Proceedings of Meetings on Acoustics

Volume 21, 2014 http://acousticalsociety.org/

167th Meeting of the Acoustical Society of America
Providence, Rhode Island
5 - 9 May 2014

Session 3aSAb: Structural Acoustics and Vibration

3aSAb9. Prediction and assessment of environmental vibrations from railway operations on Marmaray

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Marmaray project involves upgrading of commuter lines on both sides of Bosphorus with an uninterrupted, modern, high-capacity commuter rail system. The line totals approximately 76 km including an immersed tunnel under Bosphorus. In this study prediction and assessment of environmental vibration levels due to railway traffic along 20-km portion between Gebze and Pendik on the Asian side are presented. Experimentally obtained existing soil-structure coupling and structural amplification factors for the whole line are applied to the theoretically calculated vibration levels for use in assessment studies. Vibration mitigation measures are devised with respect to Turkish Environmental Noise Regulation and criteria by the Federal Transit Administration.

Published by the Acoustical Society of America through the American Institute of Physics

©2014 Acoustical Society of America [DOI: 10.1121/1.4884780]
Received 30 May 2014; published 11 Jun 2014

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INTRODUCTION

Marmaray project involves upgrading of commuter lines on both sides of Bosphorus strait with an uninterrupted, modern, high-capacity commuter rail system. The line totals approximately 76 km including an immersed tunnel under Bosphorus(Figure 1). Railway tracks in both sides of Bosphorus will be connected to each other through a railway tunnel connection under the Istanbul Strait. The line goes underground at Yedikule, continues through the Yenikapı and Sirkeci new underground stations, passes under the Istanbul Strait, connects to the Üsküdar new underground station and emerges at Sögütlüçesme. The main structures and systems; include the immersed tube tunnel, bored tunnels, cut-and-cover tunnels, at - grade structures, three new underground stations, 37 surface stations (renovation and upgrading), operations control centre, maintenance facilities, upgrading of existing tracks including a new third track on ground, completely new electrical and mechanical systems and procurement of modern railway vehicles.

Figure 1. Marmaray Map [1]

In this study prediction and assessment of environmental vibration levels due to railway traffic along 20-km portion between Gebze and Pendik on the Asian side are presented. In the 20-km portion analyzed, there are two commuter lines (T1 and T2) and an intercity line (T3). The intercity line which serves high speed trains terminates in Pendik.

VIBRATION ASSESSMENT CRITERIA

In the analyses, two assessment criteria are applied: Turkish Environmental Noise Regulation (TENR) and Federal Transit Administration (FTA) criteria [2-3]. TENR first enforced in 2005. It has been revised twice since then. The latest revision appeared in June 2010. The vibration measures introduced in 2005 remained unchanged through the revisions. In TENR, vibration criteria are specified for residential and office uses, and other land uses are not covered. The usual practice in the projects in Turkey is to employ Turkish version of ISO 2631-2 standard unless otherwise specified. As FTA has been spelled out in the contract documents of the Marmaray project, FTA criteria are used for land uses other than residential and office uses. In Figure 2, the vibration criteria by TENR and FTA are compared.

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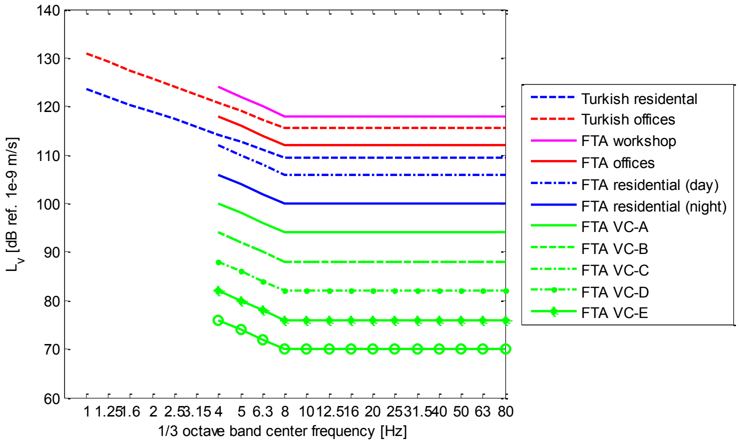

Figure 2: Comparison of assessment criteria

PREDICTION METHODOLOGY

A prediction method for ground vibration generated by surface railway traffic developed by the Dynamics Group of the Institute of Sound and Vibration Research (ISVR), at University of Southampton [4-7] has been utilized to calculate vibration levels along the tracks on Marmaray.

