On Environmental Ground Borne Noise & Vibration abatment by implemeting Floating Slabs at Athens Metro network - Measurements campaign results

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Abstract: - This paper describes the FS implementation , on 4 major extensions of Athens Metro lines 2 and 3, already in service: (a) extension of line 2 from Sepolia to Ag.Antonios station, (b) extension of line 2 from Dafni to Ilioupoli (Ag. Dimitrios station), (c) extension of line 3 from Ethniki Amyna to Stavros (D.Plakentias station)and, extension of line 3 from Monastiraki to Egaleo. Ground borne noise and vibration mitigation measures evaluation in normal operation conditions presented hereafter guarantees, especially in TO location along these extensions, allowable ground borne noise and vibration levels in nearby buildings & sensitive receptors. The measured Floating slab solutions measured within an extensive measurements campaign proven to achieving an overall ground borne and vibration attenuation of approx.15-16 dB(A) in soil surface. A comprehensive comparative presentation of the results is an important tool in evaluating the expected environmental protection potential of similar mitigation measures regarding noise & vibration emissions & generated annoyance from urban railway networks operation.

Key-Words: - environmental noise, urban LRT operation, Metro, Ground borne noise, vibration

1 Introduction: The project & the relevant technical parameters

ATTIKO METRO S.A. is a state company which implements the development of the Athens Metro network. Nowadays, the two Lines of the Athens Metro are 51.1km long in total (including 20.7 km of suburban railway line from D. Plakentias station to the Airport) with 34 modern Stations and serve approximately 700,000 passengers on a daily basis. In addition, Line 1 (ISAP original oldest metro line in Athens) serves more than 415,000 passengers. Therefore, combined with the Tramway network and the Suburban Railway, the Athens Metro System ensures the development of a full Modern Transit Model in the greater Athens metropolitan area. The ATHENS METRO project [1] is underground, therefore, its main objective, i.e. the rapid transfer of citizens in the wider area of the capital is widely achieved. For the construction of the underground Metro stations and tunnels, up-to-date methods, ensuring safety, workmanlike and rapid completion of the project, were applied as presented hereafter:

- Tunnel Boring Machine (TBM).
- Open Face Shield (OFS).
- Earth Pressure Balance machine,
- New Austrian Tunnelling Method (NATM) and
- Cut and Cover method.

Four main extensions, of the original Athens Metro lines 2 and 3, are already in service within the above network:

- extension of line 2 from Sepolia to Ag. Antonios station
- extension of line 2 from Dafni to Ilioupoli (Ag.Dimitrios station)
- extension of line 3 from Ethniki Amyna to Stavros (D.Plakentias station)
- extension of line 3 from Monastiraki to Egaleo station

The aim of the ground borne noise and vibration special mitigation measures evaluation in real operation conditions presented hereafter is to determine their effectiveness in order to guarantee, especially in turnout (TO) locations, allowable ground borne noise and vibration levels in nearby buildings and sensitive receptors and minimum annoyance to the inhabitants that was practically difficult to achieve with the typical STEDEF solution. Within the relevant detailed acoustic study [2], the alignment in all extensions were divided into homogeneous sections, i.e. sections along which the tunnel and soil types, depth and distance from nearby buildings and presence or not of a switch can be considered as constant, with particular emphasis on section with turnouts on direct fixation. For each section and each sensitive building, the ground borne noise and vibration levels were numerically predicted, and then verified within the relevant measurement's campaign. The permissible levels of noise and vibration, the maximum values of ground borne noise from train operations enforced in Athens Metro Extensions project, were based, on the recommended by the American Public Transport Association, criteria given in the table 1 below.

Table 1
Maximum Permissible Ground Borne Noise Levels from Metro Operation in dB(A)

Community Area Category	Single Family Dwellings	Multi-Family Dwellings	Hotel/Motel Buildings
Low Density Residential	30	35	40
Average Residential	35	40	45
High Density Residential	35	40	45
Commercial	40	45	50
Industrial/Highway	40	45	50

Type of Building or Room	Single Event Maximum Permissible Ground Borne Noise Level in dB(A)
Concert Halls	16
Radio and TV Studios	25
Museums, Auditoriums & Music Rooms	30*
Churches and Theatres	35
Hospital Operation and Sleeping Rooms	35-40
Courtrooms and Parliament	35
Schools and Libraries	40
University Buildings	35-40
Offices	35-45
Commercial Buildings	45-55

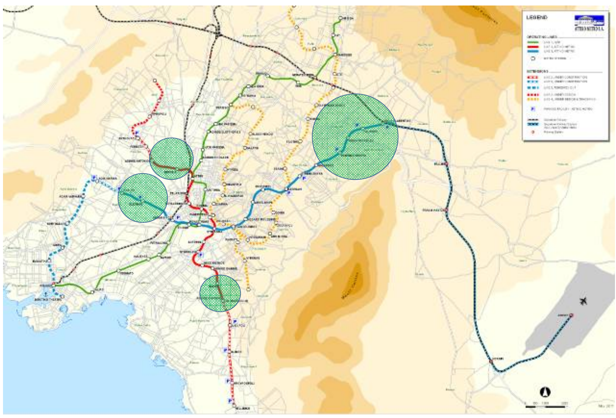


Fig. 1 Athens Metro lines , Operating Extensions (in green circle) & Future Development plan

The following general parameters were adopted :

- a booted twin block ties track,
- UIC54 rails, with a basic sleeper spacing is 700 mm
- material properties applied:
  for concrete:
  - Young's modulus: $E=3.216x\ 10^{10} N/m^2$
  - Poisson's coefficient: $\nu = 0.25$
  - volumic mass : $\rho = 2500\ kg/m^3$

  for UIC54 rails:
  - Young's modulus: $E = 21\ x\ 1010\ N/m^2$
  - Poisson's coefficient: $\nu = 0.3$
  - volumic mass : $\rho = 7850$ kg/m3
  - section: $A = 69.34\ cm^2$
  - bending inertia: $Iy = 2346\ cm^4$
- unsprung mass = 1822 kg/axle corresponding with the driven wheel set
- axle load of vehicle = 14 tons (max.);
- bogie axle to axle distance = 2 m
- a "VAE" turnout conception design with the UIC 54 rails posed on their original base plate pads

A detailed simulation, in order to investigate the static and dynamic behaviour of different configurations of a representative Athens Metro turnout & relevant anti N&V mitigation measures was also executed (case study TO No. 33 located in Stavros Extension) [3], i.e .

- Scenario 1: a solution without floating slab (FS) under the turnout –;
- Scenario 2: a complete floating slab (FS) in the area under turnout –;
- Scenario 3: a partial floating slab (length of ±10m) located under the frog area

Especially regarding the ground characterization of Athens Metro extensions tunnel and based on the available geotechnical data, the following 5 distinct categories have been defined for the dynamic soil modulus:

Table 2
Dynamic soil modulus/Athens Metro extensions

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

2 A brief presentation of the linear dynamic analysis of the alternative scenarios

The turnout No. 33 is placed in a NATM tunnel with soil category 2 and it was considered as the worst case scenario. Soil category 2 is considered with a transfer function as in figure hereafter, based on measurement campaign in the operating lines 2 & 3 of the Athens Metro system [4].

