SUTIP2/C/QCBS/08-2015

Development of a bridge and tunnel laboratory at the Georgian Technical University

ADDITIONAL ASSIGNEMENT 2: A ROUND OF MODELING OF ROAD AND NOISE BARRIER CONSTRUCTION-RELATED VIBRATION IMPACT ON 9 RESIDENTIAL BUILDINGS IN PHONICALA

DRC – Diagnostic Research Company
Via Montesicuro, 60131, Ancona, Italy

Summary

Introduction

This report refers to the study carried out to estimate and evaluate the vibrations generated by the construction of the new highway and noise mitigation structures, as well as vibrations generated during operation of the highway.

This report supplements the earlier report Ambient vibration survey and dynamic identification of residential buildings Phonichala, Tbilisi - submitted on April 20,2017 that measured the natural frequencies of the 9 buildings in the Ponichala district Tbilisi. The scope of the **additional assignment 2** includes the study of two sources of vibration:

- **vibrations caused by construction works of new road and noise mitigation structures; and**
- **vibrations generated by the operation of the new road;**

The report evaluates the effects of vibrations induced by machineries used in construction of the road during and operating activities on the buildings and voluntary annexes which are potentially more exposed; the level of vibrations generated by the transit of vehicles during the operational phase of the road is also estimated; and the effects of vibration induced by the construction of noise mitigation measures.

The investigated structures are located in Phonichala distric, Tblilisi (Figures 1 and 2. “Location of buildings”).

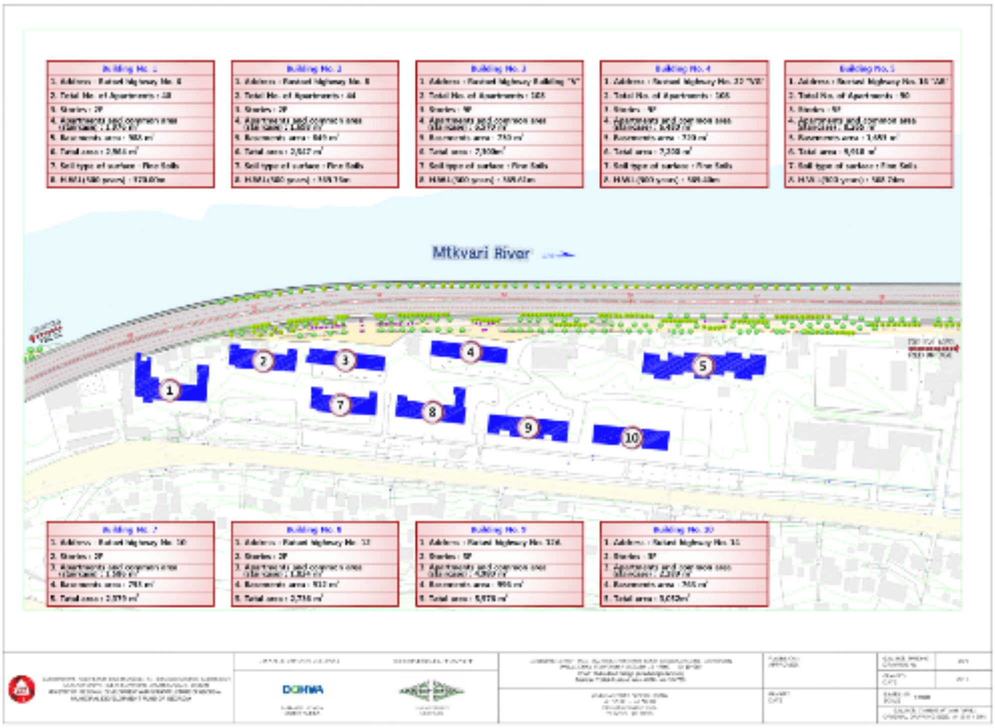


Figure 1 Location of studied buildings

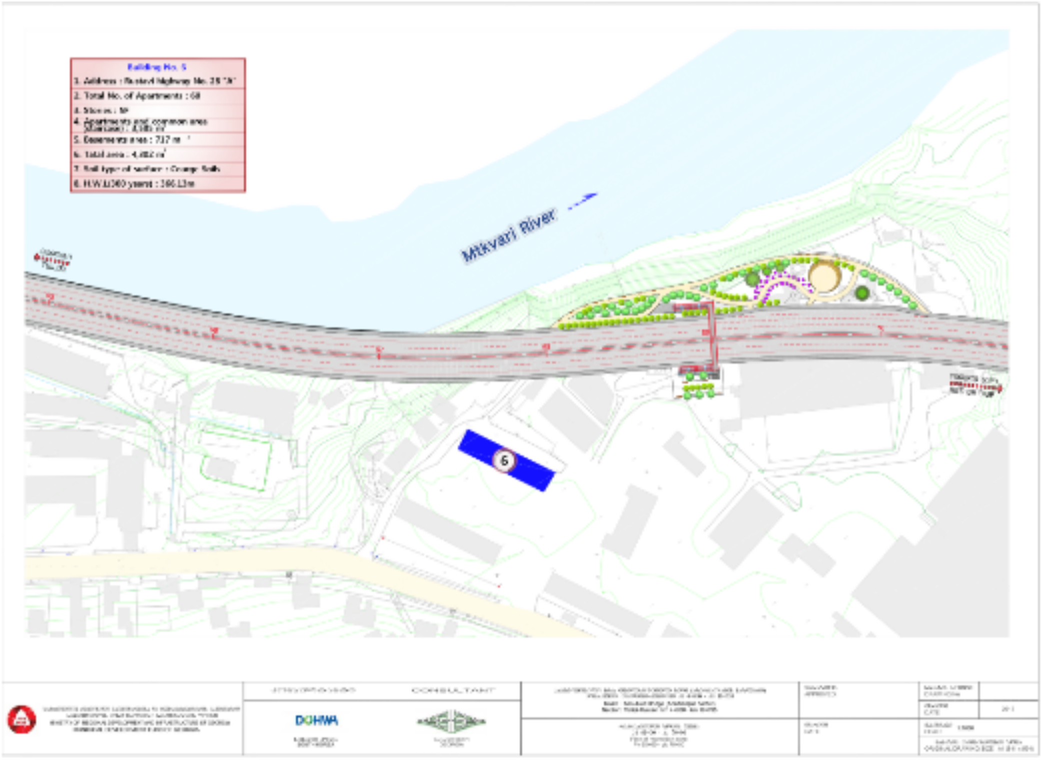


Figure 2 Location of studied buildings

The modelling and analysis performed have been based on the calculation method of propagation of vibrations between source and receiver, considering the damping characteristics of the ground and the phenomena of primary amplification and attenuation within the building. The generation of vibrations are defined based on experimental databases from similar works involving the use of all the categories of machinery necessary to complete the work. More details regarding the methodology are provided in Chapters 2 and 3 of this Report.

1. Vibrations – Impact Levels and Standards

In cases when the vibration impact is considered as a potential or actual risk, significant impacts are observed when sources of vibration generation are located relatively close to the buildings (usualy no more than a few tens of meters).

