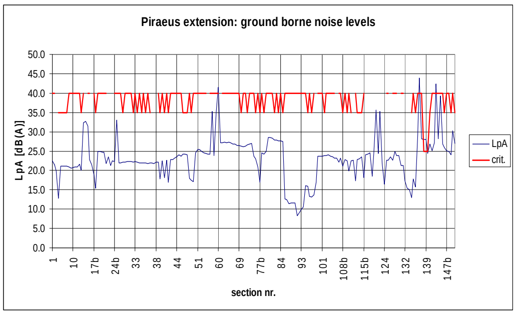

Fig. 14 Piraeus extension ground borne noise levels

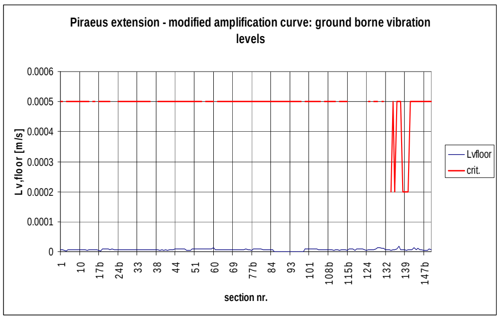

Fig. 15 Piraeus extension – modified amplification curve: ground borne vibration levels

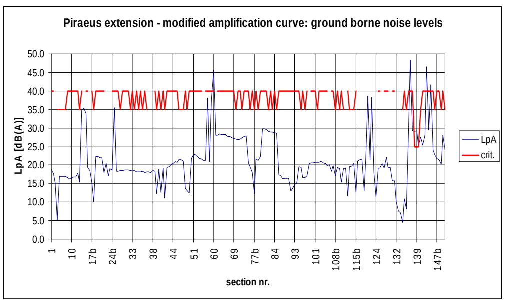

Fig. 16 Piraeus extension – modified amplification curve: ground borne noise levels

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.

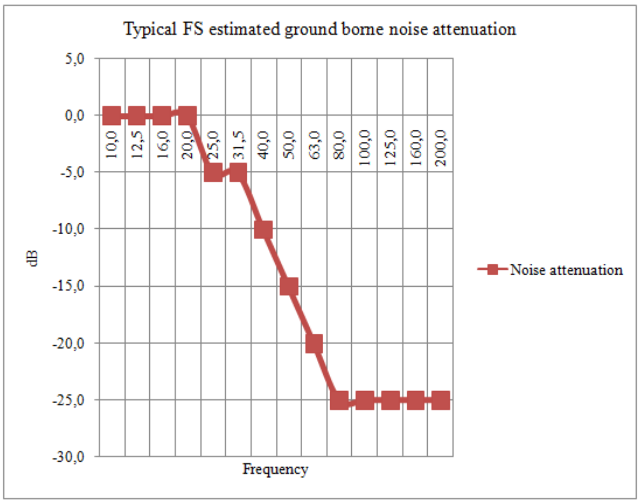

Fig. 17 Estimated noise attenuation due to Floating Slab implementation

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].

Table 8. Estimated ground borne vibration and noise levels in selected sections with and without FS

$L_{v,floor}$ [μm/s]

Section nr.	Chainage	Original TF		Average TF		Criterion
		No FS	Typical FS	No FS	Typical FS	
59-60	4358.551-4409.297	22.5	12.4	13.3	4.8	500
137	8269.253-8320	28.0	15.3	17.3	5.9	500
138b	8320-8370	20.3	12.1	7.6	4.2	200
139	8370-8413.689	20.5	12.2	7.7	4.2	200
140	8413.689-8523.689	13.6	8.1	5.1	2.8	200
143	8618.207-8668.954	24.3	13.4	14.6	5.2	500
145	8748.262-8775.268	20.5	11.4	11.5	4.4	500

L_{pA} [dB(A)]

Section nr.	Chainage	Original TF		Average TF		Criterion
		No FS	Typical FS	No FS	Typical FS	
(59)-60	4358.551-4409.297	41.5	21.3	45.6	21.1	40
137	8269.253-8320	44.0	23.4	48.2	23.7	40
138b	8320-8370	28.0	18.8	29.1	11.2	25
139	8370-8413.689	28.1	18.9	29.2	11.2	25
140	8413.689-8523.689	24.3	15.3	25.3	7.6	25
143	8618.207-8668.954	42.4	22.0	46.6	22.0	40
145	8748.262-8775.268	39.3	19.4	41.7	17.6	40

In conclusion and under the relevant assumptions, it has been found that calculated ground borne noise levels were allowable compared to the criterion for all sections *except in 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 and vibration abatement tool ensuring minimization of the annoyance.