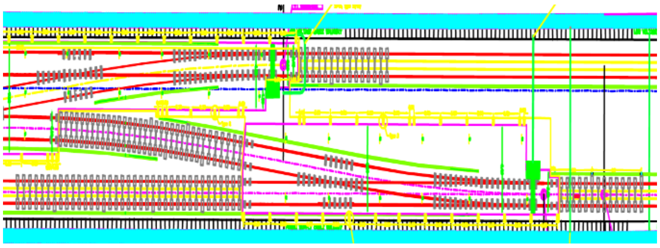


Fig. 2 Athens Metro TO 33 in Stavros Extension

The relevant transfer function from tunnel invert to soil surface for the soil category 2 (as per relevant measurements results) is presented in figure hereafter [4].

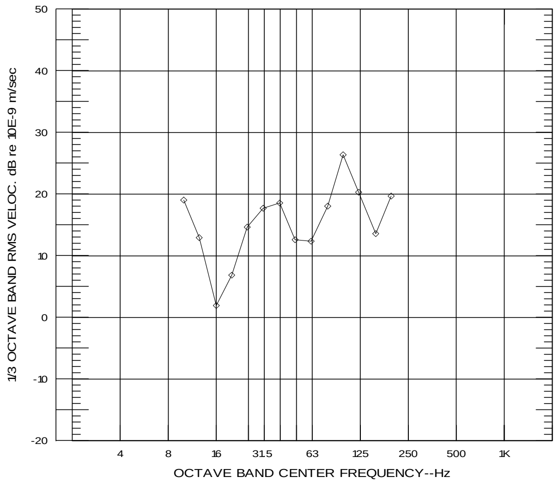


Fig. 3 Transfer function from tunnel invert to soil surface for soil category 2

In order to model and precisely determine the maximum deflection during a vehicle passage, the generated 3D solid finite element model (Static and dynamic behavior of turnout - Analysis performed with SYSTUS™) is composed of the following type of elements [4]:

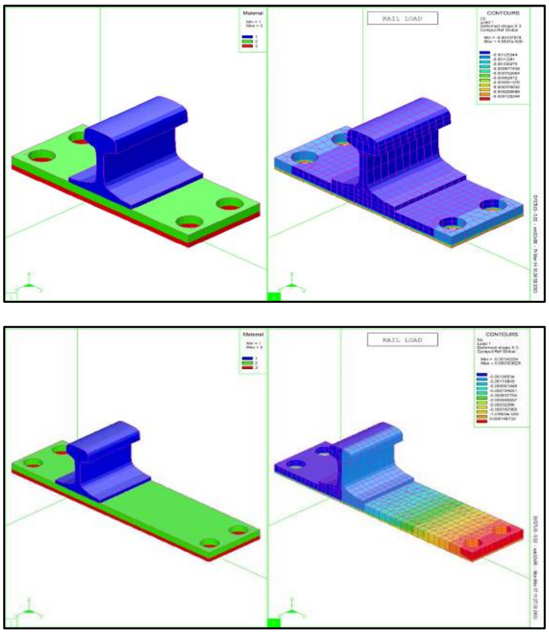
- beam elements (with 6 degrees of freedom (DOF) per node) for the rails and base plates;
- shell elements (with 6 DOF per node) for the tunnel wall;
- solid elements (with 3 DOF per node) for the concrete filling.

Two separate models have been used to tune the material properties and determine the equivalent translation and rotational stiffness of the combination of the two types of base plates and the original base plate material. The relevant results of those analyses are presented in following figures:

- R54-37 base plate and the obtained total displacement for a total rail load of 33 kN.
- R54-39 base plate and the obtained total displacement for a total rail load of 33 kN.

For each type of plate the stiffness in the 6 directions is determined by applying corresponding loads. The rigidity is determined from the resulting displacements.

- **Scenario 1: NO floating slab**: in the final model of the tunnel and turnout for this scenario, 3 load cases are considered: each load case corresponds to the position of 1 bogie on the track (track 1 – track 2 – on the frog - central part of the turnout). The first vertical bending mode of the track is around **59 Hz.**



(a)

(b)

Fig. 4 Model of (a) R54-37 base plate & (b) R54-39 base plate

- **Scenario 2: COMPLETE floating slab (FS)** introducing a 3D solid finite element model with beam elements (with 6 degrees of freedom(DOF) per node) for the rails and base plates, shell elements (with 6 DOF per node) for the tunnel wall and solid elements (with 3 DOF per node) for the concrete slab, the concrete filling and for the anti vibration layer. The model of the NATM tunnel section, rails (turnout), base plates, concrete slab, and the proposed anti-vibration layer and concrete filling material is presented hereafter . The first vertical bending mode of the track is approx. **17.6 Hz**.

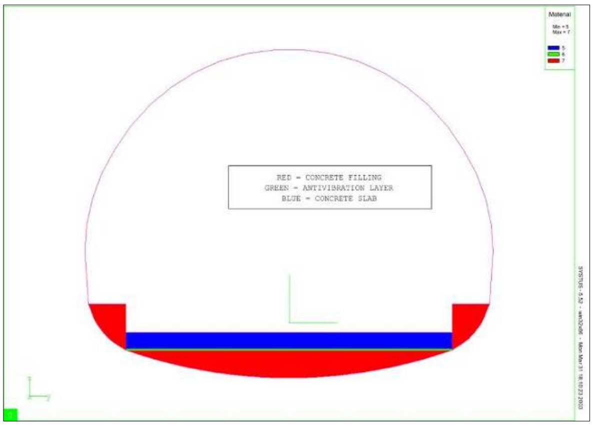


Fig. 5 3D model of the NATM tunnel with a complete FS implementation.

- **Scenario 3: LIMITED floating slab at frog area.** The generated 3D solid finite element model in this case is presented hereafter (NATM tunnel section, rails (turnout), base plates, concrete slab, anti vibration layer and concrete filling material for the partial alternative scenario). The first vertical bending mode of the track is round 18.7 Hz.

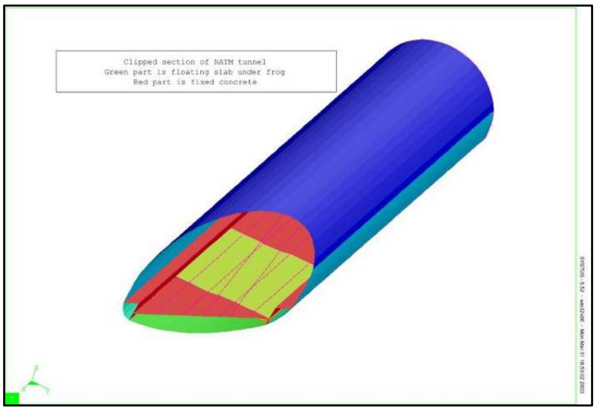


Fig. 6 3D geometrical model of the NATM tunnel for scenario 3

A linear harmonic response analysis [3], [4] was performed for each one of the previous described models. The purpose of this analysis is to determine the construction's behaviour in the third octave frequency span from 10 to 200 Hz. Each system (model) is submitted to the dynamic vertical force, exerted by the wheel running over the frog section at a speed of 80 km/h. The force sweeps in frequency from 0 to 225 Hz. The response is measured on the tunnel invert at the location of the frog. The response is calculated for 5 different cases (reference case):

- A rigid system in which no the original elastomer material is used: direct fixation on slab with no elastomer (Scenario 1 – A)
- A full concrete structure with the original base plate pads between the base plates and the concrete (Scenario 1 – B)
- A complete floating slab (length +/- 50 m) covering the total length of the turnout (Scenario 2)
- A limited (partial) floating slab in the frog area (length +/- 10 m): with the bogie on the frog area slab (Scenario 3)
- The same limited (partial) floating slab in the frog area (length +/- 10 m): with bogie on turnout next to slab (Scenario 3).