The effects of vibrations on buildings can vary from a nuisance to people (when the vibration can be sensed but no actual damage occurs) to structural damages.

Vibration sources such as construction activities and road traffic, are among the sources considered potentially dangerous to buildings and structures.

In general structural damages to buildings are extremely rare and are in general caused by other causes. Structural damages occur when the permissive levels of vibration are exceeded.

Degrees of damage are methodologically defined and vary from those that do not affect the structural safety of the buildings but affect the value of assets – e.g. formation of cracks in the plaster, increase in existing cracks, damage of architectural elements etc.

The classification of damage categories used in analysis of vibration impacts is determined by ISO 4866 and is the following:

- **Damage threshold**: Formation of cracks on the surfaces of the thread-like drywall, increase of existing cracks on the plaster surfaces or on the surfaces of dry stone walls; also cracks in the mortar joints in the thread-like construction in brick and concrete;
- **Minor damage**: Widening of cracks, detachment and fall of plaster or pieces of plaster drywall; formation of cracks in blocks of brick or concrete;
- **Major damage**: Damage of structural elements; cracks in the support columns; opening of joints; set of cracks in masonry.

In the present work the effects of vibrations in terms of nuisance/annoyance to people are not considered, and only the potential damage to structures are evaluated.

STANDARDS

UNI 9916 and DIN 4150

The damage to buildings caused by vibrations are defined by **UNI 9916 "Criteria for measurement and evaluation of effects of vibrations on buildings"**, usually in substantial agreement with the technical content of **ISO 4866** and **DIN 4150**. The standard provides guidance on the choice of appropriate measuring methods, data processing and evaluation of the vibratory phenomena in order to allow also the evaluation of the effects of vibrations on buildings (risk of structural damage), with reference to their structural response and structural integrity. According to the UNI 9916, the physical quantity which best represents vibratory phenomenon is not the acceleration, but the speed reached by the vibration.

DIN 4150 distinguish between short duration (transient) and long duration phenomena according to the following tables 1 and 2.

Category	Types of constructions	Speed of vibration in mm / s *			
		Measurement at the foundation			Measurement at the last floor
		Frequency ranges (Hz)			Various frequencies
		<10	10 to 50	50 ÷ 100 **	
1	Buildings used for commercial purposes, industrial buildings and similar	20	20 to 40	40 ÷ 50	40
2	Residential buildings and similar	5	5 ÷ 15	15 ÷ 20	15
3	Buildings very sensitive to vibrations, not included in the previous categories and of great intrinsic value	3	3 ÷ 8	8 ÷ 10	8

* Is the maximum of the three componentes of the velocity at the point of measurement
** For greater frequencies of 100 Hz may apply the values in this column

Table 1 Reference values for the speed of vibration in order to evaluate the action of the vibrations of short duration on buildings (DIN 4150)

Note: “Frequency ranges (Hz)” refer to the frequency ranges generated by vibration source. For each range – different values/ranges of vibration speed apply. In analysis, the most restrictive values of vibration speed (generated at frequency range of < 10 Hz) was applied.

Category	Type of Contruction	Speed of vibration (mm/s)
		measurement at the last floor, all frequencies
1	Building used for commercial purposes, industrial buildings and similar	10
2	Residential buildings and similar	5
3	Buildings very sensitive to vibrations, not included in the previous categories and of great intrinsic value	2.5

Table 2 Reference values for the speed of vibration in order to evaluate the action of the vibrations of long duration on buildings (DIN 4150)

Understandably, for coherence and unquestionable credibility of the findings and analysis of this vibration impact verification assignment, the key questions are:

– To what category the core buildings and annexes to these, taken separately, belong?

– Because depending on duration of vibration emmissions impacting the buildings the nature of impact and permissive thresholds are different - what kind of vibration impacts – Long or Short are to occure? - and,

– What are the permissive damage thresholds should be referred to in analysing and deriving conclusion on whether the vibrations will damage the buildings and the annexes – when factoring in a. category of buildings and b. type of vibration?

These parameters are clearly guided by methodological standards applied internationally and cannot and have not been set arbitrarily. Given the objective of this assignment, these three important aspects deserve more detailed explanation.

Categorization of buildings: Table 2 above contains building categorization determined by DIN 4150 – category 1: Commercial/Industrial buildings and similar; Category 2: Residential building and similar; and Category 3: Sensitive buildings. Based on the review of the structural integrity data and parameters derived by NEP Srl. as the result of a series of tests and analyses (e.g. concrete sampling and testing, foundations assessment, assessement of voluntary additions etc.) – the main core parts of all buildings can be safely assigned to Category 2: Residential building and similar. Although main/core parts of the bulding are of about 4 decades old, they are in sufficiently good shape to not to be considered under sensitive category. However, given the improvised way in which voluntary additions were designed and erected with no reference to sound design and construction practices, these certainly belong to Category 3: Sensitive buildings.

Short or long vibrations: In case of construction of the road and noise mitigation structures, as well as in case of road operation, the buildings will be subject to short vibration impacts – impacts that occure for short period of time (e.g. the period of time when roller compactor is working or when a heavy vehicle is crossing in front of an impacted building). Characterization of Long (transitent) and Short vibrations is defined in DIN 4150-3. Nevertheless, only for demonstration purpose, in comparison of modelled vibration impact to the damage thresholds, thresholds for both – short and long vibration impacts by category of buildings assigned to main/core structutres and the annexes – have been referred (as it can be seen in Tables 13,14,18 and 21).

Damage threshold limits applied in the analysis: As it is showed in Tables 1 and 2, according to DIN 4150, for Category 2: FResidential buildings and similar (to which main/core buildings belong), the threshold for vibration velocity is 5 mm/s for both – long and short duration vibrations. As for Category 3 Sensitive buildings (category for the Voluntary Additions), for short vibrations the threshold is 2.5 mm/s and for long – 5 mm/s.

If desired, however, attributable to a single rating scale in dB, making the necessary calculations it turns out that among levels of weighted acceleration and speed levels exists the following relation (this for frequency greater than or equal to 8 Hz):

$$L_{a,lim} = L_{v,lim} - 29 \quad (1)$$

$$L_{v,lim} = 20log\left[\frac{v}{v_0}\right] \quad (2)$$

Where:
v_0 is the reference velocity, fixed at 10^{-6}(mm/s)
v is the current velocity (mm/s)

The weighted accelerations are given by:

$$L_{a,lim} = L_{v,lim} - 29 = 20log\left[\frac{5}{10^{-6}}\right] - 29 = 105\text{dB} \quad (3)$$

The highlighted figures in Table 3 are the values of vibration velocity (mm/s) calculated and expressed in dB.