The dynamics of the layered ground is modeled using dynamic flexibility matrices. These matrices are obtained using Fourier transformations. The ground structure has a half space or a rigid foundation at the bottom. A total of n parallel layers of different material overlie the bottom layer, which is numbered as layer $(n+1)$. The material constants are elastic modulus, E_j, Poisson ration, ν_j, density, ρ_j and loss factor , η_j, for the j^{th} layer. For the half space the material constants are E_{n+1}, ν_{n+1}, ρ_{n+1} and η_{n+1}. The dynamic flexibility matrix of layer l_R to layer l_P can be written as:

$$[Q(x,y)]=\begin{bmatrix} Q_{11}(x,y) & Q_{12}(x,y) & Q_{13}(x,y) \\ Q_{21}(x,y) & Q_{22}(x,y) & Q_{23}(x,y) \\ Q_{31}(x,y) & Q_{32}(x,y) & Q_{33}(x,y) \end{bmatrix} \tag{1}$$

The components of this matrix show the response on the top surface the layer l_R to unit harmonic loading on the point $P(0,0)$ on the top surface of the layer l_P. The components of the matrix are complex and they are called displacement Green's functions.

Fourier transformed displacement and stress vectors for the top $\{\tilde{S}\}_{j0}$ and bottom $\{\tilde{S}\}_{j1}$ surfaces of the j^{th} layer are:

$$\{\tilde{S}\}_{j0}=\begin{Bmatrix} \{\tilde{u}\}_{j0} \\ \{\tilde{\tau}\}_{j0} \end{Bmatrix} \tag{2}$$

$$\{\tilde{S}\}_{j1}=\begin{Bmatrix} \{\tilde{u}\}_{j1} \\ \{\tilde{\tau}\}_{j1} \end{Bmatrix} \tag{3}$$

The relationship between these displacement and stress vectors is obtained from the Fourier transformed Lamé equation for the j^{th} layer.

$$\{\tilde{S}\}_{j1}=e^{\alpha_{j1}h_j}[A]_{j1}[A]_{j0}^{-1}\{\tilde{S}\}_{j0} \tag{4}$$

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h_j is the depth of the layer. A_{j0} and A_{j1} are 6 by 6 matrices obtained using the parameters of the ground layer.

For the non-rigid half space, the displacement and stress vectors can be written:

$$\{\tilde{u}\}_{n+1,0} = [R][S]^{-1}\{\tilde{\tau}\}_{n+1,0} \tag{5}$$

with the matrices $[R]$ and $[S]$ obtained using the parameters of half space.

The Fourier transformed dynamic flexibility matrix of layer l_R to layer l_P can be written:

$$\left[\tilde{Q}(\beta,\gamma)\right] = [G]_{11}\left([R][S]^{-1}[T]_{21} - [T]_{11}\right)^{-1}\left([F]_{12} - [R][S]^{-1}[F]_{22}\right) \qquad \text{for } l_R = l_P \tag{6}$$

where $[T]$, $[F]$ are transformation matrices obtained using $[A]$ matrices.

The equations of motion for the rail-sleeper-ground system can be written as:

$$\begin{bmatrix} EI\beta^4 - \omega^2 m_R + k_P & -k_P & 0 \\ -k_P & k_P + k_B - \omega^2(m_S + m_B/3) & -(k_B + \omega^2 m_B/6) \\ 0 & -(k_B + \omega^2 m_B/6) & (k_B - \omega^2 m_B/3) \end{bmatrix} \begin{Bmatrix} \overline{w}_1(\beta) \\ \overline{w}_2(\beta) \\ \overline{w}_3(\beta) \end{Bmatrix} = \begin{Bmatrix} P_0 \\ 0 \\ -\overline{F}_3(\beta) \end{Bmatrix} \tag{7}$$

The displacement and loading at the contact point between the ballast and the ground is related by the equations:

$$\overline{w}_3(\beta) = \overline{H}(\beta)\overline{F}_3(\beta) \tag{8}$$

$$\overline{H}(\beta) = -\frac{1}{\pi}\int_0^\infty Q_{33}(\beta,\gamma)\frac{\sin \gamma b}{\gamma b}\,d\gamma \tag{9}$$

The details of the formulation can be found in [4-7]. The displacement response can be calculated from these formulations. The vibration velocity can then be obtained from the displacement response.