In this perspective, Urban Mass Transportation Systems as Attiko Metro S.A., among other multi view approaches, which are a must for a successful establishment, needs to include a comprehensive environmental noise and vibration management and control, as a main parameter for a sustainable business and a modern green trend [22]. Mass transit operation authorities have a responsibility, other than producing the needed transport services, to achieve their social responsibilities regarding urban population annoyance an urban acoustic environment degradation, including a dangerous climate change.

References

[1] http://www.ametro.gr/page/default.asp?la=2&id=5

[2] M. HUSSEIN, "Modelling vibration from surface and underground railways as an evolutionary random process". Computing in Civil and Building Engineering, Proceedings of the International Conference, W. TIZANI (Editor), 30 June-2 July, Nottingham, UK, Nottingham University Press, Paper 276, p. 551, ISBN 978-1-907284-60-1.

[3] G.R. Watts, "The Effects of Traffic Induced Vibrations on Heritage Buildings –Further Case Studies", Research Report 207, Transport and Road Research Laboratory, Department of Transport, UK, 1989.

[4] K. Vogiatzis "Environmental vibration monitoring & assessment at sencitive receptors during Metro construction in the urban centre of Thessaloniki, Greece, WSEAS TRANSACTIONS on ENVIRONMENT and DEVELOPMENT - ISSN: 1790-5079 255, Issue 9, Volume 7, September 2011.

[5] K. Vogiatzis, On Environmental Ground Borne Noise & Vibration abatement by implementing Floating Slabs at Athens Metro network – Measurements campaign results WSEAS TRANSACTIONS on ENVIRONMENT and DEVELOPMENT - ISSN: 1790-5079 255 Issue 11, Volume 7, November 2011.

[6] K. Vogiatzis, S. Chaikali & Gl. Siouti "Environmental noise protection in Greece - Recent legal framework & action tools", 18th International Congress on Sound and Vibration ICSV 18, 10-14 July 2011, Rio de Janeiro, Brazil.

[7] K. Vogiatzis & H. Mouzakis "Criteria for vibration from railway & light rail transportation projects construction for the protection of buildings and the avoidance of annoyance" ΕΠΙΣΤΗΜΟΝΙΚΟ ΚΤΙΡΙΟ, Β/1999, pp. 57-59.

[8] S. Chaikali & K. Vogiatzis, "Environmental Noise as an important legal conception in the rehabilitation of the acoustic urban environment", 16th International Congress on Sound and Vibration ICSV 16, 5-9 July 2009, Krakow, Poland.

[9] TT&E Consultants Ltd – D2S International, "AM LINE 3 EXTENTION: HAIDARI-PIRAEUS-FORESTATION PIRAEUS UNIV. Ground borne Noise & Vibration Study" April 2008.

[10] K. Vogiatzis, P. Vanhonacker & P. Carels, "Design, Development and Implementation of a High Performance FST System for Direct Fixation Turnouts in the Athens 2004 Olympics Infrastructure Extension Program of Athens Metro" 8th International Conference and Exhibition, Railway Engineering – 2005, London UK, 29-30 June 2005.

[11] Ver, Ventres and Myles "Wheel rail noise - part III: Impact noise generation by wheel and rail discontinuities", Journal of Sound and Vibration, Vol. 46, 395-417, 1976.

[12] Sato and Satoh "Cause and effects of wheel load variation on the high speed operating line", Rail road track mechanics and technology, A.D. Kerre, Pergamon Press, 1978.

[13] Saurenman H.J., Nelson J.T. and Wilson G.P., "Handbook of urban rail noise and vibration control", U.S. Department of Transportation Administration, report No UMTA-MA-06-0099-82-1, 1982.

[14] TT&E Consultants SA. - D2S International –«NOISE & VIBRATION STUDY FOR FLOATING SLAB IN DIRECT FIXATION TURNOUTS - CASE STUDY: NATM TUNNEL SOIL II - SEGMENT 33 - STAVROS EXTENSION - Finite Element simulation: Static and dynamic behaviour of turnout - Analysis performed with SYSTUS™, April 2003.

