

# ENVIRONMENTAL VIBRATION MONITORING & ASSESSMENT AT SENSITIVE RECEPTORS DURING METRO CONSTRUCTION IN URBAN CENTRE OF THESSALONIKI, GREECE

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**Abstract:** - The construction of the Thessaloniki Metro integrates state-of-the-art technology and the most demanding standards concerning both quality and operation, rendering it, thus, the most modern Metro System in the whole of Europe and ensuring the protection of the urban environment. The network consists of 2 Depots, 13 modern center platform stations, 9.5 km of Line (with two independent single track tunnels), 18 ultra-automatic and state-of-the-art trains. The elaboration of an extensive Environmental Monitoring Programme as part of the “*Required Pertinent Monitoring Designs-Programmes*” of the project specifications for the “DESIGN, CONSTRUCTION AND COMMISSIONING OF THESSALONIKI METRO” was enforced in order to ensure the protection and minimization of annoyance from worksite operation in the network. For each construction site and in the location of the closest receptors, Vibration Acceleration in time domain ( $\text{m/sec}^2$ ), Vibration velocity ( $\text{mm/sec}$ ) were recorded and then ppv for all recordings was calculated as well as rms weighted acceleration ( $\text{m/sec}^2$ ) and VDV values, following Fourier analysis for the vibration velocity recordings according to DIN 4150 (Part 3). Included in this article are the relevant assessment and evaluation results of this state of the art monitoring program with emphasis on sensitive receptors such as archaeological areas and sensitive land uses (e.g. schools and hospitals..)

**Key-Words:** *Environmental Vibration, Metro, Environmental monitoring, Vibration dose, Transportation vibration*

## 1 Introduction

In September 2003 the decision was made for this specific Project to be constructed by means of National and European Union funds. The construction of the Thessaloniki Metro (fig. 1) integrates state-of-the-art technology and the most demanding standards concerning both quality and operation, rendering it, thus, the most modern Metro System in the whole Europe ensuring protection of the urban environment.



Fig. 1

The basic characteristics of the THESSALONIKI METRO network are the following:

- ✓ a Depot in the Pylea Region (Votsi) covering a surface of 50,000 square meters.
- ✓ 13 modern center platform stations
- ✓ 9.5 km of Line (with two independent single track tunnels) constructed mostly (7.7 km) by means of two Tunnel Boring Machines. The remaining section of the Line will be constructed by the Cut and Cover method
- ✓ 18 ultra-automatic and state-of-the-art trains, fully air-conditioned, which will be run without a train driver, with an attendant aboard the train.
- ✓ platform screen doors, which guarantee greater safety level
- ✓ a Depot in the Pylea Region (Votsi) covering a surface of 50,000 square meters.

As regards the problems, the Project was faced with the task of protecting the city's twenty three centuries of history which made the execution of extensive archaeological excavations imperative and the selection of a design-construction method required a longer time for the projects maturing process to ensure the minimization of environmental effects.

The elaboration of an extensive Environmental Monitoring Programme as part of the “*Required Pertinent Monitoring Designs-Programmes*” of the project specifications for the “DESIGN, CONSTRUCTION AND COMMISSIONING OF THESSALONIKI METRO” was in compliance with the obligation of the Contractor to take all the required measures in order to minimise environmental impacts due to the project according to the approved provisions of the Project's Environmental Impact Assessment Study.

The constructor is obligated to ensure all mitigation measures required in order to minimize environmental impacts according to the approved Environmental Provisions of the Project, JMD 19766/28.7.1993, renewed by the MD EYPE /138853/22.12.2003 and further amended by the MD EYPE/180802/31.12.2004), in relation to the contents of the special report entitled “Environmental Report of Assessment of Variations of Environmental Impacts due to the Updating of the Alignment of Thessaloniki Metro”, that was approved by the relevant MD 182170 from Ministry for the Environment.

The relevant EIA study outlines the activities and methods required for the control of environmental issues related to the construction and commissioning of the Thessaloniki Metro as well as the minimization of environmental impacts deriving from these same issues.

The measures to be taken will aim at minimizing air pollution, noise and vibrations to all receptors, restoring urban greenery and flora following the completion of operations, minimizing intrusion to local residents, maintaining traffic flow and ensuring safety at the areas of performance of works, as well as controlling the individual factors that may have an impact on the environment as well as on human health.

In order to accomplish the above, it was necessary to develop respective environmental policy, to be implemented through the management and organization structures of the Project. Therefore in order to minimize the environmental impacts associated with the processes that will take place during the construction of the project, the following issues needed to be ensured:

- ✓ compliance with all available laws, both general as those of the Hellenic state, as well as specific, as those emanating from local government and all regulations and international standards.
- ✓ cooperation of the project relevant services with the local authorities as well as other organizations related to the environmental sector, so as to jointly formulate rules and practical

guidelines that will assist in the protection of natural resources and the environment in general.