The assumptions made in the modeling process are outlined as:

1. The soil is modeled as layered media with a dynamic stiffness as developed in [4-7].
2. The ballast is modeled with its equivalent mass and stiffness parameters. The sub ballast and subgrade are modeled as layers above the soil layers.
3. Sleepers are considered as masses with under sleeper pads resting on the ballast layer.
4. The rail is modeled as a beam resting on resilient rail pads mounted on sleepers.
5. Rail irregularity serving as the main excitation on the system is described by average rail conditions in [8-9].
6. The car and the bogie are represented by a 1/8 car model [10].

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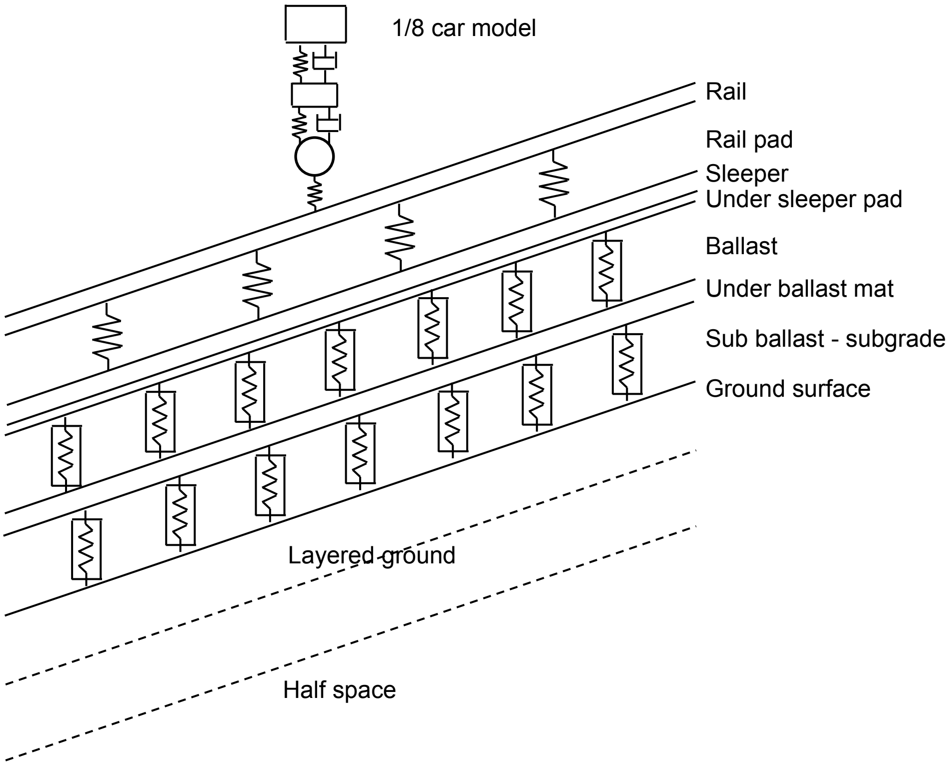

Figure 3. Physical model of the system

The procedural steps in the prediction of ground borne vibration are summarized as:

1. Vibration velocity at the track platform due to a set of system and geological parameters for a specified car speed is calculated.
2. This velocity is used to calculate the vibration velocity on the site of interest by considering propagation on the ground surface by

$$v(d) \propto v_t e^{-\frac{\omega \eta d}{2c}} \tag{10}$$

   where v_t is the vibration velocity under the track platform, ω is the frequency, d is the distance from the track, η is the soil loss factor, c is the surface wave propagation speed.
3. Vibration velocity at the building is predicted by introducing “Soil-Structure Coupling and Structural Amplification” obtained from previous measurements (Figure 4) [11].
4. Assessment is carried with respect Turkish Environmental Noise Regulation and FTA criteria.
5. For sections with turnouts, a 10 dB increase is applied to the predicted vibration velocity levels.