Category	Type of Constructions	Duration of vibration	Velocity mm/s	Level dB
2	Residential buildings and similar	short	5	105
Category	Type of Constructions	Duration of vibration	Velocity mm/s	Level dB
3	Buildings very sensitive to vibrations	short	3	100.5
Category	Type of Constructions	Duration of vibration	Velocity mm/s	Level dB
3	Buildings very sensitive to vibrations	long	2.5	99

Table 3 Level limit reference to compare for analysis – according to effective DIN Standards

ISO4866

The principles for carrying out vibration measurement and processing data regarding the effects of vibration on structures are established by the International Standard **ISO4866 “Mechanical vibration and shock, Vibration of fixed structures, Guidelines for the measurement of vibrations and evaluation of their effects on structures”.**

The most common and frequent structural damage from man-made sources occurs in the frequency range from 1 to 150 Hz.

Natural sources, such as earthquakes and wind excitation, usually contain damage-level energy at lower frequencies, in the range from 0,1 Hz to 30 Hz.

The ISO4866 reports several reference values of structural responses for various sources.

Moreover this Standard provides simplified guidelines for classifying buildings according to their probable reaction to mechanical vibration transmitted by the ground.

Table B.2 gives 14 simplified classes taking into consideration the following factors:

a) type of structure (as ascertained from Table B.1 of ISO Standard);
b) foundation (see Clause B.5 of Standard);
c) soil (see Clause B.6 of Standard);
d) “political importance” factor.

Category of structure		Group of building (see Clause B.1)	
		1	2
Resistance to vibration decreasing	1	Heavy industrial multistorey buildings, five to seven storeys high, including earthquake-resistant forms Heavy structures, including bridges, fortresses, ramparts	Two- and three-storey industrial, heavy-frame buildings of reinforced concrete or structural steel, clad with sheeting and/or infilling panels of block work, brickwork, or precast units, and with steel, precast or *in situ* concrete floors Composite, structural steel and reinforced-concrete heavy industrial buildings
	2	Timber-frame, heavy, public buildings, including earthquake-resistant forms	Five- to nine-storey (and more) blocks of flats, offices, hospitals, light-frame industrial buildings of reinforced concrete or structural steel, with infilling panels of block work, brickwork, or precast units, not designed to resist earthquakes
	3	Timber-frame, single and two-storey houses and buildings of associated uses, with infilling and/or cladding, including "log cabin" and earthquake-resistant forms	Single storey moderately lightweight, open-type industrial buildings, braced by internal cross-walls, of steel or aluminium or timber, or concrete frame, with light sheet cladding, and light panel infilling, including earthquake-resistant types
	4	Fairly heavy multistorey buildings, used for medium warehousing or as living accommodation varying from five to seven storeys or more	Two-storey, domestic houses and buildings of associated uses, constructed of reinforced block work, brickwork or precast units, with reinforced floor and roof construction, or made wholly of reinforced concrete or similar, all of earthquake resistant type
	5	Four- to six-storey houses and buildings of associated urban uses, made with block work or brickwork, load-bearing walls of heavier construction, including "stately homes" and small palace-style buildings	Four- to ten-storey domestic and similar buildings, constructed mainly of lightweight load-bearing block work and brickwork, calculated or uncalculated, braced mostly by internal walls of similar material, and by reinforced concrete, preformed or *in situ* floors at least on every other storey
	6	Two-storey houses and buildings of associated uses, made of block work or brickwork, with timber floors and roof Stone- or brick-built towers, including earthquake-resistant forms	Two-storey domestic houses and buildings of associated uses, including offices, constructed with walls of block work, brickwork, precast units, and with timber or precast or *in situ* floors and roof structures
	7	Lofty church, hall, and similar stone- or brick-built, arched or "articulated" structures, with or without vaulting, including arched smaller churches and similar buildings Low heavily constructed "open" (i.e. non-cross-braced) frame church and barn-type buildings including stables, garages, low industrial buildings, town halls, temples, mosques, and similar buildings with fairly heavy timber roofs and floors	Single- and two-storey houses and buildings of associated uses, made of lighter construction, using lightweight materials, prefabricated or *in situ*, separately or mixed
	8	Ruins and near-ruins and other buildings, all in a delicate state All class 7 constructions of historical importance	—

Table B.1 — Categorization of structures according to the building group (ISO 4866)

The buildings under exam belong to the subgroup in column 1, "ancient, historical or old buildings".

In the present case, the **category of foundation of buildings falls into "Class C"** (see Table B.2), which includes the following types:

- light retaining walls;
- large stone footing;
- strip foundation;
- plate foundation;
- no foundations (walls directly built on soil).

The category of soil falls into "Type C" (see Table B.2)**,** which includes horizontal bedded soils, poorly compacted firm and moderately firm non-cohesive soils, firm cohesive soils.

Class of building[a]	Category of structure (see Table B.1)							
	1	2	3	4	5	6	7	8
	Categories of foundations (upper case letter) and types of soil (lower case letter) (see Clause B.5 and Clause B.6)							
1	A a							
2	A b	A a	A a	A a				
3		A b B a	A b B a	A b	A a A b			
4		A c B b	B b	A c	A c B a B b			
5		B c	A c		B c	B a		
6		A f		A d	B d	B b C a	B a	
7			A f	A e	B e	B c C b	B b C a	
8						B e C c	B c C b	
9		B f				C d	B d C c	A a
10			B f			C e	B e C d	A b
11				C f	C f		C e	B a
12						C f		B c C a
13							C f	B d C b C c
14								C d C e C f

← Level of acceptable vibration decreasing

[a] High class number = high degree of protection required

Table B.2 — Classification of buildings according to their resistance to vibration and the tolerance that can be accepted for vibrational effects (ISO 4866)

According to Standards, is possible to identify the class of buildings (Table B.2) for each building being examined.

The buildings belong to category 8 and 11, witch correspond to high degree of protection required, as reported in Table 4.

Building Code	Group of Building	Category of structure	Category of Foundations	Type of Soil	Class of Building
2	1	6	C	c	**8**
3	1	4	C	c	**11**
4	1	4	C	c	**11**
5a	1	4	C	c	**11**
5b	1	4	C	c	**11**
5c	1	4	C	c	**11**
6	1	5	C	c	**11**
7	1	6	C	c	**8**
8	1	6	C	c	**8**
9a	1	4	C	c	**11**
9b	1	4	C	c	**11**
10	1	6	C	c	**8**

Table 4 – class of buildings accordng to ISO 4866

2. METHODOLOGICAL APPROACH AND INPUT DATA

The study was carried out to estimate vibrations induced in the receptors (i.e. buildings) and to evaluate its effects in terms of damage to buildings (UNI 9916, DIN 4150-3), analysing three different configurations:

a) vibration caused by **works of new road construction;**
b) vibration coming from the **operation of the new road**;
c) vibration generated by construction of the **noise mitigation structures**.