The relevant estimated results are presented in the figure hereafter in a third octave band basis [3],[4].

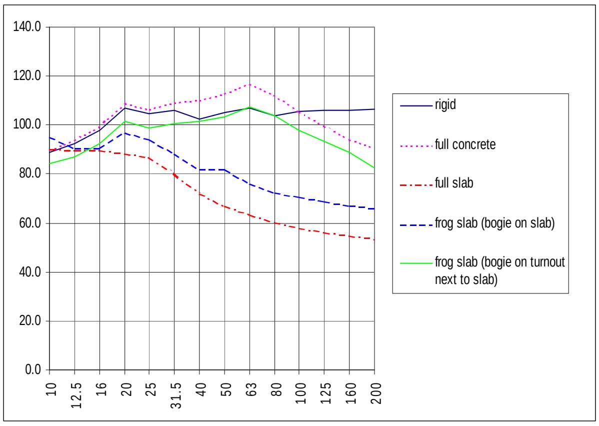


Fig. 7 1/3 octave band analysis for all scenarios and relevant cases

The estimated ground borne noise levels on the soil surface are estimated through the insertion of the relevant transfer function from the above figure are presented for each case hereafter.

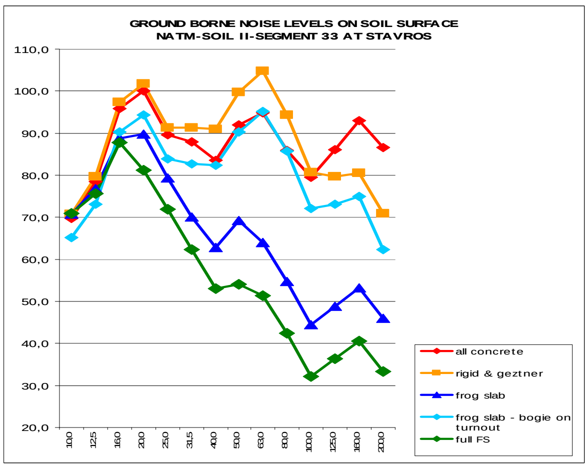


Fig. 8 Estimated ground borne noise levels on the soil surface for all cases

In conclusion it was resulted that the full floating slab (FS) mitigation measure solution ensures a complete ground borne noise and vibration attenuation with an overall reduction of some 15 to 16 dB(A) on the soil surface. The "limited" frog area FS even though presents some acceptable noise levels with the bogie in the middle of the frog area, however, in the case with the bogie on the full concrete area next to the frog slab, the expected noise level at the soil surface are approximately estimated at some 49 dB(A), exceeding by far the given criterion.

The full floating slab (FS) solution [5] for the TO areas was therefore considered as the best solution, eensuring both environmental criterion (in this case 40 dB(A) in the range 10-200 Hz) A special “CDM-ISO-DFSA®” floating slab-track was selected by Attiko Metro S.A. and placed in all turnouts in the Athens Metro extension program. The FS implementation completed in the tunnel invert at Stavros extension is presented hereafter .

Fig. 9 FS implementation at AM Stavros extension

3 Acoustic Measurements campaign - Locations, in situ Conditions & Equipment setup

The main goal of the relevant campaign was the measurement of ground borne noise and vibration level, which is generated on the tunnel at the places where crossovers or turnouts were constructed on FS and also simultaneously at adjacent buildings, during the operation along the relevant extensions of Athens Metro's lines 2 and 3. Additional objectives were also the measurement of the predominant frequency of each FS on which crossovers are fixed, as well as measurements at buildings over normal STEDEF track work and a typical crossover with no FS implementation [6]. More analytically

- ✔ Measurements at FS locations including (a) dynamic characteristics of the FS : natural frequency of the unloaded system using the impact of a PCB hummer and sensors on the slab, and on the tunnel’s wall, approx. in the middle of the FS length and (b) vibration velocity on the tunnel wall and simultaneously in the nearest to the FS dwelling, during train operation and for up to 5-10 train pass byes.
- ✔ Vibration velocity measurements in the buildings, during train operation ensuring minimum background noise i.e. very early in the morning or late in the night, in order to evaluate ground borne noise criteria compliance.
- ✔ Vibration velocity measurements at the tunnel wall simultaneously with the above relevant closest building measurements.

The train pass-bye signal was recorded simultaneously by two DAT recorders: one in the tunnel wall, and one in the building. The analysis of the data was done by using an analog B&K spectrum analyzer, in the frequency range from 10 to 200Hz.

Measurements were executed were direct fixation on a floating slab was implemented in TO locations i.e. at C/O 15 at Ilioupoli extension, C/O24, T/U 25, C/O26, C/O27, C/O28 and C/O 29 at Stavros extension and also the X-OVER 52 at Agios Antonios extension where the rails were fixated in tunnel invert in order to compare the relevant results for both conditions with & without FS implementation. The vibration velocity level was simultaneously measured on the tunnel wall, (and also the tunnel invert at Agios Antonios extension) and on the soil surface (free field) of the closest, to each rail axis, building. The vibration level was measured using accelerometers that were rigidly fixed on the tunnel wall and on the floating slab where the above mentioned crossovers/turnouts are placed. Geophones and the appropriate amplifiers were used to measure simultaneously the vibration velocity level on soil surface of the closest to the crossover building. Measurements were carried out during the night in order to eliminate the influence of traffic. Ambient vibrations’ level was recorded and compared to the vibration level that is generated during Metro pass byes. Especially at TO 52 along Agios Antonios extension where the crossovers are directly fixed on the tunnel invert, the accelerometers were placed on the tunnel invert and on the tunnel wall. In order to avoid vibrations that are generated during the operation of the buildings and adjacent road axis, all series of measurements were carried out during the night or early in the morning prior to rush hours. However, traffic conditions in Messogion avenue were very intense even during the night or early morning and has affected some of the building measurements especially in the area of Ethniki Amyna station.