- ✓ reduction of resources consumed for daily requirements
- ✓ reduction of waste generation
- ✓ avoidance of air pollution, water, and ground pollution by ensuring special handling of the generated quantity of materials requiring special management.
- ✓ adoption of technologies, where such are available to fulfil the goals of the project.
- ✓ training of employees so that they may become aware of all environmental impacts that may be caused by the activities in which they are involved, as well as become aware of the JV's environmental policy.

## 2 Managing the acoustic and vibration environment during Metro construction

The adopted maximum permissible limit of emission of **airborne noise** - in the case of a typical Metro construction site – according to the standing environmental provisions is  $L_{eq}(T) \leq 65 \text{ dB(A)}$  **where T=worksite operation..**

Within the frame of the respective General Specifications and Specification for Designs and Performance of Civil Works, for the Project emphasis is also given on the following points:

- ✓ Formation of a database of existing state of airborne, ground borne noise and vibrations
- ✓ Estimate of peak noise emissions from the operation of the construction sites at the boundary closest to the manmade environment under protection
- ✓ Evaluation of potential occurrences of noise exceeding the limit – based on the standing legislation – under “WITH Works” conditions (construction site operating status), and then
- ✓ Implementation of suitable soundproofing devices and management measures

Particularly with reference to environmental vibrations, the relevant EIA of the project gives the proposed peak vibration velocity limits based on the CHABA Report [1],[2] as well as per Athens Metro EIA's provisions :

Table 1

|                                   | PROPOSED VIBRATION LIMITS DURING METRO CONSTRUCTION |                                    |
|-----------------------------------|-----------------------------------------------------|------------------------------------|
|                                   | Weighted acceleration                               | Equivalent velocity <sup>(1)</sup> |
| OTHER BUILDINGS                   | 0,5 to 1 m/sec <sup>2</sup>                         | 13 to 28 mm/sec                    |
| SPECIAL USE MONUMENTS & BUILDINGS | 0,05 m/sec <sup>2</sup>                             | 1,3 mm/sec                         |
| SPECIAL USE MONUMENTS & BUILDINGS | 0,05 m/sec <sup>2</sup>                             | 1,3 mm/sec                         |

<sup>(1)</sup> For frequencies >10 Hz: velocity in mm/sec = 28.4 \* acceleration ( m/sec<sup>2</sup>)

In particular, is noted, that for the protection of museum exhibits and archaeological monuments in the recent extensions of the Athens Metro the limit of 0.2 mm/sec which has also been adopted which is significantly lower and therefore stricter than the corresponding limits of DIN 4150 (Part 3) [3], where the peak vibration velocity values for buildings being particularly sensitive to vibrations, for the foundation and the overlying floors, are as follows:

- ✓ Foundation: for frequencies < 10Hz at 3 mm/sec
- ✓ Overlying floors: for all frequencies 8 mm/sec

Furthermore for increased protection, it was taken into account that the most adverse adoption of vibration criterion (protection of archaeological site of Kerameikos and the Museum, in the case of the underground crossing of the Athens Metro extensions) is the ppv(z) value of 0.16 mm/s on the archaeological findings at the surface of the archaeological site and the frequency range of 1-150 Hz [1], whereas it is noted that the value of 0.08 – 0.1 mm/s ppv is a magnitude that is actually found at the threshold of vibration perceptivity by humans, namely a limit that is significantly lower than the typical vibration levels generated by human steps inside a building.

According to the above, for Thessaloniki Metro the following were introduced [4]:

- ✓ Implementation of a complete monthly noise programme per operation surface construction site with the corresponding submission of monthly reports
- ✓ Implementation of a complete monthly programme of vibrations with the respective submission of monthly reports, both for the total number of operating construction sites, as well as for selected locations along the alignment (during the tunnel mining operations) namely at the interior of sensitive uses and archaeological/

listed monuments and buildings, that will be identified within the frame of the above special study and will be approved by the agency.

- ✓ Implementation of the updated peak vibration limits (ppv in mm/sec). The particle velocity is recorded in three directions, X, Y & Z that are perpendicular to each other and the velocity vector is calculated with the following formula

$$PPV = \sqrt{\{(PVX)^2 + (PVY)^2 + (PVZ)^2\}}$$

- ✓ Estimate of the Vibration Dose Value (vdv) with the use of recorded values of rms acceleration within the frame of the above monthly vibration recording programme.

