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

Cet article technique présente le travail effectué pour 4 extensions Metro en Tunnel pour Attiko Metro (Athènes) lignes 2 et 3, soit en construction soit déjà en service: (a) l'extension ligne 2 de Sepolia ç Thyssion, (b) l'extension ligne 2 de Dafni à Ilioupouli (en opération déjà pour JO Athènes 2004),(c) l'extension de la ligne 3 de Ethniki Amyna à Stavros (aussi en opération déjà pour les JO Athènes 2004)et (d) l'extension de la ligne 3 de Monastiraki à Egaleo.
L'étude des vibrations et bruits solidiens dans les bâtiments riverains à la voie, causés par le passage des rames sur les appareils de voie, a comme but de dimensionner les interventions constructives nécessaires dans la voie menant à limiter les vibrations et les bruits solidiens dans les bâtiments riverains en dessous des critères en vigueur à Athènes.
Pour ce faire, les extensions ont été divisées en sections homogènes, soit des sections où les caractéristiques mécaniques et dimensionnelles (tunnel = type de construction, profondeur, sol = couches et caractéristiques mécaniques, etc..) pouvaient être considérées comme constantes, avec un intérêt particulier pour les sections avec appareils de voie en fixation directe.
Cet article décrit l'étude de la solution dalle flottante sous les appareils de voie en différentes variantes : (a) une dalle flottante complète, sous la totalité de la surface de l'appareil de voie, assure une atténuation des vibrations et bruits solidiens de l'ordre de 15 à 16 dB(A) dans les bâtiments riverains en surface et (b) un traitement « dalle flottante » local limité au cœur de l'appareil de voie . Cette dernière variante, bien qu'elle élimine les vibrations causées par le passage sur le cœur, engendre des bruits solidiens non acceptables quand les rames passent sur les partis de l'appareil de voie non isolées.

This paper describes the work performed for 4 metro extensions in tunnels, on lines 2 and 3 of the Athens Metro, either planned and under construction or already in service: (a) extension of line 2 from Sepolia to Thivon, (b) extension of line 2 from Dafni to Ilioupoli (already in operation for the Olympic games Athens 2004), (c) extension of line 3 from Ethniki Amyna to Stavros (already in operation for the Olympic games Athens 2004), extension of line 3 from Monastiraki to Egaleo.
The aim of the ground borne noise and vibration evaluation presented hereafter is to determine the required mitigation measures in order to guarantee, in each turnout location along these extensions, allowable ground borne noise levels in nearby buildings. In order to reach this objective, the extensions were divided into homogeneous sections, i.e. sections along which the tunnel and soil types, depth and distance from nearby buildings can be considered as constant, with particular emphasis on section with turnouts on direct fixation. In this paper the study of the floating slabs under the turnouts is discussed.
A full floating slab solution over the complete length of the turnout ensures a complete ground borne and vibration attenuation with an overall noise level of some 15-16 dB(A) in buildings at soil surface. A limited floating slab solution only at the frog area presents an acceptable noise level with the bogie in the middle of the frog area but is not acceptable since the estimated noise level in buildings at the soil surface is considerably higher than the given criterion when the bogie is passing over the turnout in a section which is outside the limited floating slab

Prof. Constantinos Vogiatzis
University of Thessaly
Department of Civil Engineering
Pedion Areos
G-38821 Volos
Greece
E-mail : tte@tee.gr

Dr. ir.Patrick Vanhonacker
D2S International
J. Vandenbemptlaan 71
B-3001 Heverlee
Belgium
E-mail : patrick.vanhonacker@d2sint.com

Ir.M.Eng.Patrick Carels
CDM SA
Reutenbeek 9
B-3090 Overijse
Belgium
E-mail : patrick.carels@cdm.be

Presentation of the project

This paper describes the work performed for four extensions, on lines 2 and 3 of the Athens Metro, either planned and under construction or already in service:

- extension of line 2 from Sepolia to Thivon
- extension of line 2 from Dafni to Ilioupoli (already in operation for the Olympic games Athens 2004)
- extension of line 3 from Ethniki Amyna to Stavros (already in operation for Athens 2004 Olympics)
- extension of line 3 from Monastiraki to Egaleo

These extensions are presented in the figure 1 next page.