Two different instrumentation setups were used for recording vibrations in tunnel and on soil surface (adjacent to chosen buildings) during train operation. A different setup was used also to record free vibrations of the slabs:

- Tunnel measurement's Setup: Two WILCOXON accelerometers 731A with P31 power amplifiers were used in order to record vertical acceleration on the tunnel wall, on the tunnel invert and on the top of the floating slabs. The voltage sensitivity of the accelerometer on the tunnel wall was 100 V/g while the sensitivity of the accelerometer on tunnel invert or on floating slab was 10V/g. The power amplifier has a 450 Hz low pass filter. The output of each accelerometer was recorded by a digital 8 channel TEAC RD-130TE data recorder.
- Building's/ Sensitive Receptor's (soil surface) measurement's Setup : Geophones with a 4Hz high pass and a special amplifier was used in order to record velocity on soil surface of the closest buildings to the tunnel. The sensitivity of the geophone was 28.8V/m/sec. The analogue output was recorded by an analogue 8 Channel Kyowa tape recorder.
- FS dynamic characteristics measurement's Setup : A WILCOXON accelerometer 731A with P31 power amplifier was used in order to record vertical acceleration on the floating slab, the voltage sensitivity of the accelerometer 100 V/g. A PCB hummer was used in order to impose impulses on the floating slab. The recorded signals during train operation were analyzed by a Digital analyzer Type 2131 of B&K. Linear average was used (averaging time 16 sec).

4 Measurement's campaign results

The relevant results at location C/O 15 at Dafni-Ilioupoli extension are presented in the figures hereafter both in tunnel wall and in free field conditions in the facade of the nearest residential building.

Fig. 10 Location of measurements in tunnel & soil surface at C/O 15 location at Dafni-Ilioupoli extension

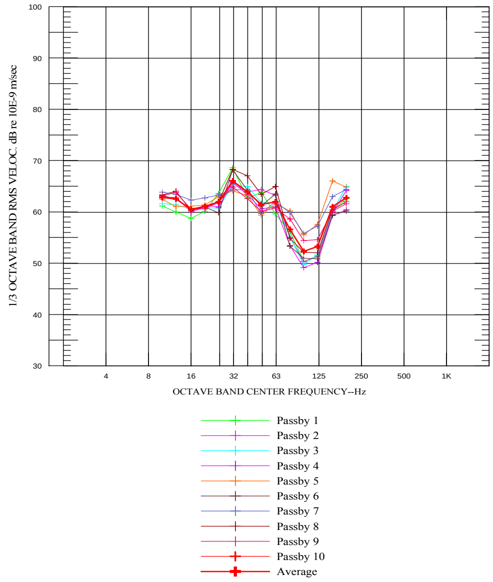


Fig. 11 Vibration velocity level on the wall of the NATM II tunnel at C/O 15 (K.P 9.436). Ilioupoli extension - Soil Category 3.

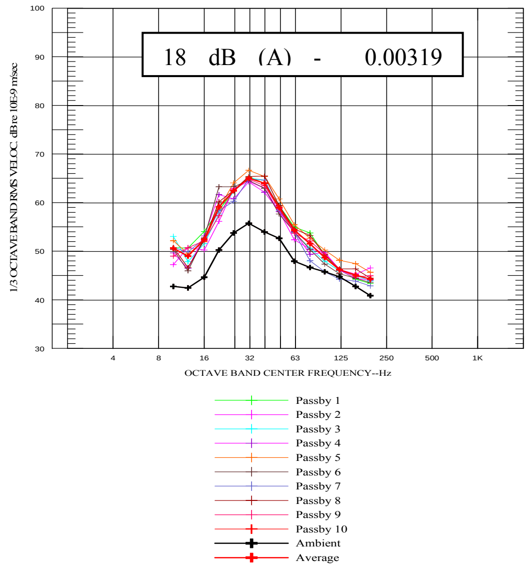


Fig. 12 Vibration velocity level in free-field at the face of the nearest building above C/O 15

The relevant results at locations C/O24, T/U 25, C/O26, C/O27, C/O28 and C/O 29 at Stavros extension are presented in the figures hereafter both in tunnel wall and in free field conditions in the facade of the nearest receptor.

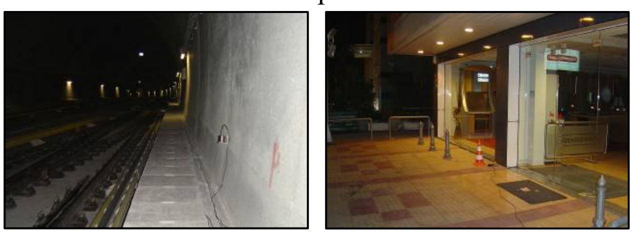


Fig. 13 Location of measurements in tunnel & soil surface at C/O 24 location at Stavros extension

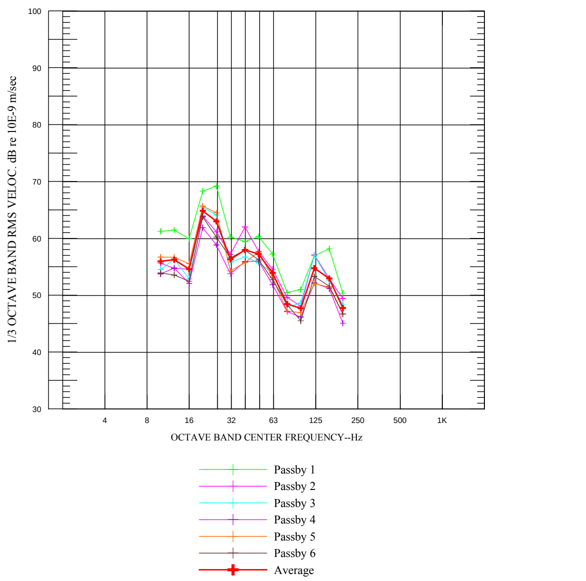


Fig. 14 Vibration velocity level on the wall of the NATM III (3 tracks) tunnel at C/O 24 (K.P.12.652) in Stavros extension. Soil Category 2.

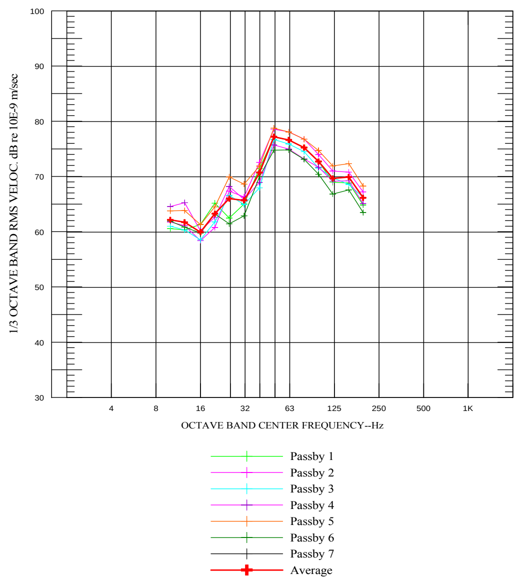


Fig. 17 Vibration velocity level on the wall for the TBM tunnel at at T/U 25 (K.P 12.701) in Stavros extension. Soil Category 2.