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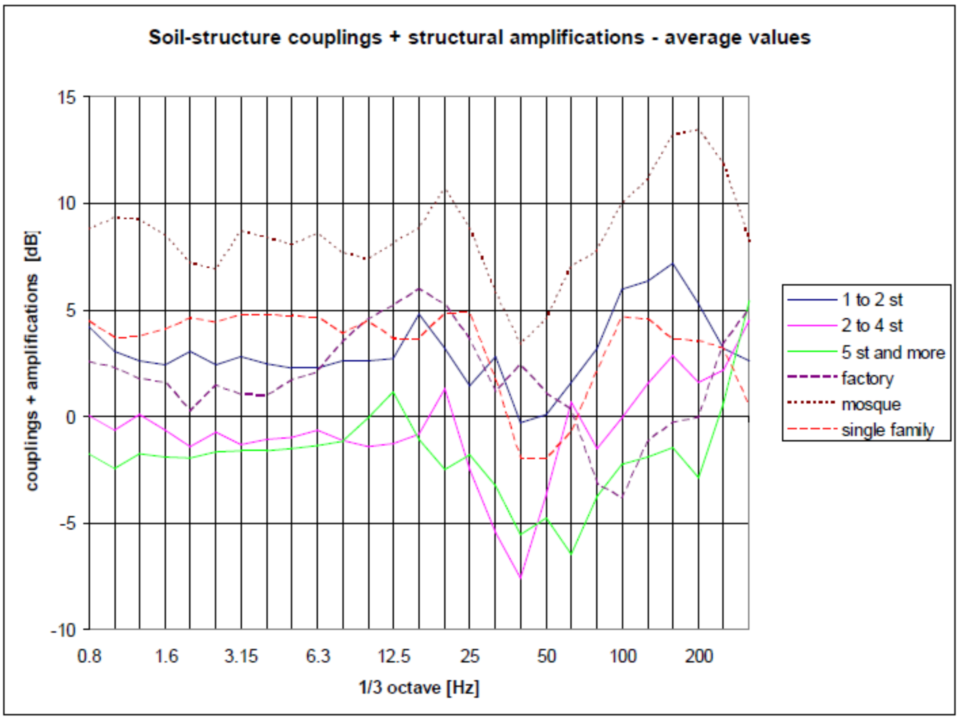

Figure 4. Soil-structure couplings and structural amplifications for Marmaray

SYSTEM PARAMETERS

Ground types that are present along the railway line are given in Table 1. The parameters used in the vibration analysis are given in Table 2. Geological parameters for ground types are obtained through geological surveys. Car parameters are assigned from technical documents supplied by manufacturers as well as track parameters. All these parameters serve as inputs into the prediction scheme.

Table 1. Ground types along the railway line

MG	Made ground. Blocks, concrete, asphalt of anthropogenic origin.
Qal	Alluvial deposits, sand, silt, clay, pebbles. Quaternary.
Toma	Sand, silts, clays, pebbles. Plio-quaternary.
TQK	Sand, silts, clays, pebbles. Pliocene.
Tomk	Sand, silts, clays, pebbles. Oligocene.
IRa	Igneous rocks: Andesites and "Granites"
IRd	Igneous rocks: Dolerites
Ct	Sandstones, siltstones, mudstones. Trakya formation. Carboniferous
Dk	Sandstones, mudstones, limestones, greywackes. Kartal formation. Devonian.
Sd	Limestones, greywackes, mudstones, shales. Siluro - Devonian

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Table 2. System parameters

Track structure		1/8 vehicle model (CR)	
$EI_R=6.28\times10^6$ Pa m^4	$k_{usp}=140\times10^6$ N/m^3	$m_c=5707$ kg	$k_1=1.4\times10^6$ N/m
$m_R=60.21$ kg/m	$k_{usp}=90\times10^6$ N/m^3	$m_b=1014$ kg	$k_2=0.59\times10^6$ N/m
$k_P=1.36\times10^8$ N/m	$\eta_{usp}=0.18$	$m_w=410$ kg	$c_1=8.7\times10^3$ Ns/m
$\eta_P=0.174$	$k_{ubm}=140\times10^6$ N/m^3		$c_2=21\times10^3$ Ns/m
$k_B=5.63\times10^8$ N/m^2	$k_{ubm}=90\times10^6$ N/m^3	1/8 vehicle model (IC)	
$\eta_B=1$	$\eta_{ubm}=0.18$	$m_c=6919$ kg	$k_1=8.75\times10^5$ N/m
$m_B=741$ kg/m	$b_1=1.3$ m	$m_b=2273$ kg	$k_2=3.04\times10^5$ N/m
$m_S=222.2$ kg/m	$L_{w1}=2.2$ m	$m_w=742$ kg	$c_1=8.7\times10^3$ Ns/m
	$L_{w2}=5.1$ m		$c_2=21\times10^3$ Ns/m