[15] TT&E Consultants SA "Work Execution Contract CON-02/003: Design, Procurement, Installation & Commissioning of Electromechanical Infrastructure Equipment and Track Work for the Extensions of Athens Metro Lines 2 &3: Noise and vibration measurements", December 2004.

[16] TT&E Consultants SA "Work Execution Contract CON-02/003: Design, Procurement, Installation & Commissioning of Electromechanical Infrastructure Equipment and Track Work for the Extensions of Athens Metro Lines 2 &3 : TRACKWORKS - Noise and vibration measurements before and after rail pads replacement at TO 2-51 at Ag.Antonios SEPOLIA", C.J.V. AKTV – E/M METRO, April 2008.

[17] Ungar and Bender "Vibrations produced in building by passage of subway trains: parameter estimation for preliminary design", Internoise 75, Sendai, Japan, 27-29 August 1975, pp. 491-498.

[18] TT&E Consultants Ltd - "Ground borne Noise & Vibration Study for AM Extensions", October 2002

[19] ET&T Ltd- ATTIKO METRO S.A. " Final report on 2nd series of vibration measurements in PPC Building for the standard building transfer function,TSA-004,1994.
[20] K. Vogiatzis, P. Vanhonacker, "Noise & Vibration Evaluation of a Floating Slab in Direct Fixation Turnouts in Stavros extension of Athens METRO", ICASTOR Journal of Engineering, Vol. 2, No. 3(2) (2009), Indian Centre for Advanced Scientific and Technological Research
[21] K. Vogiatzis, “Ground borne Noise and Vibration Assessment from Metro operation in the New Athens Metro Extension to Piraeus” Recent Researches in Applied Mechanics - ISBN: 978-1-61804-078-7 Proceedings of the 3rd International Conference on Theoretical and Applied Mechanics (TAM '12) and the 3rd International Conference on Fluid Mechanics and Heat and Mass Transfer (FLUIDS-HEAT '12).
[22] Davorin Krajl, “Green Innovation Trends and Systems Thinking” WSEAS TRANSACTIONS on ENVIRONMENT and DEVELOPMENT - ISSN: 1790-5079 255 Issue 4, Volume 6, April 2010

Konstantinos E. Vogiatzis
Volos, Greece, 06/02/1956
Degrees:
1) Rural and Surveying Engineering, National Technical University of Athens (U.N.T.A.) July 1977.
2) Civil Engineering (Transportation planning), National Technical University of Athens (U.N.T.A.) December, 1980.
3) Urban and Rural Planning : Diplômé de Formation Interdisciplinaire en Aménagement et en Urbanisme (D.F.I.A.U.) Centre of Research in Urban Planning of Paris, November 1980.
4) PhD. in REGIONAL ANALYSIS AND RURAL PLANNING (Doctorat en Analyse Regional et Aménagement du Territoire) OPTION: REGIONAL PLANNING. University of Paris 1 PANTHEON-SORBONNE, January 1981.
Present position:
Ass. Professor in Transportation Noise - Environmental & Land Use Planning & Head of the Laboratory of Transportation Environmental Acoustics (L.T.E.A.), University of Thessaly / Faculty of Civil Engineers, Volos Greece
Books
1. K. Vogiatzis, “Environmental Engineering & Institutional Framework for Implementation”, Symmetria Publications, June 2010
2. K. Vogiatzis, S. Chaikali, A. Chatzopoulou “Protection of the Greek Noise Landscape - Institutional Framework of the Environmental Noise” Papasotiriou Publications, 2009
Research interests
Prof. K. Vogiatzis is an Expert in Environmental Noise, Monitoring and Assessment and he has a large number of publications in international journals and conferences. The most important research interests focus to the protection from urban environmental noise emissions, with emphasis to air borne & ground borne noise & vibrations. Important interest is also given to the mass urban transportation media networks as per Metro, Tram & high speed trains, as well as airport operation & urban road transportation infrastructure focusing on the integrated environmental &land use planning management.
Membership & Official Representations
1) IIAV (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
6) National Technical Chamber of Greece
7) Hellenic Institute of Transportation Engineers
8) Consultant in Ministry of Environment in France – Programs GEUS I & II (Gestion d’ Environnement Urbain Sonore)
9) Hellenic Institute of Civil Engineers