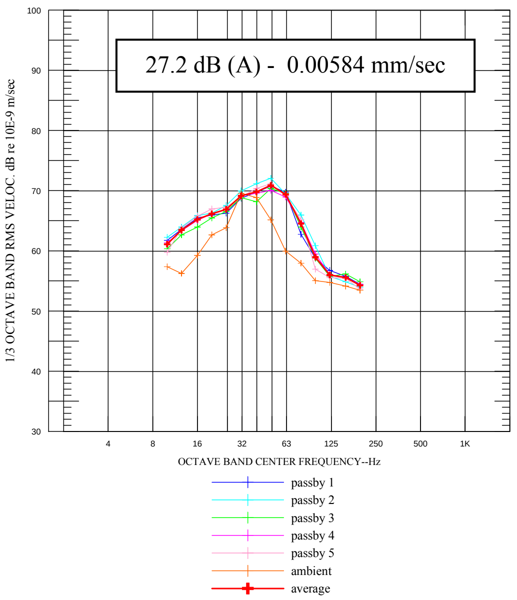


Fig. 15 Vibration velocity level in free-field at the face of the nearest building above C/O 24

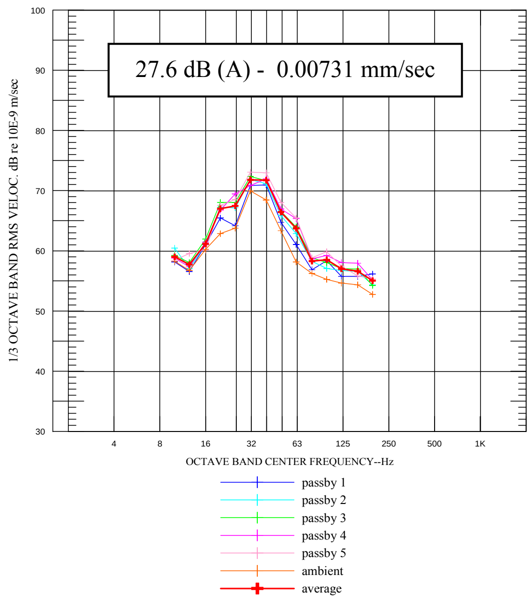


Fig. 18 Vibration velocity level in free field at the face of the nearest building above T/U 25

Fig. 16 Location of measurements in tunnel & soil surface T/U 25 at Stavros extension

Fig. 19 Location of measurements in tunnel & soil surface C/O 26 at Stavros extension

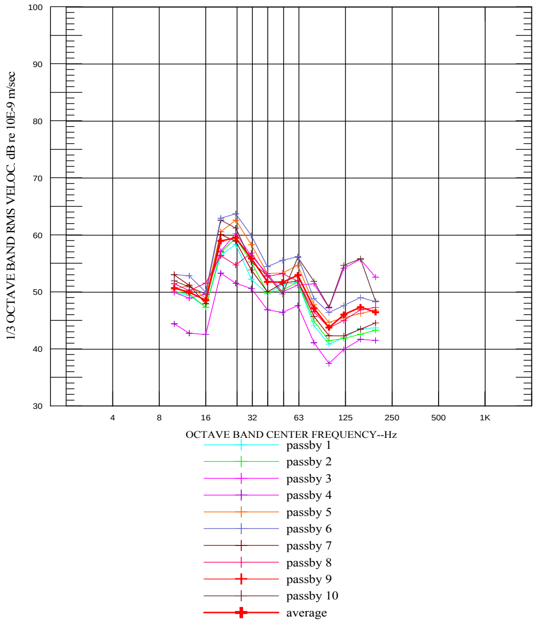


Fig. 20Vibration velocity level on the wall for the TBM tunnel at C/O 26 at the (K.P 14.512) in Stavros extension. Soil Category 2/3.

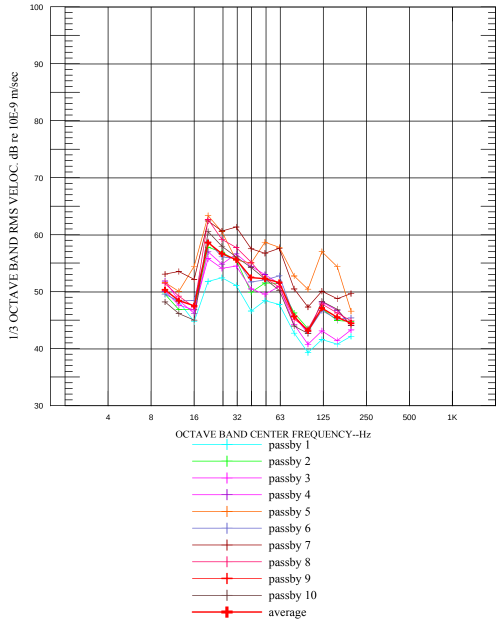


Fig. 23 Vibration velocity level on the wall for the TBM tunnel at C/O 27 at the (K.P 14.583) in Stavros extension. Soil Category 2/3.

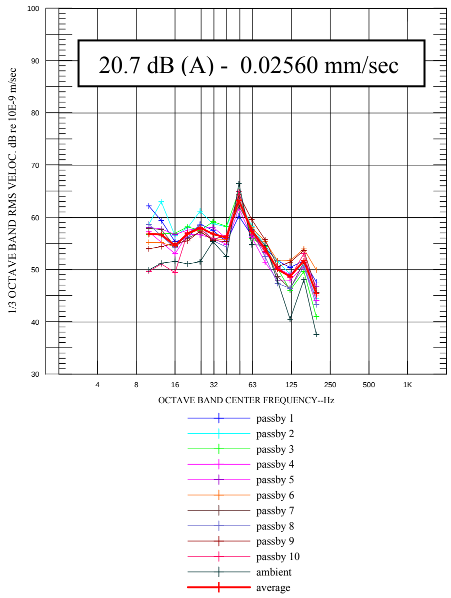


Fig. 21 Vibration velocity level in free field at the face of the nearest building above C/O 26

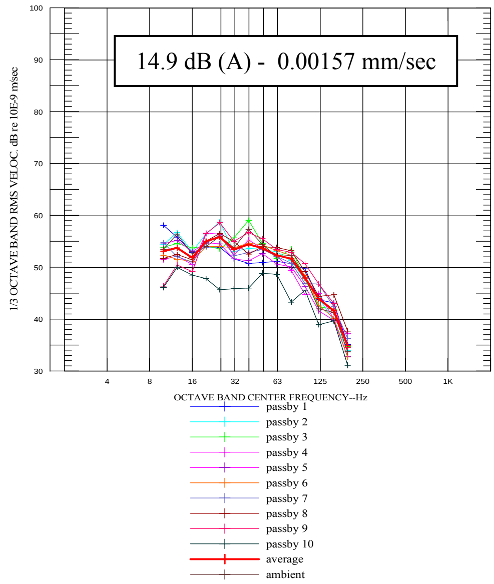


Fig. 24 Vibration velocity level in free field at the face of the nearest building above C/O 27

Fig. 22 Location of measurements in tunnel & soil surface C/O 27 at Stavros extension

Fig. 25 Location of measurements in tunnel & soil surface C/O 28 at Stavros extension

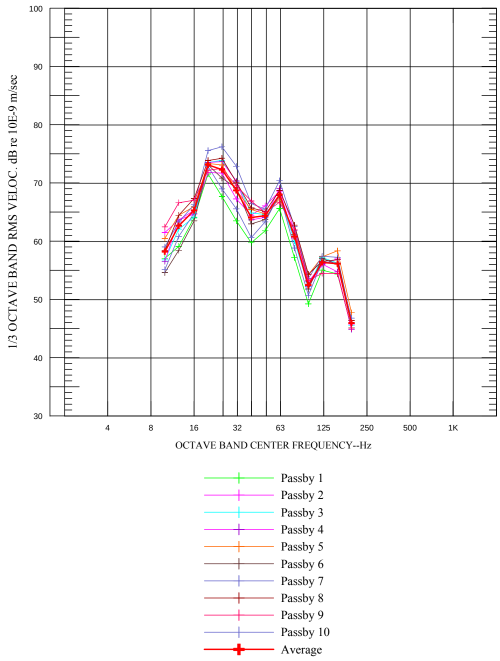


Fig. 26 Vibration velocity level on the wall for the TBM tunnel at C/O 28 at the (K.P 16.293) in Stavros extension. Soil Category 1.