Calculations are performed using the following procedural steps:

1) Identification of buildings potentially impacted (EPI);
2) Analysis of the construction project with particular attention to the sections of the motorway nearby the buildings;
3) Analysis of the geotechnical/dynamic characteristics of the foundation soils at the EPI;
4) List of heavy machinery used in the construction of the motorway at the EPI;
5) Analysis and adoption of available data concerning the spectra of the vibrations generated by the employed construction machines;
6) Estimation of the level of vibrations, in order to evaluate the attenuation due to the propagation of waves in the ground, the formulations proposed in the literature;
7) Estimation of vibrations in buildings by the application of the functions/algorithms describing the propagation in the wave-path from the source of the transfer functions of the above points;
8) Evaluation of vibration levels set up in the EPI by comparison with the limits set by the regulations;
9) Identification of critical issues and possible mitigation measures.

The **road construction** method and specifications of equipment for the generation of vibrations such as the ones used for piling, soil compacting and other works, are all known in advance of construction phase. Traffic load levels for the new road by type of vehicles is also known (data provided in engineering design documents provided by Dohwa). Thus, the levels of vibrations during the road construction and operation could be determined using the model.

In assessing vibration coming from the **construction of the noise mitigation structures**, in the absence of the detailed design, safety thresholds/permissive levels of vibration at the source points of potential vibrations derived by modelling, will be used to define the specifications and recommendations about the methodology of construction and types of equipment which are considered suitable for the work in terms of generation of vibrations.

The derived list of suitable equipmentand methods of foundations (piling, micropiling, beam, etc) will be the base for selecting and designing precise mitigation measures for construction works without causing damage to the buildings.

CENSUS OF BUILDINGS AND THEIR STRUCTURAL CONFIGURATION

The list of structures under investigation and the limit of the future motorway are shown in Tables 5-6-7. In the tables the progressive distance changes along the urban road, the state of conservation and the results of the dynamic investigation performed under Task 1 of this Additional Assignment 2 (see column Dynamic Data) are shown.

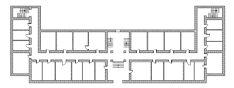
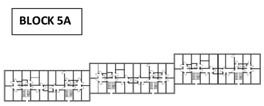
Building Code	Structural Scheme	Progressive Distance (m)	Minimum Distance from the Road (m)	Destination of Use	Number of Floors	State Conservation	Types of Construction	Dynamic Data		
								Mode Number	Frequency (Hz)	Damping (%)
2	 TYPICAL PLAN	5Km + 300	9	Residential Building	2	Poor	Brickwork by squared stone blocks	1	6.69	0.39
								2	7.28	3.64
								3	7.73	3.01
								4	8.48	2.19
3		5Km + 370	22	Residential Building	9	Poor	Precast concrete panel	1	1.89	0.84
								2	2.01	0.94
								3	3.28	0.90
								4	5.77	2.97
4		5Km + 470	19	Residential Building	9	Poor	Precast concrete panel	1	1.75	0.75
								2	2.10	1.20
								3	2.95	0.74
								4	5.46	1.19
5a		5Km + 660	27	Residential Building	5	Poor	Precast concrete panel	1	3.19	3.76
								2	4.56	1.32
								3	4.71	2.01
								4	5.54	4.20

Table 5 summary of investigated building, distance from the road and dynamic data

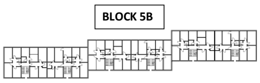
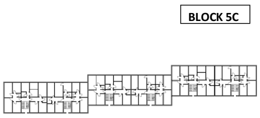
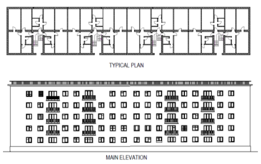
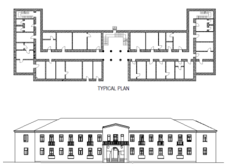
Building Code	Structural Scheme	Progressive Distance (m)	Minimum Distance from the Urban Road (m)	Destination of Use	Number of Floors	State Conservation	Types of Construction	Dynamic Data		
								Mode Number	Frequency (Hz)	Damping (%)
5b		5Km + 660	27	Residential Building	5	Poor	Precast concrete panel	1	2.98	0.36
								2	4.53	1.48
								3	4.75	1.41
								4	6.63	0.82
5c		5Km + 660	27	Residential Building	5	Poor	Precast concrete panel	1	3.05	2.42
								2	4.52	4.51
								3	4.86	1.52
								4	5.68	3.72
6		5Km + 780	30	Residential Building	5	Poor	Brickwork by solid bricks with cement mortar	1	3.33	1.08
								2	3.85	1.89
								3	4.05	0.62
								4	4.97	1.02
7		5Km + 370	52	Residential Building	2	Poor	Brickwork by squared stone blocks	1	5.17	3.23
								2	6.06	2.22
								3	6.35	2.44
								4	6.75	1.28

Table 6 summary of investigated buildings, distance from the road and dynamic data

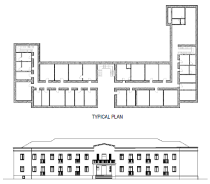
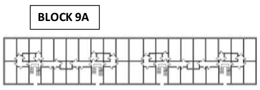
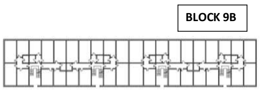
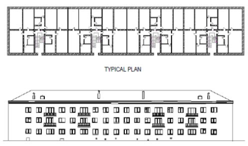
Building Code	Structural Scheme	Progressive Distance (m)	Minimum Distance from the Urban Road (m)	Destination of Use	Number of Floors	State Conservation	Types of Construction	Dynamic Data		
								Mode Number	Frequency (Hz)	Damping (%)
8		5Km + 440	57	Residential Building	2	Poor	Brickwork by squared stone blocks	1	4.25	4.89
								2	6.79	2.89
								3	6.99	3.07
								4	8.84	2.38
9a		5Km + 520	80	Residential Building	5	Poor	Precast concrete panel	1	3.16	0.92
								2	4.68	1.48
								3	5.03	3.03
								4	5.85	2.41
9b		5Km + 520	80	Residential Building	5	Poor	Precast concrete panel	1	3.17	0.67
								2	4.63	1.89
								3	5.05	2.94
								4	5.86	0.69
10		5Km + 600	87	Residential Building	3	Poor	Brickwork by squared stone blocks	1	4.93	1.25
								2	6.14	1.73
								3	6.42	1.78
								4	6.86	1.12

Table 7 summary of investigated building, distance from the road and dynamic data

Since all Buildings are used as residential units, the vibration values identified in the forecasting model have to be compared to the thresholds of reference for such type of buildings.

Buildings are in a very poor state of maintenance. Masonry buildings are made of blocks of stone, bricks and mortar; concrete buildings are made by load bearing panels and reinforced concrete elements.

HIGHWAY SECTIONS IN CORRESPONDENCE OF BUILDINGS impacted

The following two sections of the motorway are representative of the typology of structure in proximity of the buildings of interest.

As visible, in proximity of buildings from 1 to 10 (excluding 6) an important embankment has to be built (Fig. 3). On the other hand, Section 6 (Fig. 4) important excavation works are needed.