The aim of the ground borne noise and vibration evaluation presented hereafter is to determine the required mitigation measures in order to guarantee, in each turnout location along these extensions, allowable ground borne noise levels in nearby buildings of max. 40dB(A) (general case). In order to reach this objective, the extensions were divided into homogeneous sections, i.e. sections along which the tunnel and soil types, depth and distance from nearby buildings can be considered as constant, with particular emphasis on section with turnouts on direct

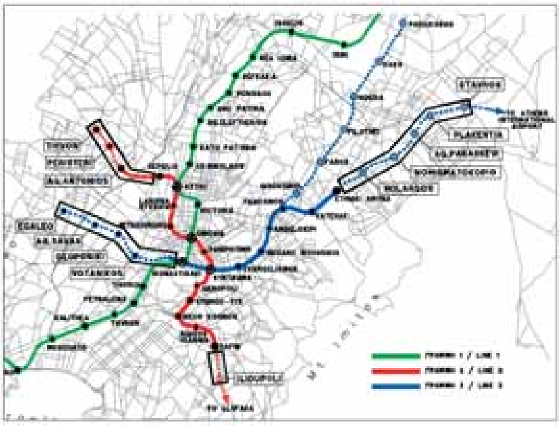

Fig. 1 : Athens Metro extensions

fixation. For each section and each sensitive building, the ground borne noise and vibration levels were numerically predicted.

General technical parameters

The study team of TT&E Consultants (GR) in joint venture with D2S International (B) had to consider for this study (see ref.8.1) a booted twin block sleeper track, with UIC54 rails.

- According to the « Design and performance technical specification for track work », the basic sleeper spacing is 700 mm (tangent track)
- According to the « Detailed final design submission for wheel set – Technical specification 0-G00-RS-825-G-071 A », prepared by Rolling Stock Subgroup AEG for Attiko Metro S.A., an unsprung mass of 1822 kg/axle, has been considered corresponding with the driven wheel set
- The basic turnout conception was a “VAE” design with Rails UIC 54 installed on resilient PUR base plate pads
- Additional track and rolling stock related data are as follows :
- Axle load of vehicle = 14 tons (max.)
- Bogie axle to axle distance 2 m

The goal of the simulation, presented in this paper, is to investigate the static and dynamic behavior of different configurations of a representative Athens Metro turnout (No. 33 located in Stavros Extension), see figure 2. The following configurations were investigated :

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

Furthermore the following material properties are applied:

- for concrete:

Young’s modulus:	= $216^{E}3 N/m^2$
Poisson’s coefficient:	= 0.25
volumic mass :	= 2500 kg/m^3

- for UIC54 rails:

Young’s modulus:	= $21^{E}10$ N/m2
Poisson’s coefficient:	= 0.3
volumic mass :	= 7850 kg/m3
section A:	= 69.34 cm2
bending inertia Iy:	= 2346 cm4

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

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

Tabl. 1 : Dynamic soil modulus/Athens Metro extensions

The turnout No. 33 is placed in a NATM tunnel with soil category 2 and it was considered as the worst case for all turnouts to be studied in the 4 extensions. Soil category 2 is considered with a transfer function as in figure 3 hereafter, based on measurement campaign in the operating lines 2 & 3 of the Athens Metro system (see ref. 8.2)