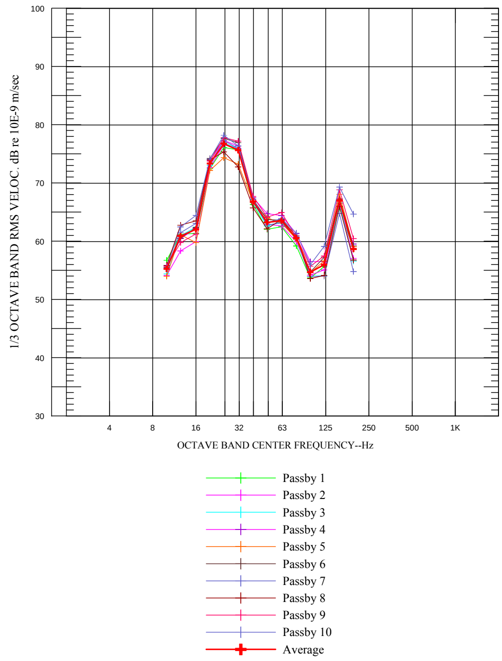


Fig. 29 Vibration velocity level on the wall for the TBM tunnel at C/O 29 at the (K.P 16.555) in Stavros extension. Soil Category 2.

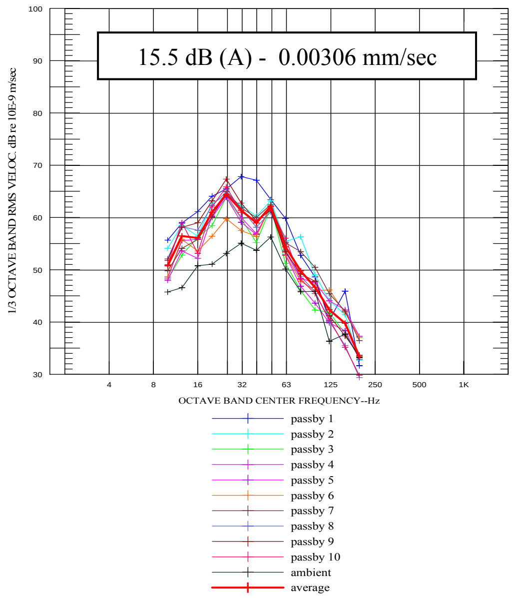


Fig. 27 Vibration velocity level in free field at the face of the nearest building above C/O 28

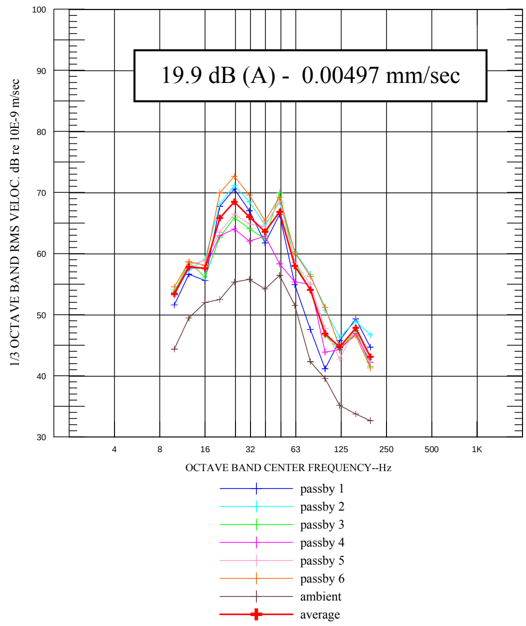


Fig. 30 Vibration velocity level in free field at the face of the nearest building above C/O 29

Fig. 28 Location of measurements in tunnel & soil surface C/O 29 at Stavros extension

Regarding the X-OVER 52 at Agios Antonios extension where the rails were directly fixated in tunnel invert an additional measurement campaign was executed in order to compare the relevant results for both conditions with & without FS implementation. The relevant results [6] are presented hereafter.

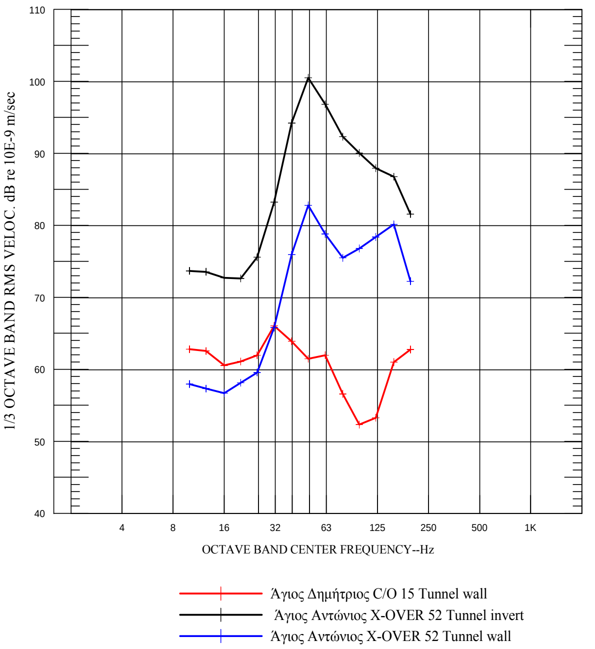


Fig. 31 Comparison of the average vibration velocity levels on NATM II tunnel's wall at C/O 15 (K.P 9.436) in Dafni- Ilioupoli extension vs tunell's wall & invert of NATM II tunnel at X-OVER 52 (K.P. 0.545) in Agios Antonios extension.

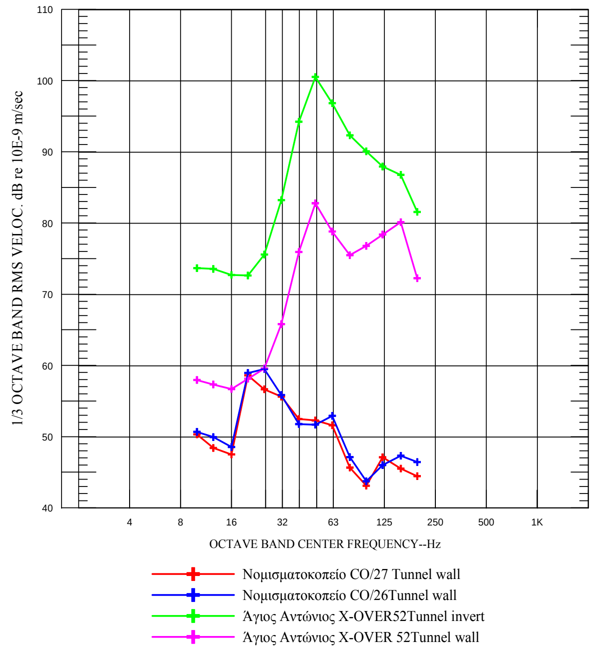


Fig. 33 Comparison of the average vibration velocity levels on TBM tunnel's wall at C/O27 (K.P 14.583) and C/O 26 (K.P 14.512) in Stavros extension vs tunell's wall & invert of NATM II tunnel at X-OVER 52 (K.P.0.545) in Agios Antonios extension.