In brief, it is stated that the main methods of reduction of vibrations during the construction of fixed track projects are concentrated in the following major entities:

- ✓ organisation of a construction site work schedule that will aim at: minimising the use of the most adverse equipment for the vibration environment and at a lighter (reduction of intensity and frequency of shocks) and less intensive schedule of utilisation of boring machines, hammers, drills and vibration generating equipment in general,
- ✓ notification of residents of the area concerning the anticipated disturbance,
- ✓ avoidance of similar works during the night and potentially during the noon hours (especially during the summer period) and finally, when so required,

Table2

| Building/ Structure/ Area                                                                                                                                 | Peak Particle Velocity (ppv in mm/sec)                                                                                       |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>✓ Monument</li> <li>✓ Archaeological findings</li> <li>✓ Exhibits in Archaeological sites or Museums</li> </ul>    | <b>0.2 mm/sec</b><br>(at the base of the monument, ancient exhibit, at the floor or the wall of the building, as applicable) |
| <ul style="list-style-type: none"> <li>✓ Special requirement buildings : (Hospitals, Theatres, Schools, Libraries, Concert halls, Auditoriums)</li> </ul> | <b>0.5 mm/sec</b>                                                                                                            |
| <ul style="list-style-type: none"> <li>✓ Other buildings : (Classification according to ISO 4866)</li> </ul>                                              | <b>Based on DIN 4150 (Part 3)</b>                                                                                            |

The compliance with the above criteria & limits imposes the implementation of a special monitoring programme during construction.

### 3 The Environmental Vibration Monitoring Programme during Thessaloniki Metro construction

The vibration monitoring programme will provide all the information and measures required which the Contractor will take for each one of the construction sites in order to minimise nuisance and potential damages due to the operations and the performance of works. According to the above analysis, the implementation of a complete monthly programme of vibrations with the respective submission of monthly reports is required to effectively meet the environmental requirements, for the total number of operating construction sites, to the interior of adjacent sensitive uses and archaeological/ listed monuments and buildings that will be identified within the frame of the above special study and approved by the agency. The environmental vibration monitoring programme is implemented as follows:

- ✓ on a monthly basis for one location of the receptor closest to each operating construction site, with recording of the peak particle velocity (ppv) and simultaneous recording of rms acceleration for the calculation of the Vibration Dose Value (vdv) and their evaluation according to the relevant British Standard BS6472:1992 [5]
- ✓ once to the interior of the closest – adjacent to the alignment – sensitive uses and archaeological/ listed monuments and buildings during the performance of tunnel mining operations.
- ✓ during the performance of operations in the immediate vicinity of archaeological monuments, recording – throughout the period of performance of operations – of vibration velocity at the base of the section of the monument closest to the operation site. In case of surface operating construction sites, the nearest sensitive receptor will be selected.
- ✓ the source of vibrations during construction was in the closest location towards the receptor as described above.

The implementation of the above special vibration monitoring programme during the period of construction will ensure the following:

1. Simultaneous recordings at the source (vibrator machinery - worst case scenario i.e. JCB hammer in max operation) and the closest receptor, in real time conditions
2. The measurements was executed with the use of suitable high sensitivity accelerometers WILCOXON (100V/g), in directions X, Y & Z

with amplifiers. The sensors will operate in the frequency range of 0-450 Hz.

3. All recordings were in the area from DC έως 100 Hz )
4. Digitization of recordings by using an “anti-aliasing” at 100 Hz. with sampling of 1000 Hz
5. The signals from the amplifiers were recorded at a multi-channel digital recorder.
6. The real time analysis of the signals will allow the automatic calculation of ppv & rms in total for the three directions. The vibration velocity is calculated from the acceleration, taking into account the following formula correlating velocity and acceleration to the centre frequency of each 1/3 of the octave :

$$\text{Velocity ref } 10^{-9} \text{ m/sec} = \text{Acceleration ref } 10^{-6} \text{ g} + 64 - 20 \log f$$

where f is the centre frequency of each 1/3 of the octave. This formula is based on the transformation of acceleration in dB re  $10^{-6}$  g to velocity in dB re  $10^{-9}$  m/sec.

7. The respective technical monthly reports for each construction site will also be submitted, along with individual reports per use along the alignment.
8. In case values exceeding the limits are recorded, measures will be taken to reduce the intensity of construction activity or change the method of construction at the specific location.

For each construction worksite and in the location of the closest receptors the following data were recorded and analysed:

- ✓ Vibration Acceleration in time domain (m/sec<sup>2</sup>)
- ✓ Vibration velocity (mm/sec)
- ✓ Calculation of ppv (mm/sec) for all recordings
- ✓ Calculation of the rms weighted acceleration (m/sec<sup>2</sup>) and of the VDV values (according to BS6472:1992)
- ✓ Fourier analysis for the vibration velocity recordings according to DIN 4150 (Part 3)

Environmental vibration measurements were conducted from 2008 to 2010 in the following worksites & corresponding sensitive receptions:

Table 3

| No | Worksite       | Receptor - Land use             |
|----|----------------|---------------------------------|
| 1  | DIMOKRATIAS    | HOTEL VERGINA                   |
| 2  | AGHIA SOFIA    | RESIDENTIAL                     |
| 3  | UNIVERSITY     | CAMPUS                          |
| 4  | ANALIPSI       | HOSPITAL                        |
| 5  | EFKLIDIS       | RESIDENTIAL                     |
| 6  | FLEMING        | RESIDENTIAL                     |
| 7  | NEW RR STATION | SCHOOL                          |
| 8  | VENIZELOU      | HAMZA BEY*                      |
| 9  | SINTRIVANI     | CHILDREN's FOUNDATION & LIBRARY |

\* The Hamza Bey mosque , also known as Alkazar after the cinema in its pillared courtyard, was one of the first mosques built in Thessaloniki after the fall of Constantinople, and one of the few examples of early Ottoman architecture in the Balkans. Marble columns and Early Christian capitals were embedded in walls or painted over, while the floor was raised for the cinema. For four centuries, the faithful thronged beneath the grand dome of Hamza Bey Mosque at the junction of Venizelou and Egnatia, the two roads that linked the port with the northern gate of the walled city of Thessaloniki. For the past 80 years it was concealed behind the windows of stores, mainly shoe stores, which had distorted its architecture. The Hamza Bey Mosque Complex in Thessaloniki is undergoing restoration work. The Mosque had sustained damage from a number of earthquakes and possibly fire [6].



Fig. 2: Hamza Bey mosque interior

### 3 RESULTS

The relevant recordings and evaluation for both vibration source (JCB hammer or other) & receptors with photographic coverage of all locations are presented below.

The global comparative results, are presented in Table 4 below :

#### 1. DIMOKRATIAS-HOTEL VERGINA

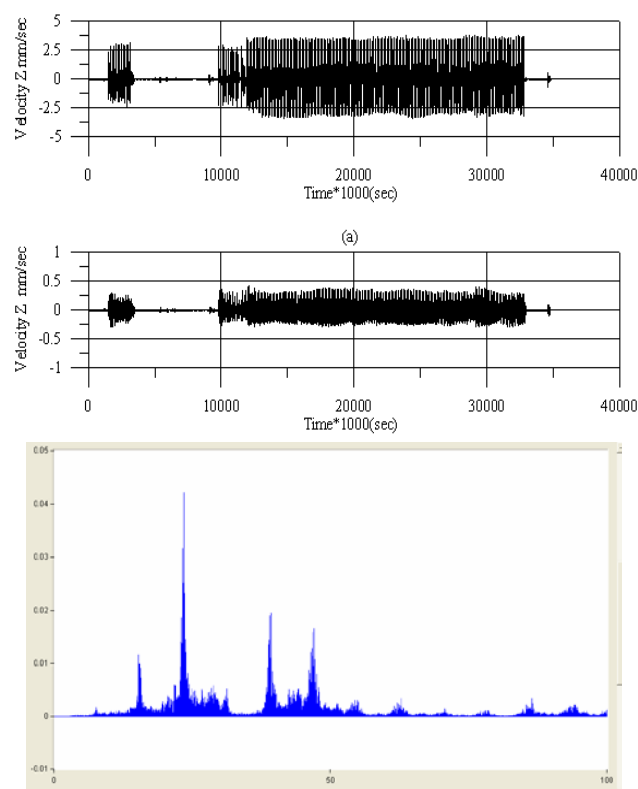


Fig. 3: Vibration Velocity :Time domain & FFT analysis - Dimokratias worksite



## 2. AGHIA SOFIA -RESIDENTIAL

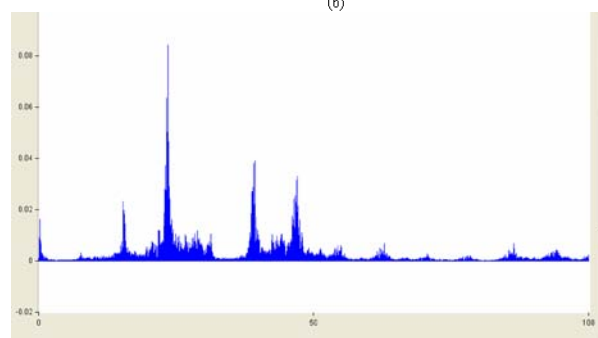
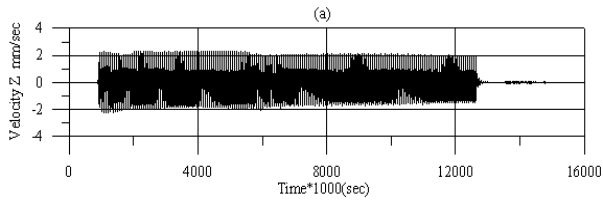
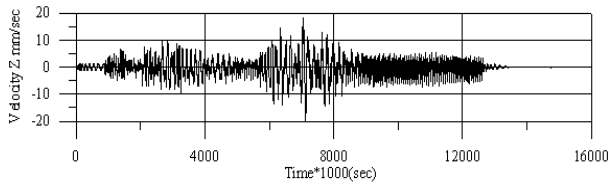