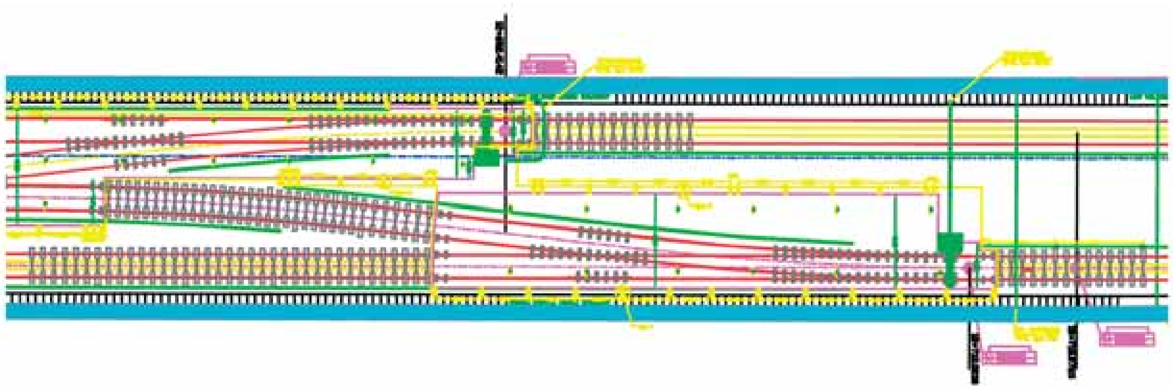

Fig 2. : Athens Metro turnout 33 in Stavros Extension

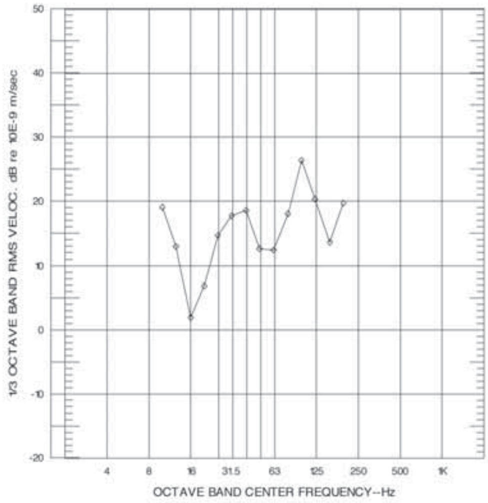

Fig. 3 : Transfer function from tunnel invert to soil surface for soil category 2 (measurement results) and for a specific tunnel depth

Linear dynamic eigen mode analysis of turnouts scenarios

The Mesh model

In order to model and precisely determine the maximum vertical rail and slab deflection during a vehicle passage, a 3D solid finite element model (Static and dynamic behaviour of turnout - Analysis performed with SYSTUS™) is generated using the following type of elements :

- 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.

Figure 4 represents the 3D geometrical model of the NATM tunnel section, rails (turnout), base plates and concrete filling material. 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

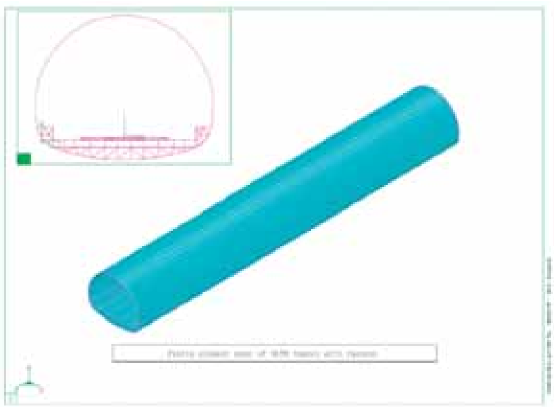

Fig. 4 : 3D model of the NATM tunnel section

resilient base plate pads. The two modelled cases and the obtained deflection curves do correspond with the data provided by the manufacturer. The results of those analyses are presented in following fig. 5 and fig. 6.
Figure 5 : model of an R54-37 base plate and the obtained total vertical displacement for a total vertical rail load of 33 kN.
Figure 6 : model of an R54-39 base plate and the obtained total vertical displacement for a total vertical rail load of 33 kN.

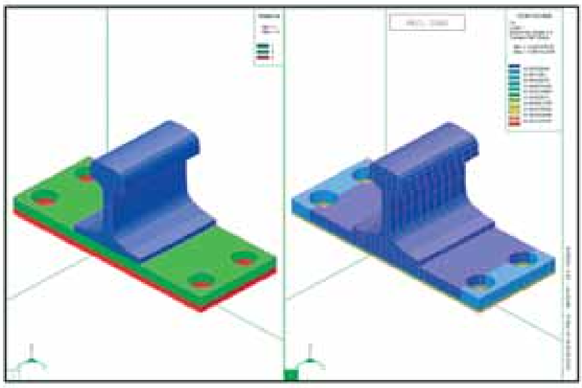

Fig. 5 : Model of an R54-37 base plate

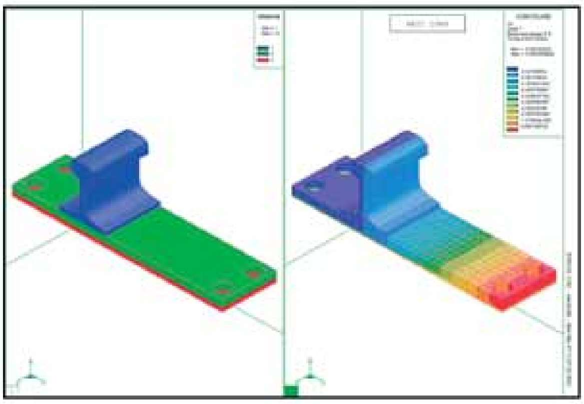

Fig. 6 : Model of an R54-39 base plate

Scenario 1 : NO floating slab

The final model of the tunnel and turnout for scenario 1 consists of :

- 444 elements for the rails and turnout;
- 450 elements for the base plates and resilient base plate pads
- 5 825 elements for the tunnel wall;
- 15 419 elements for the solid concrete parts.
- Seize of the model : 8521 nodes and 22138 elements

Three load cases are considered: each load case corresponds to the position of 1 bogie on the track (on track 1 – on track 2 – on the frog). The static loading is represented by 4 forces on the track positioned at wheel spacing and corresponding to a maximum axle load of 14 tons. The following table (table 2) gives the maximum rail deflections for the considered load cases.