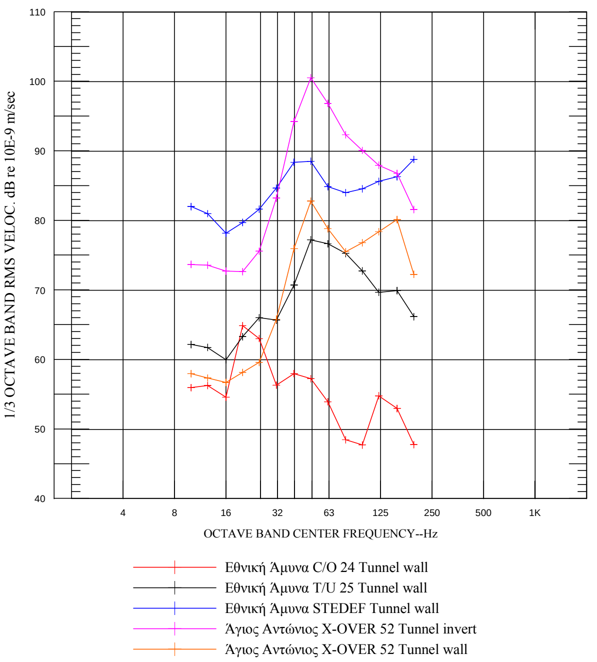


Fig. 32 Comparison of average vibration velocity levels on the NATM III tunnel's wall at C/O 24 (K.P 12.652) and at T/U 25 (K.P 12.701) in Stavros extension vs tunnel's wall and invert for the NATM II tunnel at X-OVER 52 (K.P. 0.545) in Agios Antonios extension.

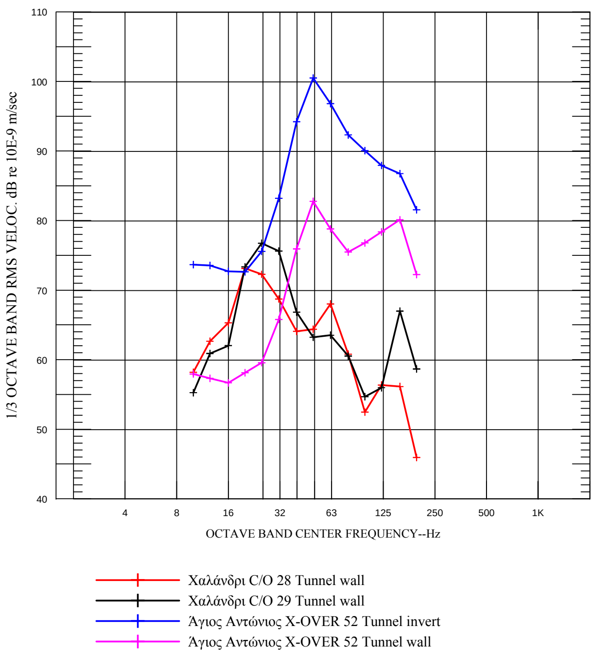
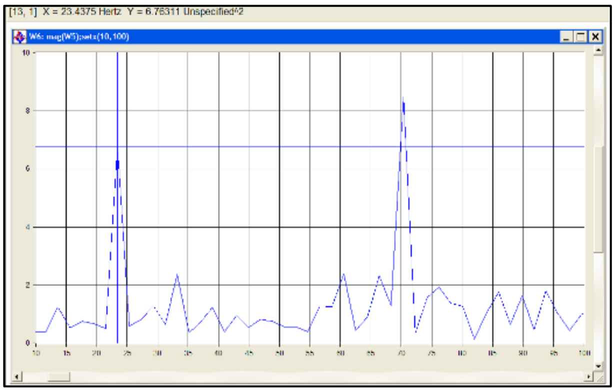
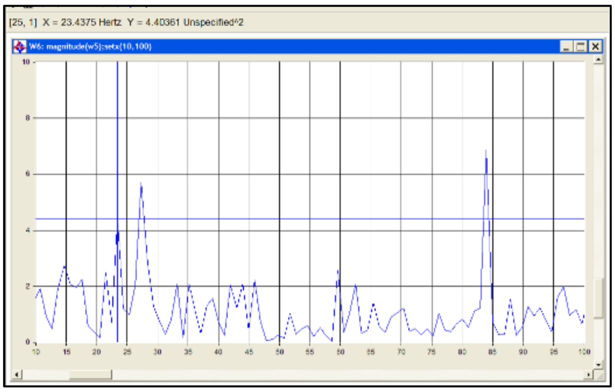


Fig. 34 Comparison of the average vibration velocity levels on TBM tunnel's wall at C/O 28 (K.P 16.293) and C/O 29 (K.P 16.555) in Stavros extension vs tunell's wall & invert of NATM II tunnel at X-OVER 52 (K.P. 0.545) in Agios Antonios extension

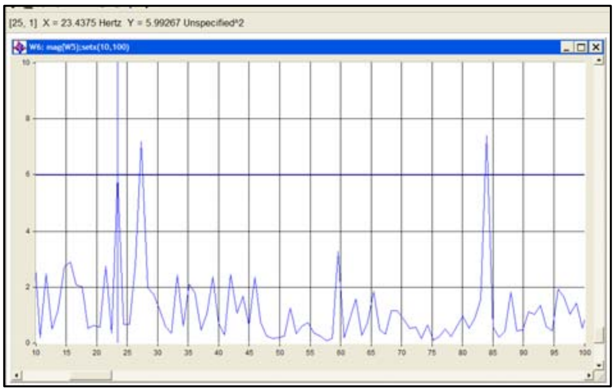
The relevant results [6] regarding the dynamic characteristics of the above measured FS in order to calculate their natural frequency for unloaded system condition using the impact of a PCB hummer and sensors on the slab, and on the tunnel's wall, approx. in the middle of the FS length, are presented hereafter.