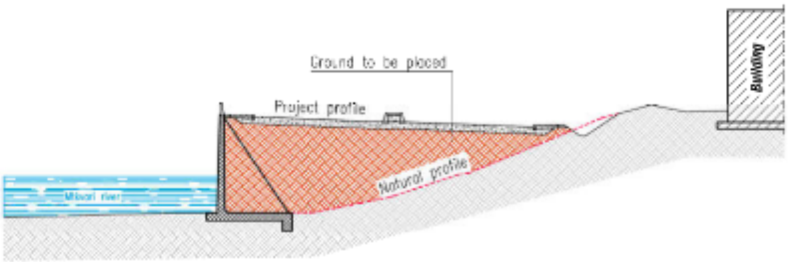


Figure 3 Cross-section on Building #2 to #10 (except #6)

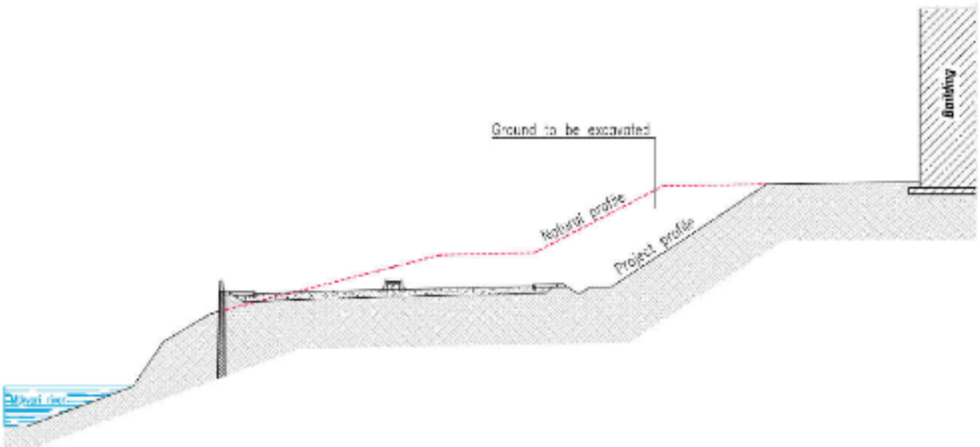


Figure 4 Cross-section on Building #2 to #10 (except #6)

DYNAMIC CHARACTERISTICS OF SOIL

Due to lateral homogeneity of the subsoil, the entire area from Building 1 to Building 6 can be represented by the average values shown below, obtained by the geotechnical investigations and geophysical measurements:

Parametres	Layer 1	Layer 2	Layer 3
V_P, m/s	800	1500	2200
V_S, m/s	450	800	>800
G_D, mpa	364	1152	1458
E_D, mpa	462	1500	2040
μ_D	0.40	0.33	0.27

Table 8 Dynamic parameters of the subsoil

where:

- V_p is the velocity of pressure (compression);
- V_s is the Velocity of Shear Waves;
- G_d is the Shear Elastic dynamic module;
- E_d is the Deformation Module;
- μ_d is the Poisson's coefficient;

TYPE OF EQUIPMENT USED IN CONSTRUCTION and SPECTRA EMISSION OF EQUIPMENT YARD

The emissions of vibration in the construction phase are widely variable in relation to the type of equipment / operating machine employed, the context of use and even the operators.

Technical reference "Environmental impact of roads and traffic" - Appl. Science Publ by LH Watkins - provides a dataset of experimental data about the emission of vibrations by various types of construction machines used in road construction. The emission spectra of the machines shown in Table 9 belongs to dataset contained in mentioned the textbook.

Hz	1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80
Pneumatic hammer - reference distance: 5 m																				
dB	70	68	70	71	72	76	77	81	87	98	88	85	98	95	97	100	101	103	102	101
Roller Compactor - reference distance: 2 m																				
dB	74.9	77.5	75.8	75.0	76.2	77.8	76.3	76.7	77.7	79.2	81.9	96.2	91.0	82.6	96.1	90.6	104.0	97.4	97.6	96.1
Heavy Truck - reference distance: 10 m																				
dB	0	0	0	40	40	41	41	42	47	52	54	56	62	69.5	79	73	71.6	72	80	78
Wheel Loader - reference distance: 10 m																				
dB	0	0	0	52	52	52	53.6	55	54	57.6	61	62	66	69.5	84.6	84.6	78	83.5	83	78
Tracked Machines - reference distance: 10 m																				
dB	0	0	0	69	69	69	69	71	68	79.5	78.5	75.5	92	91.6	96	96	96	96	97	96

Table 9 acceleration spectrums of construction machines (dB) (Sources: DOHWA detailed design document and "Environmental impact of roads and traffic" - Appl. Science Publ by LH Watkins)

The spectra of some machinery of the yard measured at 5m distance from the source of vibration are shown in Figure 5. The **Pneumatic Hammer** and the **Roller Compactor** are machineries providing the greatest impact, with emitted acceleration levels at around 100dB for a large part of the spectrum.

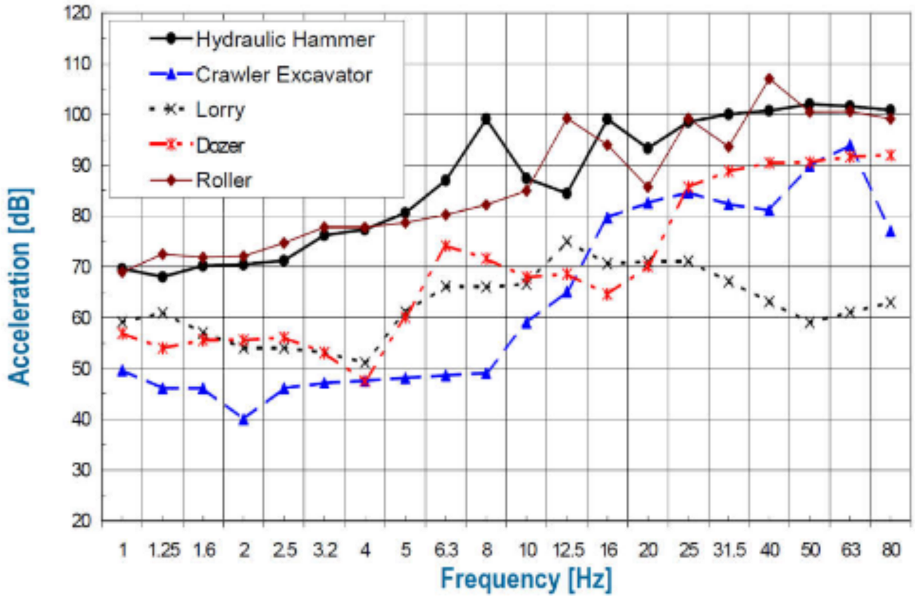


Figure 5 Acceleration spectra experimentally measured (Sources: "Environmental impact of roads and traffic" - Appl. Science Publ by LH Watkins)

Figure 6 shows the vibration velocity decay (decrease with distance) by types of source - i.e. equipment that will be used during the construction phase. In the modeling, the conservative approach was taken, that is, the highest vibration levels of the source between 40-50Hz have been taken and inputted.