Load case	Maximum vertical rail displacement (mm)	Condition
1	1.08	Bogie on track 1
2	1.04	Bogie on track 2
3	0.70	Bogie on the frog

Tabl. 2. : Max. vertical rail deflections (Scenario 1)

The first vertical bending mode of the loaded track is around 59 Hz. Figure 7 represents the corresponding mode shape (for the case of unsprung mass on the frog).

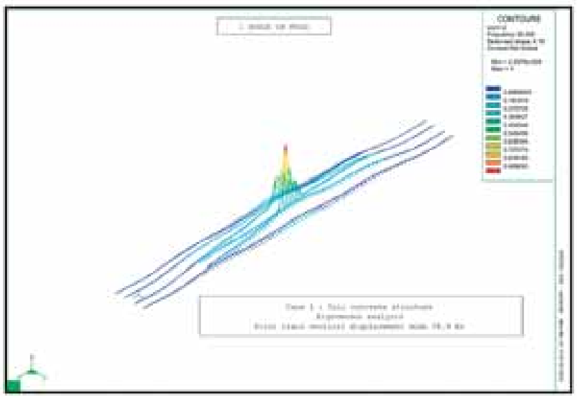

Fig. 7 : Mode shape (unsprung mass on the frog)

Scenario 2 : COMPLETE floating slab

The 3D solid finite element model in this case, is generated using following type of elements:
- 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 slab, the concrete filling and for the antivibration layer.

Figure 8 represents the 3D geometrical model of the NATM tunnel section, rails (turnout), base plates, concrete slab, the proposed anti-vibration layer and concrete filling material.

Fig. 8 : 3D geometrical model of the NATM tunnel with anti-vibration layer and concrete filling material.

The final model of the tunnel and turnout consists of :

- 444 elements for the rails and turnout;
- 450 elements for the base plates and resilient base-plate pads
- 5 825 elements for the tunnel wall;
- 11 333 elements for the solid concrete parts;
- 2 043 elements for the slab;
- 2 043 elements for the anti vibration layer.
- Seize of the model : 8867 nodes and 22138 elements

Again three load cases are considered: each load case corresponds to the position of 1 bogie on the track (on track 1 – on track 2 – on the frog). The static loading is represented by 4 forces at wheel spacing, positioned on the track corresponding to an axle load of 14 tons.

Table 3 gives the maximum deflections for the rails and the slab for each of the considered load cases.

Load case	Maximum vertical displacement (mm)	Location	Condition
1	2.16	rail	Bogie on track 1
	1.30	slab	
2	2.12	rail	Bogie on track 2
	1.30	slab	
3	1.45	rail	Bogie on the frog
	0.85	slab	

Tabl. 3 : Max. vertical deflections (Scenario 2)

The first vertical bending mode of the slab is approx. 17.6 Hz. The corresponding mode shape for the unsprung mass on the frog is represented in figure 9.

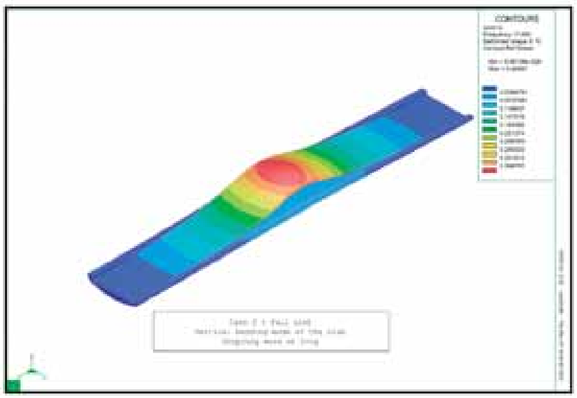

Fig. 9: Mode shapes for the unsprung mass on the frog

Scenario 3 : LIMITED floating slab at frog area

The 3D solid finite element model in this case is generated using the following type of elements :

- 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 slab, the concrete filling and for the antivibration layer

Figure 10 represents the 3D geometrical model of the NATM tunnel section, rails (turnout), base plates, concrete slab, antivibration layer and concrete filling material. The final model of the tunnel and turnout consists of :

- 444 elements for the rails and turnout
- 450 elements for the base plates and resilient base-plate pads
- 5 825 elements for the tunnel wall
- 14 723 elements for the solid concrete parts
- 348 elements for the slab
- 348 elements for the antivibration layer
- size of the model: 8625 nodes and 22138 elements!