EI_R: bending rigidity of rail	η_{ubm}: loss factor of under ballast mat
m_R: mass per unit length of rail	b_1: contact width of the track and the ground
k_P: stiffness of rail pad	L_{w1}: distance between wheels on the same bogie
η_P: loss factor of rail pad	L_{w2}: distance between the nearest wheels of two successive cars
k_B: stiffness of ballast	m_c: 1/8 vehicle mass
η_B: loss factor of ballast	m_b: bogie mass
m_B: mass per unit length of ballast	m_w: wheel mass
m_S: mass per unit length of sleeper	k_1: primary vertical stiffness of the vehicle
k_{usp}: stiffness of under sleeper pad	c_1: primary damping coefficient of the vehicle
η_{usp}: loss factor of under sleeper pad	k_2: secondary vertical stiffness of the vehicle
k_{ubm}: stiffness of under ballast mat	c_2: secondary damping coefficient of the vehicle

RESULTS

In the analysis, it is presumed that ground borne vibrations due to railway operations in MARMARAY originate from rail irregularities. It should be pointed out that results presented below stand for average rail conditions. Sample results of analyses are demonstrated.

Sample Results for Section 159-1 (40+300-40+325):

In this section, there are factory buildings on the north side of the railway, and there are 1-2 storey and factory buildings on the south side of the railway. There are no 2-4 storey, 5+ storey, cultural, hospital, school and mosque buildings in this section. There are no turnouts in this section.

Table 3. Parameters of Section 159-1

Section [m]	40+300	40+325
Train line and speed [km/h]	CR T1-T2	47
Train line and speed [km/h]	CR T3	100
Soil layers [m]	MG	4.5
	Tqk	2.5

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	DK	Half space
Under sleeper pad dynamic stiffness [MN/m^3]		140
Under ballast mat dynamic stiffness [MN/m^3]		140

Table 4. Vibration assessment for section track T1

Track	T1			
Building type	Position	No mitigation	USP	UBM
factory	north	violated	violated	complied
1-2 storey	south	complied	complied	complied
factory	south	complied	complied	complied
overall		violated	violated	complied

The results of the vibration assessment show that vibration mitigation is necessary in line T1. The vibration criteria will be satisfied with the application of under ballast mat.

Table 5. Vibration assessment for the section track T2

Track	T2			
Building type	Position	No mitigation	USP	UBM
factory	north	complied	complied	complied
1-2 storey	south	complied	complied	complied
factory	south	complied	complied	complied
overall		complied	complied	complied

The results of the vibration assessment show that vibration mitigation is not necessary in line T2.

Table 6. Vibration assessment for the section track T3

Track	T3			
Building type	Position	No mitigation	USP	UBM
factory	north	complied	complied	complied
1-2 storey	south	violated	complied	complied
factory	south	complied	complied	complied
overall		violated	complied	complied

The results of the vibration assessment show that vibration mitigation is necessary in line T3. The vibration criteria will be satisfied with the application of either under sleeper pad or under ballast mat.

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Table 7. Vibration assessment for factory building on the North Side