Fig.4: Vibration Velocity: Time domain & FFT analysis - Aghia Sofia worksite

## 3. UNIVERSITY-CAMPUS

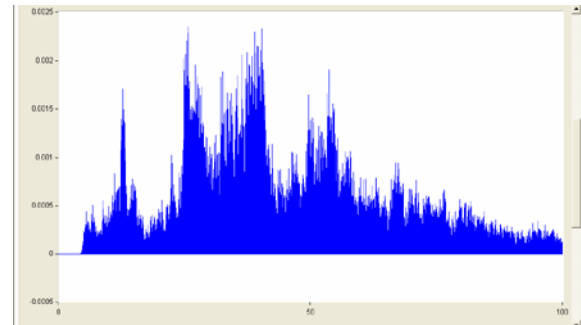
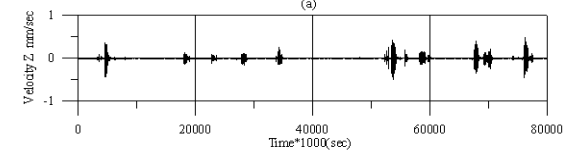
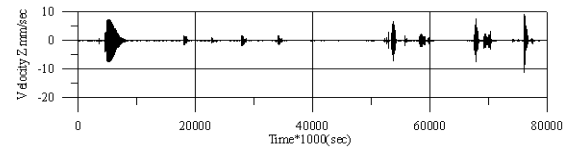


Fig. 5: Vibration Velocity: Time domain & FFT analysis - University worksite

## 4. ANALIPSI-HOSPITAL

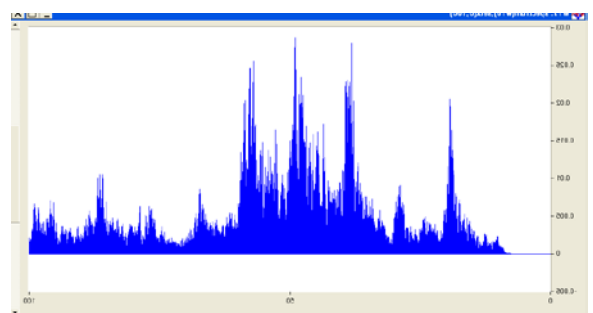
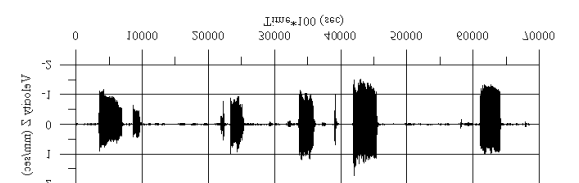
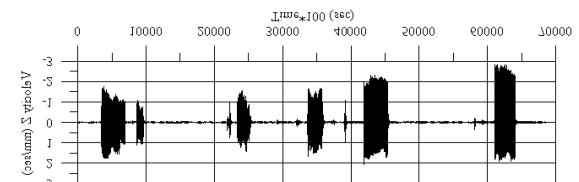


Fig. 6: Vibration Velocity: Time domain & FFT analysis - Analipsi worksite

### 5. EFKLIDIS-RESIDENTIAL

(Use of both JBC & Pilling Cast in place equipments)

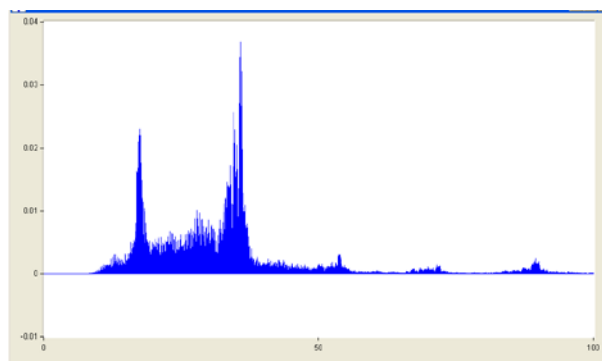
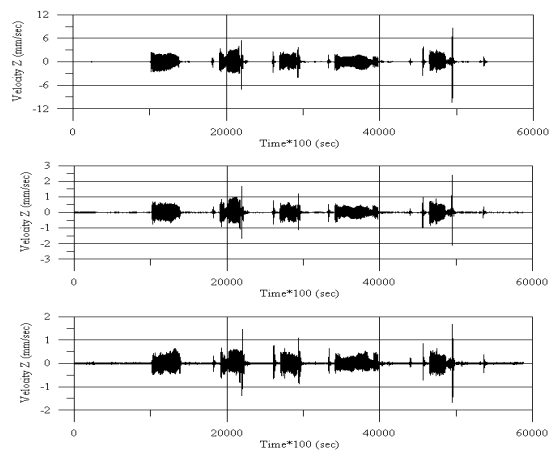