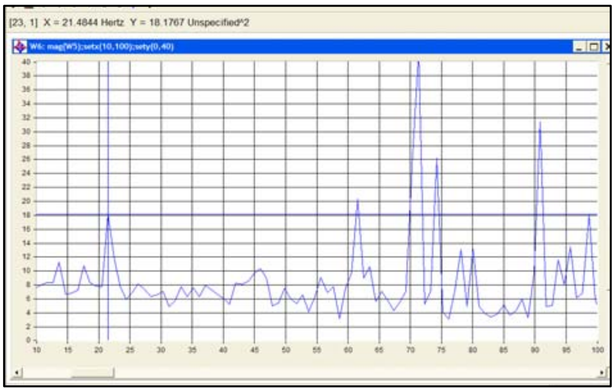
C/O15



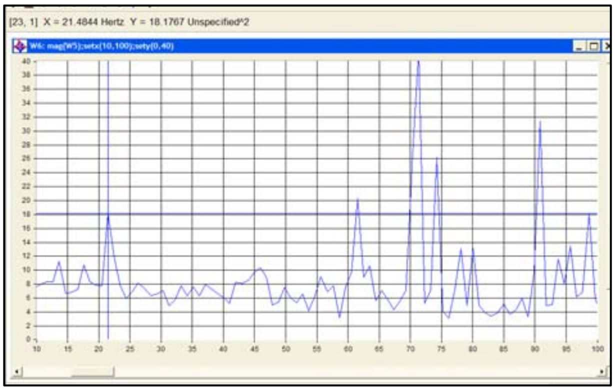
C/O24



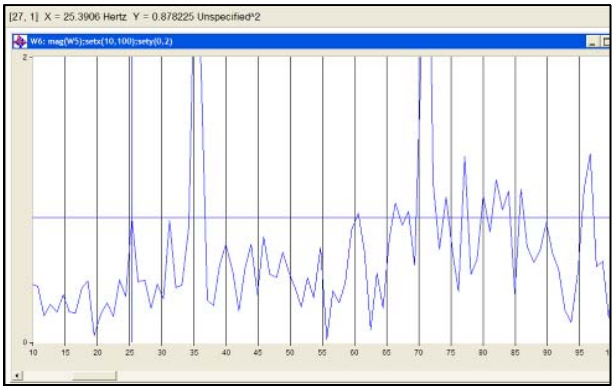
T/U 25



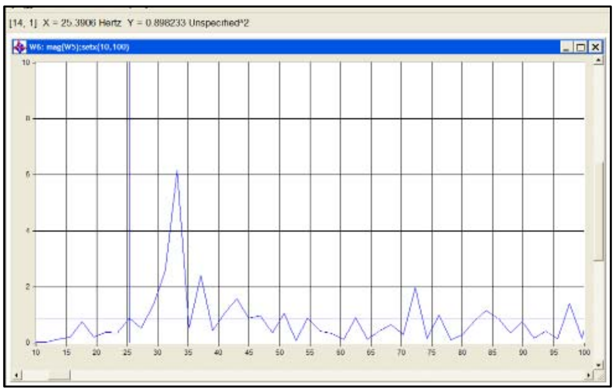
C/O26



C/O27



C/O28



C/O29

Fig. 35 FFT analysis of PCB impact hammer impulse signal measured on the above FS on all TO locations

5 Discussion

In the following table, all relevant measurement's results are presented for all C/O location with FS. According to the above results, it is concluded that all levels of ground borne noise and vibration measured at all buildings, during normal Metro operation, are within the relevant criteria

Table 3
Measurement campaign locations & results

METRO EXTENSION	C/O - T/U	Depth from surface to bottom of tunnel	Horizontal distance to receptor	Radial distance to receptor	TRACK TYPE
ILIOUPOLI	C/O 15	19,44	9,30	21,55	D.F. & F.S.
STAVROS	C/O 24	18,67	19,00	26,64	D.F. & F.S.
	T/U 25	18,63	20,00	27,33	D.F. & F.S.
	C/O 26	24,13	4,70	24,59	D.F. & F.S.
	C/O 27	24,58	0,00	24,58	D.F. & F.S.
	C/O 28	24,21	16,50	29,30	D.F. & F.S.
	C/O 29	24,22	10,65	26,46	D.F. & F.S.
AG. ANTONIOS	X-OVER 52	25,50	0,00	25,50	D.F.

C/O - T/U	Soil surface adjacent to closest building		Tunnel		
	Groundborne noise in dB(A)	Vibration velocity (mm/sec)	Groundborne noise dB(A)	Vibration velocity (mm/sec)	FS Self Frequency (Hz)
C/O 15	**18,0**	**0,00319**	**31,6**	**0,00462**	**23**
C/O 24	**27,2**	**0,00584**	**40,1**	**0,00296**	**23**
T/U 25	**27,6**	**0,00731**	**22,0**	**0,00296**	**23**
C/O 26	**20,7**	**0,02560**	**17,8**	**0,01760**	**21**
C/O 27	**14,9**	**0,00157**	**16,6**	**0,00157**	**21**
C/O 28	**15,5**	**0,00306**	**26,0**	**0,00809**	**25**
C/O 29	**19,9**	**0,00497**	**33,2**	**0,01126**	**25**

* D.F.= direct fixation F.S. floating slab

The maximum level of noise measured on soil surface corresponding to the points adjacent to closest building to X-OVER 52 in Ag. Antonios extension, where the given crossover is directly fixed on tunnel invert, with no FS implementation, The relevant values are by far much higher than all other soil surface measurements even though soil condition in this particular section of the tunnel are quite favorable, regarding considerable diminution of generating vibration at the source (i.e. tunnel invert). Floating slab length is an important parameter that has to be taken into account during design of track work for future extensions, as ground borne noise level at soil surface, in the area of C/O 24, is much higher that values measured at T/U 25 where soil conditions are similar. This result is based on the fact that the ground borne noise level measured both in tunnel and soil surface at C/O 24 is influenced by the adjacent original STEDEF track system, due to limited length which is much less than the full train length. Similar assumptions were made for Acropolis station slab resulting that FS generally needs to be extended at least at a length ≥ to operating train length. All implemented FS were proven to behave practically as modelled and calculated, regarding their dynamic characteristics, and in all cases noise and vibration levels at the above receptors, are far below the relevant criteria, with a maximum measured noise level of being 27,6 dB(A) in Stavros extension including, however, important influences from adjacent STEDEF track work and the existing elevated background noise. Therefore all floating slabs proven very effective in noise and vibration mitigation. Furthermore all measured predominant frequency of all slabs in Ilioupoli and Stavros extensions are within the adopted theoretical values even in cases of considerably reduced slab's thikness introduced because of various elevation limitations of tunnel invert level. Environmental coustic measurements executed on soil surface adjacent to some respective buildings (even during night or early morning hours) at Ilioupoli and Stavros extensions were significantly influenced by rather high levels of environmental background noise due to heavy urban road traffic flows constantly for 24 hours per day.

References:

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[3]TT&E Consultants Ltd - D2S Int.: "NOISE & VIBRATION STUDY FOR FLOATING SLAB IN DIRECT FIXATION TURNOUTS - Case Study: NATM TUNNEL SOIL II - SEGMENT 33 - STAVROS EXTENSION: A Finite Element simulation: Static and dynamic behaviour of turnout - Analysis performed with SYSTUS™", April 2003

[4] Prof. Konstantinos VOGIATZIS, Dr. Patrick 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

[5] TT&E Consultants Ltd - D2S International – ATTEMKAT Ltd: "FS CONCEPTUAL DESIGN (FSCS) AT STAVROS EXTENSION OF ATHENS METRO" - June 2003

[6] TT&E Consultants Ltd. "TRACKWORKS - Noise and vibration measurements", 2004-2005