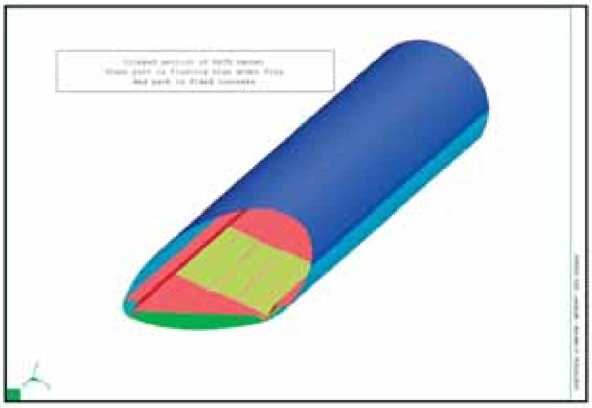

Fig. 10 : 3D geometrical model of the NATM tunnel for scenario 3

Three load cases are also considered: each load case corresponds to the position of 1 bogie on the track (on track 1 – on track 2 – on the frog . The static loading is represented by 4 forces on the track positioned at wheel spacing and corresponding to a maximum axle load of 14 tons.
Table 4 gives the maximum deflections for the rails and the slab separately for the considered load cases.

Load case	Maximum vertical displacement (mm)	Location	Condition
1	2.32	rail	Bogie on track 1
	1.51	slab	
2	2.26	rail	Bogie on track 2
	1.50	slab	
3	1.49	rail	Bogie on the frog
	0.91	slab	

Tabl. 4 : Max. rail deflections (Scenario 3)

The first vertical bending mode of the slab is round 18.7 Hz. The corresponding mode shape for unsprung mass on frog are represented in figure 11.

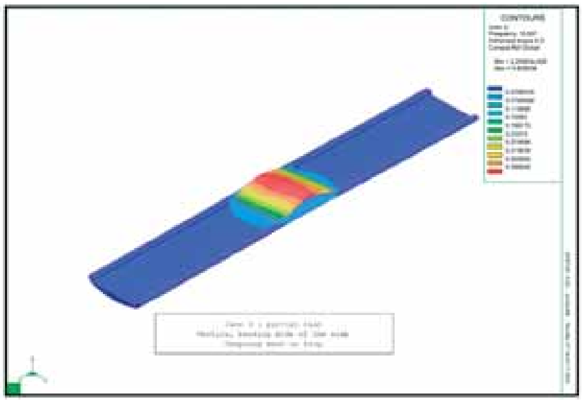

Fig. 11 : Mode shapes for the unsprung mass on the frog

Harmonic response analysis

A linear harmonic response analysis is performed using 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 calculated 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 resilient base-plate pads were used: direct fixation on slab with no elastomers (Scenario 1 – A- rigid)
- A full concrete structure with the resilient base-plate pads between the base plates and the concrete (Scenario 1 – B- full concrete)
- A complete floating slab (length +/- 50 m) covering the total length of the turnout combined with resilient base plate pads (Scenario 2)
- A limited (partial) floating slab in the frog area (length +/- 10 m) combined with resilient base plate pads: with the bogie on the frog area slab (Scenario 3)
- The same limited (partial) floating slab in the frog area (length +/- 10 m) combined with resilient base plate pads: with bogie on turnout next to slab (Scenario 3)

The relevant results are presented in the figure 12 hereafter in a third octave band basis.

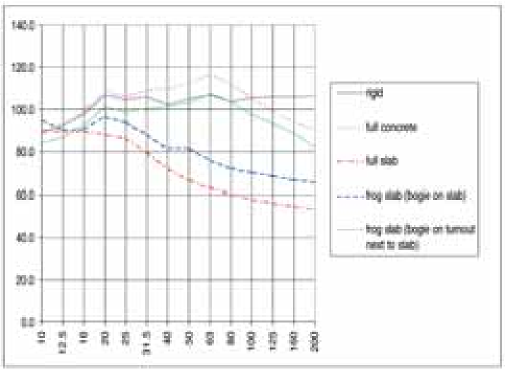

Fig. 12 : 1/3 octave band analysis for all scenarios/ cases : vibration velocity spectrum for point on tunnel invert under the frog (dB ref 10-9 m/s)