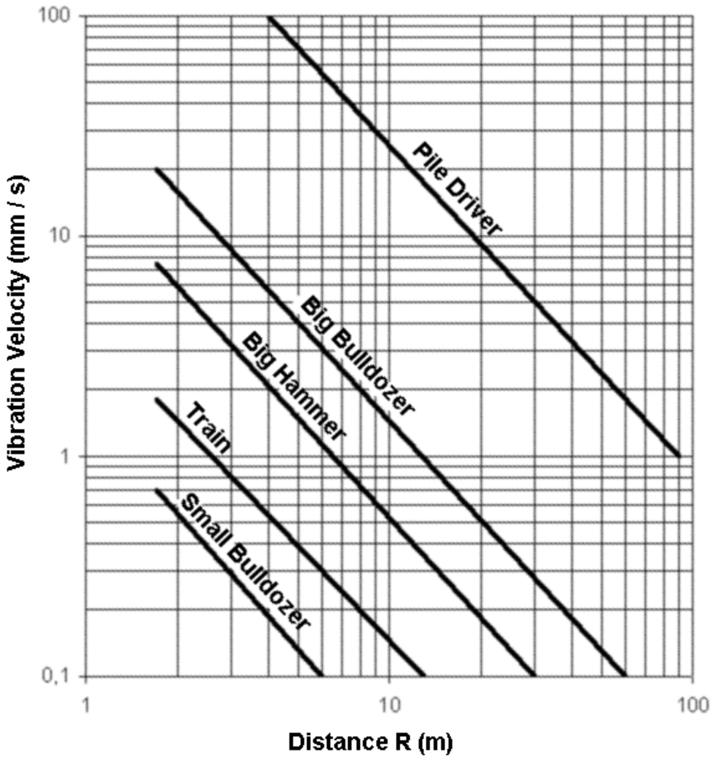


Figure 6 Decay curves of the vibration velocity (Sources: "Environmental impact of roads and traffic" - Appl. Science Publ by LH Watkins)

As reported in the Report for additional Task 2 of the "*Consulting Services for Investigation of Structural Integrity of, and Impact of Vibration and Noise on Buildings at a Segment of Tbilisi-Rustavi Road Project (Section 2, km 5,2-6,9) _ Sound Barrier (general design*)", traffic forecast for next twenty years is in continuous increment. The source for this data is the tables provided by Dohwa. In all relevant documents related to Motorway construction, the future traffic flow is evaluated up to 24 years from now, that is, for a period of 20 years after the road construction. The future maximum vehicle flow used in calculations (forecasted traffic flow for the year 2034) is 38.909 total vehicles/day, with a percentage of **5,2% of heavy vehicles**.

To emulate the worst traffic condition, this flow has been evenly spread on urban road lanes. It has been divided in a period of 8 hours, obtaining the average flux per hour, 4864 Vehicles/hour with 5,2% of heavy vehicles. As for the exploitation beginning, speed has been set to **80 Km/h** which is another conservative assumption (as discussed previously by MDF and ADB lower speed limit might be set for the Phonichala segment of the road).

Vibration propagates in the surrounding soil where it is affected by the attenuation, which depends on the nature of the subsoil, the frequency of the signal and the travelled distance.

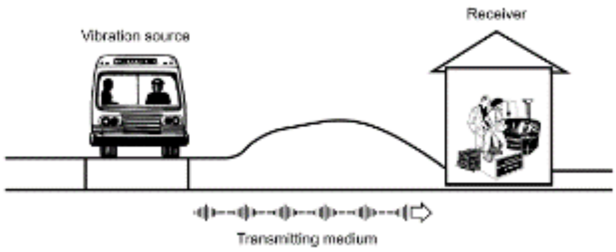


Figure 7 traffic vibrations source-receiver scenario

The characteristics and causes of traffic-induced vibrations are described in guiding methodological literature which is based on case studies. The bumps of vehicles caused by irregularities in the road surface (e.g., potholes, cracks and uneven manhole covers) induce dynamic loads on the pavement. These bursts of loads generate stress waves (motions) propagating in the subsoil when the energy reaches the foundations of a building, and waves still have sufficient energy, the motion is transferred to the foundations generating the vibration of the structure. Traffic vibrations are mainly caused by heavy vehicles such as buses and trucks due to their weight. In addition to that if the road surface roughness includes a harmonic component that, at a given speed, leads to a forcing frequency coincident with any of the natural frequencies of the vehicle and/or those of the soil, additional substantial vibrations may be induced.

According to technical reference sources, traffic produces vibrations with frequencies predominantly in the range from 5 to 25 Hz.

The predominant frequencies and amplitude of the vibration depend on many factors including the condition of the road; vehicle weight, speed and suspension system; soil type and subsoil stratification; season of the year (humidity and temperature of the road and subsoil); distance from the road; and type of building. The effects of these factors are interdependent and it is still difficult to define simple relationships among these factors. The vibrational effect of vehicle speed, for instance, also depends on the roughness of the road and not only on its kinetic energy.

In the present report, input data are based on experimental results of several tests conducted in real operating conditions and on the accepted and commonly used scientific datasets and literature.

The Appendix 1 of the reference source **Survey of traffic-induced vibrations**, A.C. Whiffin, D.R. Leonard. Transport and Road Research Laboratory. Report 418. 1971 summarizes several experimental tests, measuring the vibrations generated by test vehicles travelling along normal road and also over irregularities of the road surface. In the test, vibrations were recorded by accelerometers placed on the road surface and on the adjacent ground, whose characteristics were known, at various distances from the roadside.

The comparison of results obtained at a distance of 3.65m from the edge of road with and without artificial surface irregularity shows that the peak velocities with the irregularity were an order of magnitude greater than that recorded with normal running surface (Table 10).

Details of road constraction	**Deflection Under Deflection Bean**	**Test on normal running surface of road Measurement 3,65 from edge of road**				**Test with artificial road surface irregularity in path of vehicle**							
						Measurements on road surface close to irregularity				**Measurements 3.65m from the road**			
		Accel.	**Ampl.**	**Freq.**	**Particle Velocity**	**Accel.**	**Ampl.**	**Freq.**	**Particle Velocity**	**Accel.**	**Ampl.**	**Freq.**	**Particle Velocity**
		± g	**Microns**	**Hz**	**mm/s**	**± g**	**Microns**	**Hz**	**mm/s**	**± g**	**Microns**	**Hz**	**mm/s**
Bituminous road sections –													
Asphalt surface lean concrete base	300	0.003	1.3	23.7	0.19	0.132	71.1	21.6	9.64*	0.020	10.7	21.6	1.45*
Asphalt surface rolled asphalt base	460	0.004	1.0	29.8	0.19	0.053	35.6	19.3	4.31*	0.012	8.2	19.3	0.98*
Asphalt surface tar-costed stone base	480	0.001	0.4	26.0	0.06	0.077	53.5	18.9	6.33*	0.009	5.8	18.9	0.69*
Asphalt surface stabilised soil base	510	0.002	0.5	3.40	0.10	0.110	71.1	19.5	8.71*	0.014	9.9	19.5	1.21*
Asphalt surface dry stone base	610	0.004	1.5	26.5	0.25	0.117	73.7	20.1	9.30*	0.015	9.1	20.1	1.15*
Bitum macadam surface, lean concrete base	610	0.004	1.3	22.2	0.18	0.121	68.6	23.2	9.99*	0.018	7.9	23.2	1.15*
Concrete roads													
250mm slab on 76mm hoggin		0.002	0.5	30.0	0.1					0.007	5.8	22.2	0.81*
200mm slab on 76mm hoggin		0.002	0.5	30.0	0.1					0.016	7.6	22.4	1.07*
125mm slab on 76mm hoggin		0.004	1.3	25.8	0.21					0.018	12.4	18.9	1.47*
200mm slab on 225 mm lean concrete		0.003	1.8	18.3	0.2					0.015	8.4	21.1	1.11*