Building type	factory	
Distance [m]	T1	2
Distance [m]	T2	8
Distance [m]	T3	12

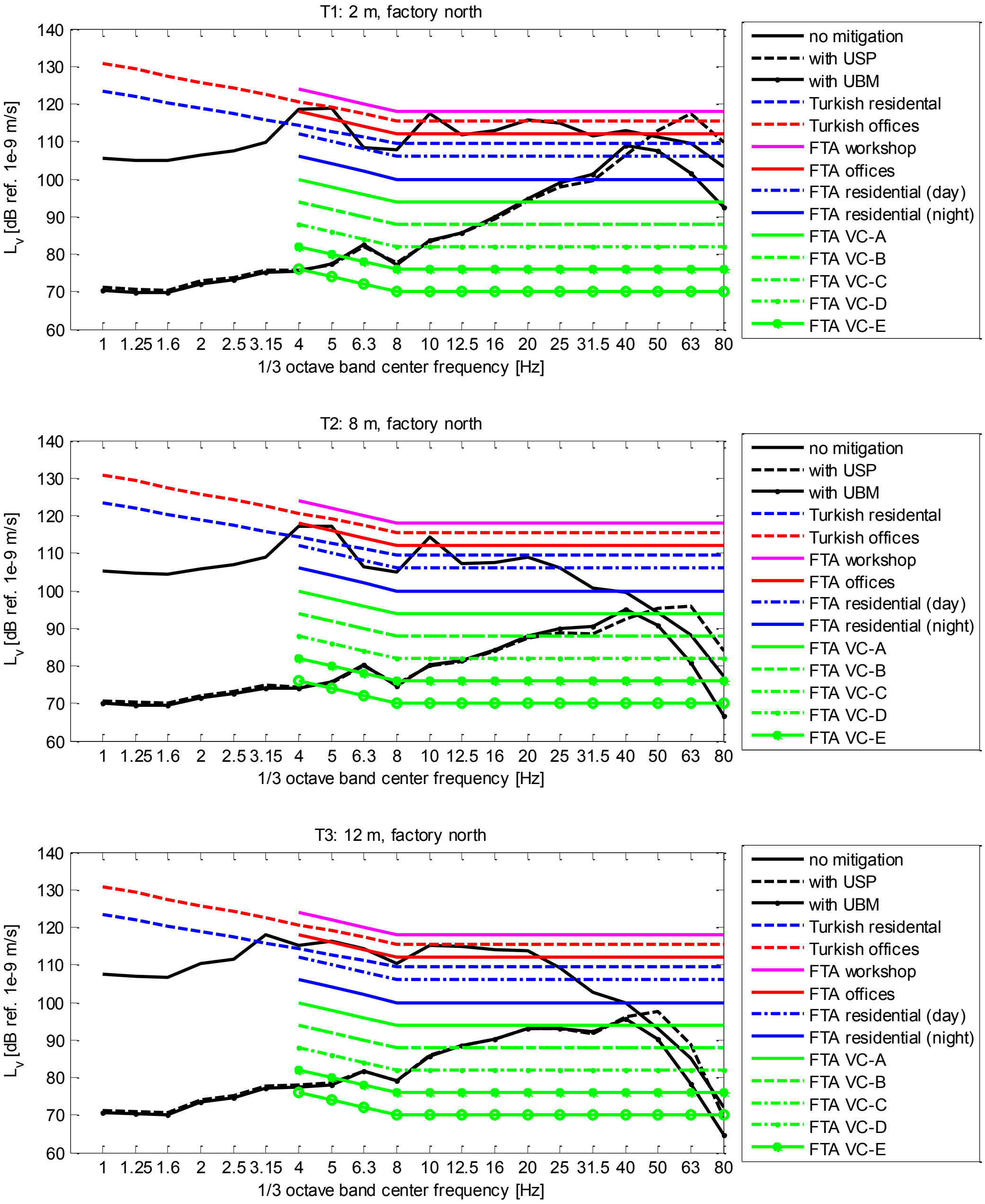

Figure 5. Vibration assessment for factory building on the North Side

Overall Results of Vibration Analyses:

Predictions of environmental vibrations generated by railroad traffic on three tracks along 20 km line in 200 sections were performed. Assessments were carried by comparisons with the relevant criteria. Necessary mitigation actions were proposed. Overall evaluations are outlined in tables 8-10.

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Table 8. Number of sections for mitigation applications on track T1

Mitigation	Number of section with 100 m length each	Number of sections with 25 m length each
No need for mitigation	104	25
USP140	77	24
USP90	-	9
USP60	-	1
USP50	-	2
UBM140	-	9
UBM90	-	6

Table 9. Number of sections for mitigation applications on track T2

Mitigation	Number of section with 100 m length each	Number of sections with 25 m length each
No need for mitigation	110	12
USP140	71	64

Table 10. Number of sections for mitigation applications on track T3

Mitigation	Number of section with 100 m length each	Number of sections with 25 m length each
No need for mitigation	82	13
USP140	97	24
USP90	2	24
UBM140	-	10
UBM90	-	5

CONCLUSION

In the analysis, it is presumed that ground borne vibrations due to railway operations in MARMARAY originate from rail irregularities. In other words the main excitation mechanism is due to rail corrugation. It should be pointed out that results obtained stand for average rail conditions.

For each of the 200 sections from 24+500 to 44+500, vibration assessment is performed in three different tracks. The length of each of the 200 sections is 100 m. For 19 sections, the analysis is performed in detail for smaller sections with length 25 m. A global summary of results is presented in Tables 8 to 10. For the sections where the application of either the under sleeper pad or the under ballast mat complies with both TENR and FTA criteria, under sleeper pad is preferred over the under ballast mat alternative in the specification due to its ease of application.

ACKNOWLEDGEMENTS

TARU ENGINEERING of Ankara, Turkey is gratefully acknowledged for the financial support.

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