Ground-noise predictions in soil surface - conclusions

The total static vertical rail displacement, for the floating slab track, does not exceed 2.16 mm in case of full floating slab or 2.32 mm in case of a 'frog' slab. The total vertical static slab displacement, for the floating slab, does not exceed 1.3 mm in case of full floating slab or 1.5 mm in case of a 'frog' slab. The first eigen frequency of the FST is approximately 17.6 Hz in case of full floating slab or 18.7 Hz in case of a 'frog' slab. The corresponding mode is a global vertical bending movement of the floating slab. The ground borne noise levels on the soil surface are calculated and presented for each case in figure 13. The following is concluded based on these relevant results :

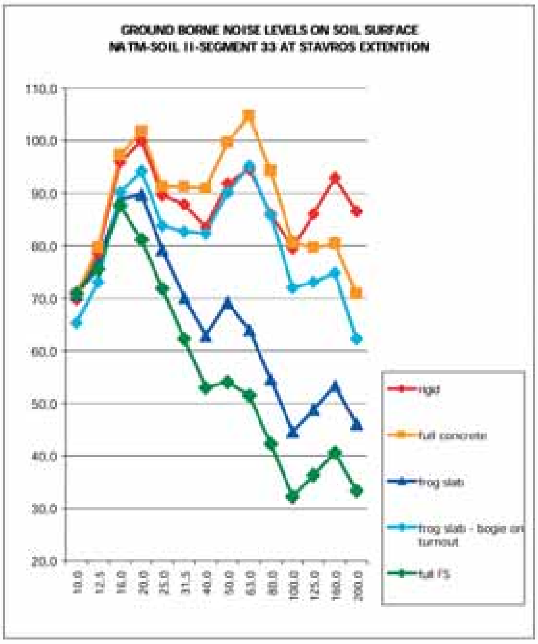

Fig. 13 : Ground borne noise levels for a typical building at the soil surface for all cases

The role of the resilient base plate pads is not important for the noise reduction of the VAE turnout. Compared to a rigid solution, the reduction was estimated at 1,5 dB(A) with a significant reduction in the 100 to 200 Hz. range, but also an important increase in the 25 to 80 Hz range.

Full floating slab 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 slab presents acceptable noise levels with the bogie in the middle of the frog area. However, with the bogie on the turnout on the full concrete area next to the frog slab, the expected groundborne noise level at the soil surface (typical building) is approximately estimated at 49.3 dB(A). This exceeds the criterion by some 9.3 dB(A).

The full floating slab solution for the turnouts area is the best solution. It meets both the environmental criterion (40 dB(A) in the 10 to 200 Hz range) and the VAE requirements for maximum vertical displacements.

- Resilient base plate pads show a non important role in noise reduction for the VAE turnout, estimated approx 1,5 dB(A), with significant reduction in the area of 100 to 200 Hz but with also important amplification in the area of 25-80 Hz compared to a complete rigid solution.

- Full floating slab ensures a complete ground borne and vibration attenuation with an overall groundborne noise level of some 15-16 dB(A) at soil surface (typical building). The limited slab implementation at frog area, even though it presents an acceptable noise level with the bogie in the middle of the frog area, however in the adjacent full concrete area (bogie on turnout next to slab), it leads to a groundborne noise level of 49,3 dB(A).

Full floating slab solution for the turnouts area is the best solution, ensuring both environmental criterion (in this case 40 dB(A) in the range 10-200 Hz) and max. required vertical slab displacement for the turnout according to VAE requirements (see ref. **Erreur! Source du renvoi introuvable.**).

Fst development & implementation

The contractor of the project has awarded the implementation of the FST to CDM (BE). Taking as a basis the FST performance specifications (mechanical characteristics and special construction requirements such as ventilation under the FST, transition stiffness etc.) and the FS conceptual design study (FS with longitudinal resilient strips) carried out by TTE/D2S , CDM has developed an FST system based upon their CDM-ISO-DFSA® technology (see e.g. ref. **Erreur! Source du renvoi introuvable.**).
The CDM proposal (see ref.**Erreur! Source du renvoi introuvable.**) was accepted by Attiko Metro S.A. and placed in all turnouts in the Athens 2004 Olympics Metro extension program (Installation between 08 and 12/2003):

- Typical project data : > 2000m² total surface
- Axle Load : 140 kN
 Gauge : Standard
- Specifications for FST : 330 mm concrete + 25mm formwork + 37mm strip
- Static Bedding Module : k-stat = 10 MN/m³ (acc. tol.: +/- 20%)
- Dynamic Bedding Module : k-dyn = 15 MN/m³ (acc. tol.: +/- 20%)
- CDM Supply : DFSA-MA-M5, COMBISTRIP with a triple layer prepared from CDM-PF (PUR) & CDM-RR (Resin Bonded Rubber)) supplied on a tailor-made lost form-work panels (fibre-cement board). The resin bonded rubber (black colour on pictures) side of the strips (better resistance to water immersion) was designed to be in continuous contact with water and was therefore installed in direct contact with the tunnel invert.