Table 10 results of measurements of traffic-induced vibrations on trunk Road (Sources: A.1 at Aleonbury Hill (Hunts); **Survey of traffic-induced vibrations**, A.C. Whiffin, D.R. Leonard. Transport and Road Research Laboratory. Report 418. 1971)

In the present study, for a more conservative approach, the tests with artificial road surface irregularity are taken in account. As reported in the following paragraphs, these values are compared with the accelerations data measured in the existing road.

SPREAD OF VIBRATIONS BETWEEN SOURCE AND RECEIVER

When a vibration is applied on the ground, its propagation in the subsoil is affected by attenuation which depends on the nature of the subsoil, the frequency of the signal and the travelled distance. To theoretically evaluate the impact of vibrational sources, by the application of analytical formulas it is possible to obtain a calculation of the attenuation of the vibrations as a result of the propagation in the soil.

There are tables and graphs allowing to parametrically estimate the attenuation or amplification caused by the various structural components of buildings. Combining these information, it is possible to estimate, with a good approximation (typically +/- 5 dB) the levels of vibration occurring at target areas and then their effects on buildings. Taking into account the above, it can be assessed if the expected source of vibration is negatively impacting the target or if levels are acceptable.

Figure 8 is an example of the dynamics of interaction source-receiver and the events occurring during the propagation of the vibrations.

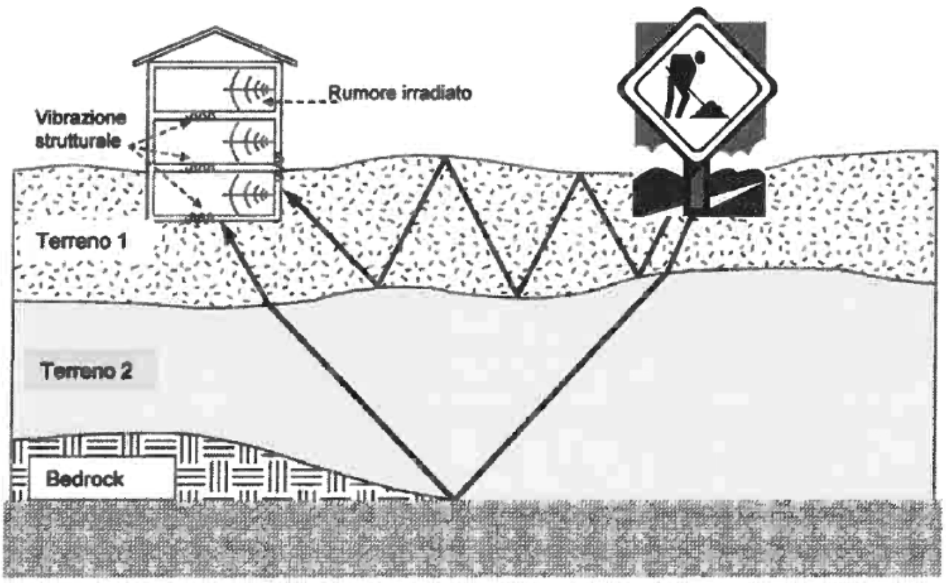


Figure 8 interaction between source and receiver through the soil propagation

Propagation of vibration in the ground

The vibration level at a receiver located at distance "x" from the source is equal to the level at the reference distance " x_0", minus the contribution of the attenuation (A_i) determined by the travel in the soil between x_0 and x:

$$L(x) = L(x0) - \sum iAi \tag{4}$$

The basic level L(x_0) is generally obtained from experimental measurements at distances ranging between 2 m and 25 m.

The components of attenuation and amplification of vibrationsto be considered in the model, as average values, values, are:

- **Geometric attenuation**,
- **Attenuation for internal dissipation of the terrain**;
- **Attenuation due to obstacles or discontinuity of the ground**.

The **geometric attenuation (A_g)** is defined as follows:

$$A_g = 20log\left(\frac{x}{x_0}\right)^n \tag{5}$$

Where “n” is an attenuation coefficient depending on the type of geometric attenuation (see Table 11):

Source location	Source type	Induced wave	n
Surface	Point	Body wave	2.0
		Surface wave	0.5
	Infinite line	Body wave	1
		Surface wave	0
In-depth	Point	Body wave	1.0
	Infinite line		0.5

Table 11 Values of attenuation coefficient due to radiation (emission) damping for various combination of source location and type (Source: **Environmental Impact of Roads and Traffic**, L.H. Watkins. Routledge. 1981)

The Exponent “n” is equal to 0.5 for the waves of surfaces (predominant in the case of source placed on the surface), and 1 for the bulk waves (predominant in the case of deep source).
The attenuation due to the absorption of the ground (**A_t**) is defined as follows:

$$A_t = 20log\left[e^{\frac{\omega\eta(x-x_0)}{2c}}\right] \tag{6}$$

Where:

- $\omega = 2\pi f$ is the pulse wave (with f = frequency in Hz);
- c = velocity of propagation in the soil in m/s;
- η = absorption factor of the soil (see Table 12).

Soil type	η
Rock	0.01
Sand, gravel	0.1
Silt, Clay	0.2 – 0.5

Table 12 Values of the damping parameter as a function of the soil type

When a wave encounters an interface between layers having different velocity of propagation, if the below layer has a lower speed, a large part of the energy is backscattered, with the result of decreasing the transmitted energy. On the contrary, if the interface is between two layers with an increase of velocity, the largest part of the energy is transmitted into the faster layer. This phenomenon is normally not taken into account, in favor of conservative interpretation of the simulation data.

Propagation of vibration in the structure of the building

When a vibration wave encounters the foundation of a building, it could be accelerated, attenuated, amplified, could modify its frequency spectra according to the type of foundation and type of construction, and coupling between foundation and soil, even the presence of water can modify this behavior. Different foundation systems can determine different levels of attenuation of the waves transmitted into the structure, because of the non-perfect coupling between the structure and the subsoil which generates dissipation phenomena.