Fig.7: Vibration Velocity: Time domain & FFT analysis - EFKLIDIS worksite

### 6. FLEMNG-RESIDENTIAL

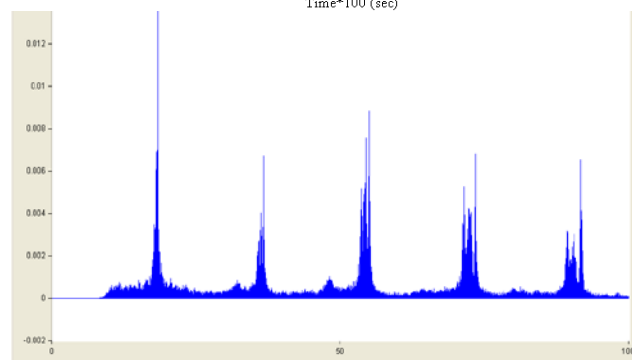
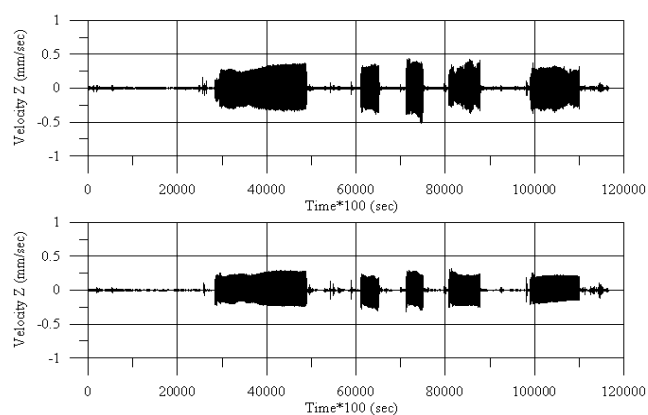