A typical construction drawing is shown in figure 14.

Figure 15 presents the material preparation and figures 16-17 the transport and the FS implementation completed in the tunnel invert at Stavros extension.

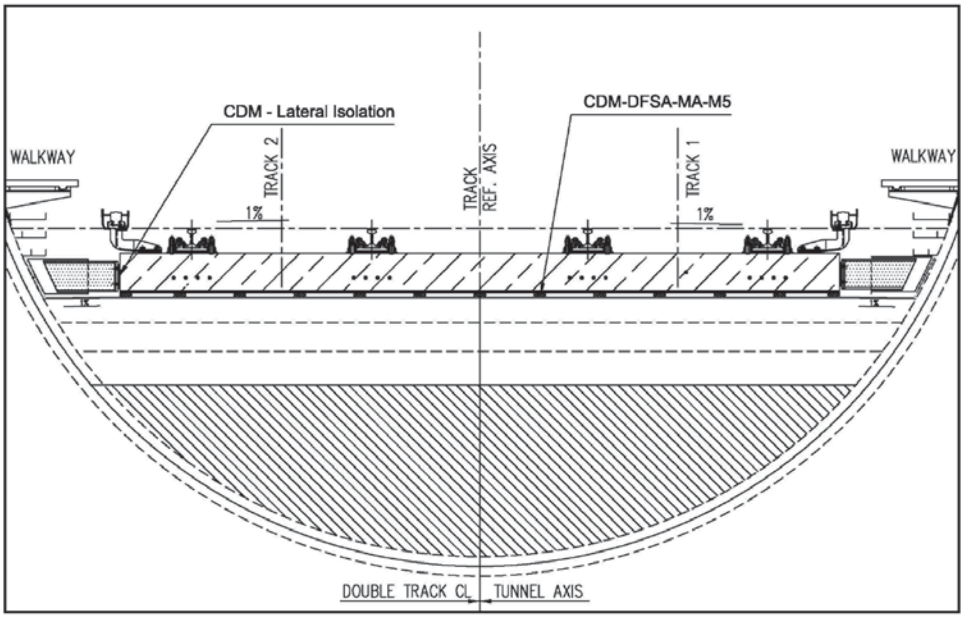

Fig. 14 : Typical construction drawing of CDM-DFSA

Fig. 15 : Mechanical Material Tests (in CDM-lab – k-stat, k-dyn, creep and shear modulus)

Fig. 16 : Fibre-cement boards with CDM-DFSA resilient strips and installation

Fig. 17 : Finished installation of FST

In situ measurements

In October 2004 (approx. 4 months of operation), the FST performance was tested by TTE/D2S (absolute groundborne vibration level measurements in the nearest buildings, FST resonance frequency) for 3 sites:

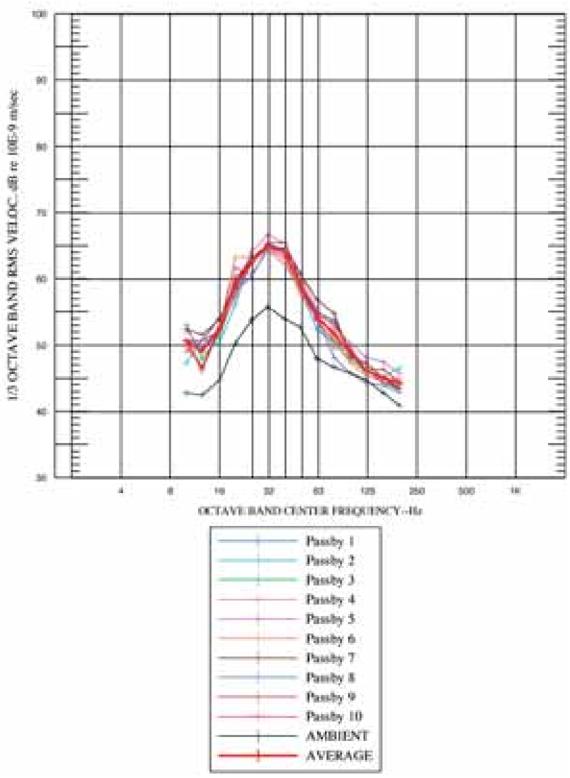

Fig. 18 : Measurements from Agios Demetrios - Ilioupouli (turnout with FST)