Fig. 8. Vibration Velocity: Time domain & FFT analysis - Fleming worksite

### 7. NEW RR STATION-SCHOOL



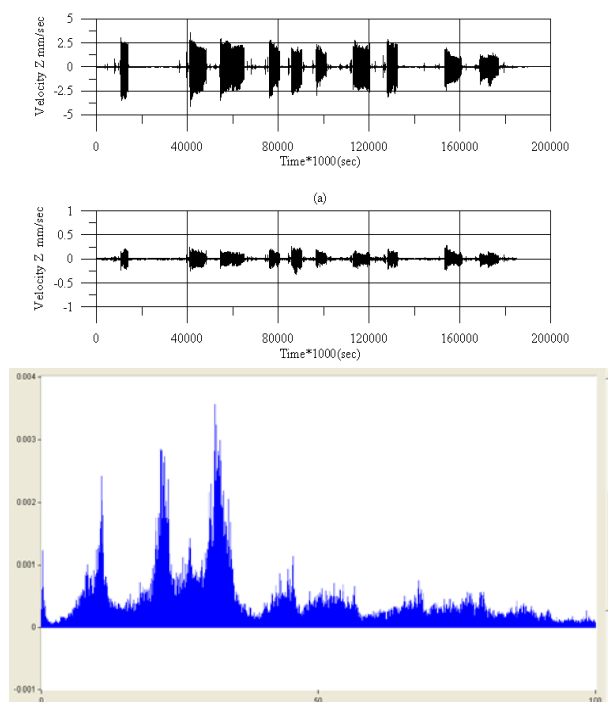


Fig. 9: Vibration Velocity: Time domain & FFT analysis - New RR Station worksite

#### 8. VENIZELOU - HAMZA BEY

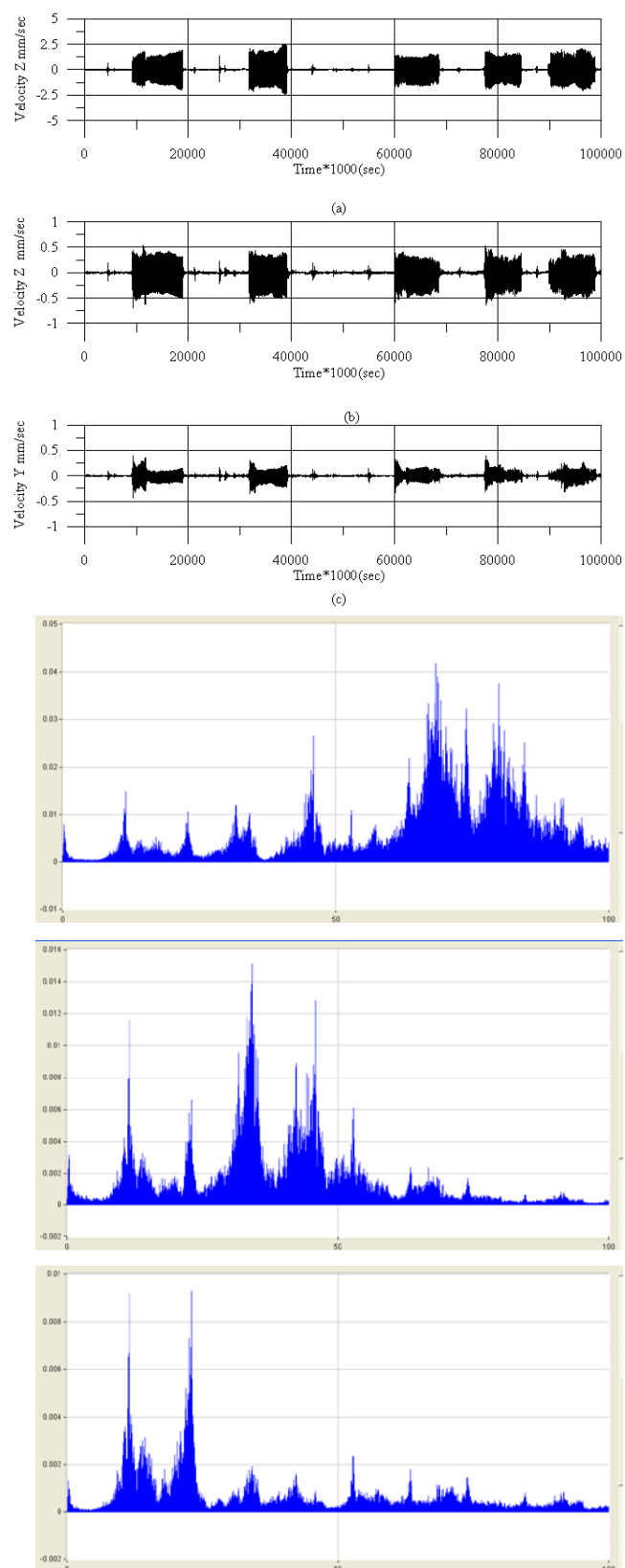


Fig.10: Vibration Velocity: Time domain & FFT analysis - New RR Station worksite at the entrance of the building, in the base of an ancient pillar and on the ground floor in the middle of the ??what?



## 9. SINTRIVANI - CHILDREN's FOUNDATION & LIBRARY

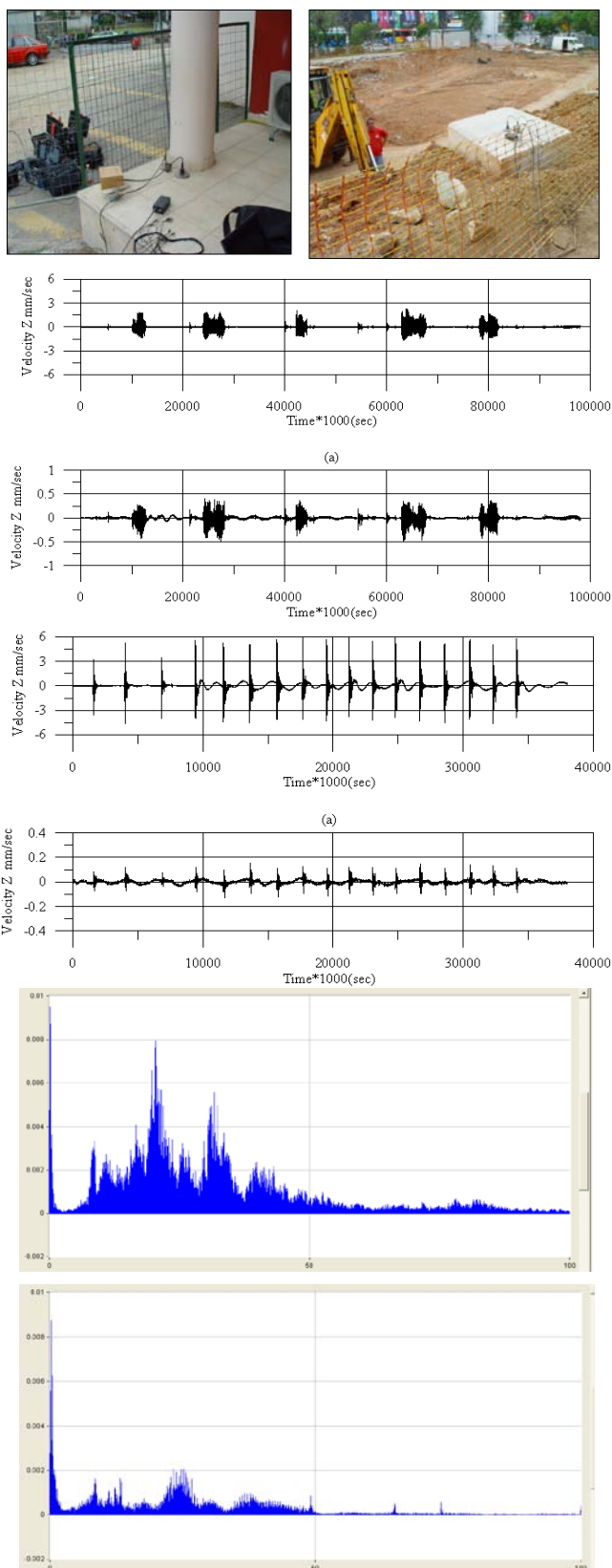


Fig. 11: Vibration Velocity: Time domain & FFT analysis - Sintrivani Station worksite at the children's foundation entrance & the Library