- Site 1 : Agios Demetrios - Ilioupouli (turnout with FST - building on top of tunnel/turnout, the most critical case)
- Site 2 : Ethniki Amina – 1st.FST direction Chalandri Station (turnout with FST – building at 11 m. from source)
- Site 3 : Ethniki Amina – direction Chalandri normal track (no FST – only original twin block solution – no turn-out – building at 34 m from source)

For the first site, in a building on top of the tunnel (turnout with FST, see fig. 18), a maximum vibration velocity level of 65 dBV (ref; 10e-9 m/sec) was measured in a frequency range of 40-50 Hz, resulting in approximately 16 dBA inside the building.

Maximum vibration levels of 70 dBV were measured at a frequency of 40 –50 Hz for a building at 11m from the second test site (turnout with FST, see fig. 19), resulting in 28 dBA inside the building.

In a building at 34m from the third site (original twin block solution on tangent track, see fig. 20), the measurements show maximum vibration levels of 72 dBV at 31.5 Hz, resulting in 27 dBA inside the building.

The results show that approximately the same vibration levels are obtained for the different sites. The measurements of the original twin block on tangent track (site 3) have however been taken at 34 m from the source, whereas the measurements of the turnouts on a floating slab (site 1 & 2) were done much closer to the source (on top and at 11m). It is concluded that the FST performs as expected, providing isolation in order to have buildings very near to the source (i.e. turnout) not experience groundborne noise problems.

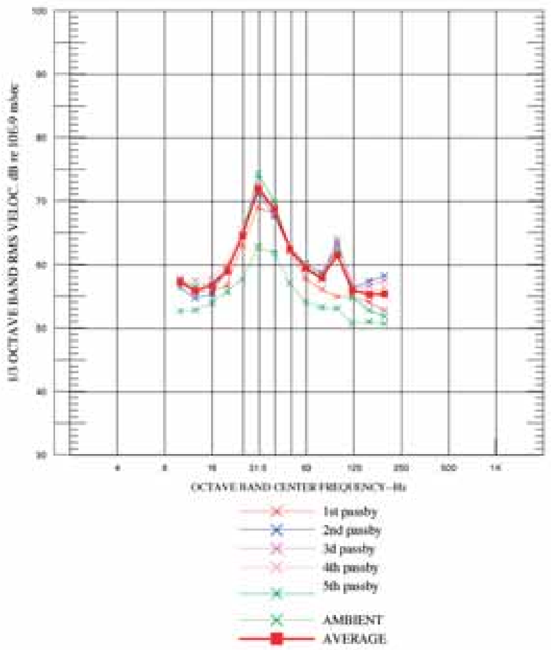

Fig. 20 : Measurements from Ethniki Amina (original twin blocks. Tangent track - building at 34 m)

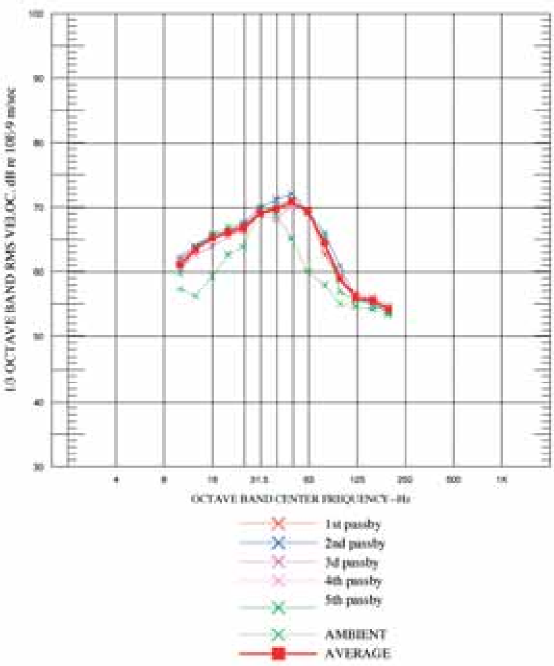

Fig. 19 : Measurements from Ethniki Amina (turnout with FST – building at 11 m. from source)