Table 4

| No | Receptor - Land use     | Max.PPV mm/sec | Rms weighted acceleration (mm/sec <sup>2</sup> ) | VDV * |
|----|-------------------------|----------------|--------------------------------------------------|-------|
| 1  | HOTEL VERGINA           | 0,440          | 2,400                                            | low   |
| 2  | RESIDENTIAL             | 2,340          | 5,100                                            | low   |
| 3  | CAMPUS                  | 0,490          | 0,850                                            | low   |
| 4  | HOSPITAL                | 1,740**        | 2,850                                            | low   |
| 5  | RESIDENTIAL             | 2,400***       | 2,250                                            | low   |
| 6  | RESIDENTIAL             | 0,310          | 0,410                                            | low   |
| 7  | SCHOOL                  | 0,313          | 0,916                                            | low   |
| 8  | HAMZA BEY marble pillar | <b>0,685</b>   | 2,528                                            | low   |
|    | HAMZA BEY floor         | <b>0,435</b>   | 2,171                                            | low   |
| 9  | CHILDREN's FOUNDATION   | 0,479          | 1,345                                            | low   |
|    | LIBRARY                 | 0,155          | 0,362                                            | low   |

\* Vibration Dose Value according the BS6472:1992 - criterion2/4 - probability of adverse comment

\*\* Important walking people near the sensors

\*\*\* Only for LCB equipment - Pilling cast in place operation were within criterion.

## 7 Conclusion

In each case of sensitive receptors as described above, the effort was based on taking the most accurate readings through a comprehensive monitoring program in order to assess the possible need of appropriate mitigation measures for the reduction of vibration levels within permissible limits, and with the simultaneous monitoring of harmful factors on a regular basis and the use of appropriate measurement equipment. All sorts of surface operations generating noise during legally defined quiet hours need to be restricted particularly in the case of the Hamza Bey protected building. In brief:

- ✓ interruption of the operation of construction sites during quiet hours was investigated at residential areas, under the condition that the smooth flow of construction of the project is not impeded.
- ✓ however, the use of noisy equipment does need to be avoided during quiet hours (e.g. drills, air compressors, pile driving equipment).
- ✓ prior to the use of particularly noisy/vibrating equipment, the residents of the area involved will be notified with reference to the potential nuisance, during the night and potentially during noon hours (particularly during the summer period).
- ✓ prior to the start of operations on the main underground project, an investigation of the

necessity for the implementation of technical works for counteracting vibration during the period of construction to avoid acoustic environment degradation was executed.

- ✓ as far as the need to implement vibration reduction measures is concerned, again particularly in the case of the Hamza Bey building, during the construction period emphasis was placed on the organisation of a work programme at the construction site which focused on minimising the use of the most adverse equipment for the vibration environment and at using a lighter (reduction of intensity and frequency of blows) less intensive schedule of use of drilling machinery, hammers, drills and other equipment that may generate vibrations.

#### References:

- [1] Von Gierke, H.E., Guidelines for Preparing Environmental Impact Statements on Noise, Committee on Hearing, Bioacoustics, and Biomechanics Assembly for Behavioral and Social Sciences (*CHABA*), *Working Group 69*, For : *National Research Council*, NTIS AD A044384, 1977.
- [2] Ass. Prof. K. Vogiatzis & Ass. Prof H. Mouzakis Criteria for vibration from railway & light rail transportation projects construction for the protection of buildings and the avoidance of annoyance *ΕΠΙΣΤΗΜΟΝΙΚΟ ΚΤΙΠΙΟ, Β/1999*, pp. 57-59
- [3] Structural Vibration in Buildings, Effects on Structures, DIN 4150: Parts 1-3 : 1986.
- [4] Report 1G00CO020R904A : Special study for noise & vibration control during construction - N&V Monitoring program , Project : CON-06/004 DESIGN, CONSTRUCTION AND COMMISSIONING OF THESSALONIKI METRO, 2006
- [5] Evaluation of human exposure to vibration in buildings (1Hz to 80 Hz), British Standard 6472 : 1992
- [6] <http://archive.ekathimerini.com/4dcgi/news/content.asp?aid%3D85094>