This phenomenon is influenced by the type of foundations (theater style, isolated on plinths, on reverse beams, piles, etc.). In the case of foundations at the stalls the large area of contact with the ground causes a coupling loss of almost 0 dB at low frequency, up to the resonance frequency of the foundation. For other types of foundations empirical curves of calculation can be used allowing to estimate the vibration levels of the foundation according to the levels of vibration of the ground. The attenuation caused by building coupling loss structure-foundation is illustrated in Figure 9 for different categories of buildings. With regard to the category of large reinforced concrete buildings with continuous foundations, the curve for the large buildings in masonry with continuous foundations (see red curve in figure 9) is applied, with a attenuation of 2 dB.

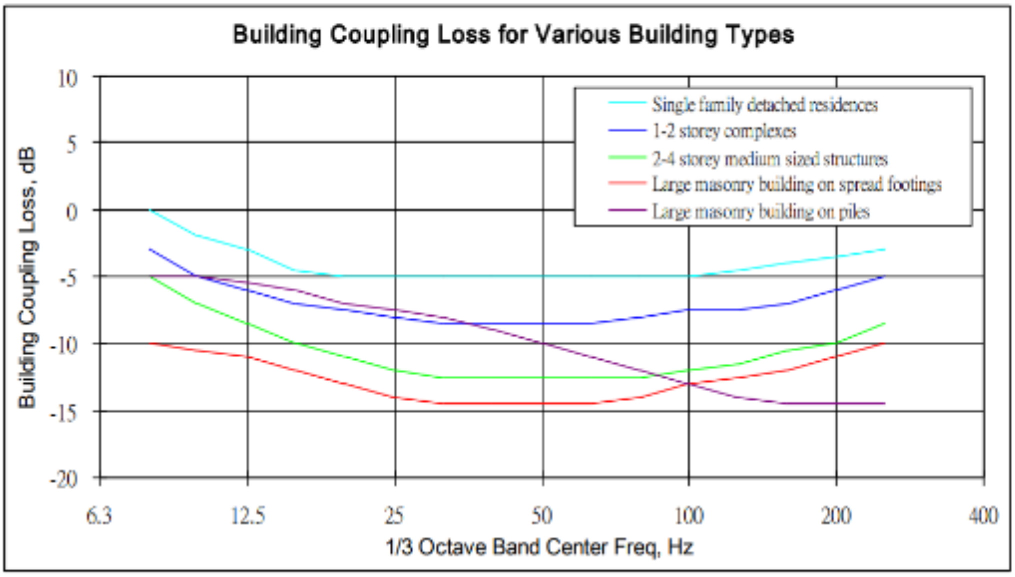


Figure 9 building Coupling loss for various building types (Source: **Environmental Impact of Roads and Traffic**, L.H. Watkins. Routledge. 1981)

Spreading from the foundation on the higher floors the vibration amplitude decreases, due to the propagation of vibration vertically along the building, from level to level; and for that these losses must be taken into account. The general assumption is that the vibration decreases of **2 to 3 dB per floor** across the spectrum. Figure 10 shows the typical range of variability of the attenuation between floors.

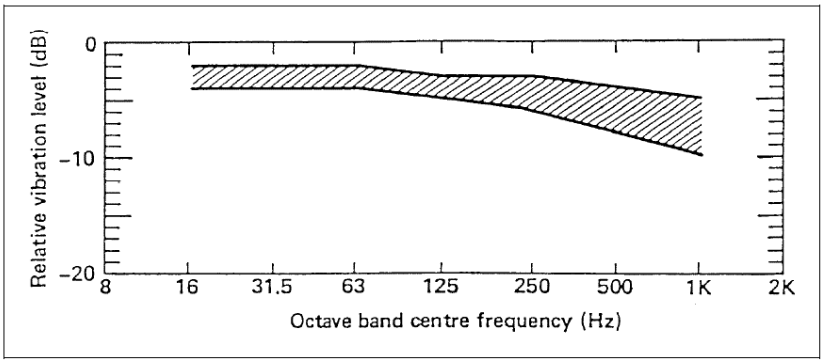


Figure 10 Attenuation from one floor to the next (Source: **Environmental Impact of Roads and Traffic**, L.H. Watkins. Routledge. 1981)

The phenomenon of resonance of the structural elements of buildings, in particular of the floors should also be examined. It occurs when the excitation frequency coincides with the natural frequency of free oscillation of the structure; for the effects of the oscillations the structure shows a significant increase of vibration in the vertical direction and minimal values at the base.

The amplification of the floors ranges in an area from 5 dB for frequencies of about 20 Hz to maximal values of 20 dB for frequencies of about 40 Hz. Again, conservatively, the analysis of the vertical vibration was limited to the first floor mezzanine since the upper floors are less impacted than the first.

Modelling vibration impact on the annexes is essentially the same as for core building structures, yet with important difference. The commonly used best international practice approach in such case is to factor in “amplification factor” called “Storey amplification”, which in simple generalized terms means that in modelling, higher vibration amplification is given to assess the impact on the annexes. This approach is conservative, it is “worst case scenario” based and thus safe, and is practiced based on relevant methodological references (e.g. Giuseppe Muscolino : Structure Dynamic behaviour – publisher: THE MCGRAW-HILL COMPANIES).

4. VIBRATION CAUSED BY NEW ROAD CONSTRUCTION WORKS

ANALYSIS OF INDIVIDUAL BUILDINGS

Using the input of the previously sections the amplitude of vibrations in the receivers (core buildings and annexes) has been calculated. Table 13 reports, for each building, the result of modeling, in particular, the amplitude of vibration generated by the most impacting source (hammer and compactor) and the Damage Thresholds (that is the threshold for minimum damage not threatening structural integrity) according to the considered standards explained in Chapter 2 Vibrations – Impact Levels and Standards.

Building Code	Minimum Distance from the Road (m)	SOURCE		RECEIVER LEVEL VIBRATION				STRANDARD THRESHOLD DIN 4150-3 /9916. impact on buildings		
				roller compactor		pneumatic hammer				
		ROLLER COMPACTOR (dB)	PNEUMATIC HAMMER (dB)	main building	annex	main building	annex	category 2 long - short duration (dB)	category 3 short duration (dB)	category 3 long duration (dB)
2	9	104,00	101,00	82,36	86,36	79,36	83,36	105	100,5	99
3	22	104,00	101,00	76,93	80,93	73,93	77,93	105	100,5	99
4	19	104,00	101,00	78,38	82,38	75,38	79,38	105	100,5	99
5a	27	104,00	101,00	74,67	78,67	71,67	75,67	105	100,5	99
5b	27	104,00	101,00	74,67	78,67	71,67	75,67	105	100,5	99
5c	27	104,00	101,00	74,67	78,67	71,67	75,67	105	100,5	99
6	30	104,00	101,00	73,40	77,40	70,40	74,40	105	100,5	99
7	52	104,00	101,00	63,00	67,00	60,00	64,00	105	100,5	99
8	57	104,00	101,00	61,24	65,24	58,24	62,24	105	100,5	99
9a	80	104,00	101,00	55,49	59,49	52,49	56,49	105	100,5	99
9b	80	104,00	101,00	55,49	59,49	52,49	56,49	105	100,5	99
10	87	104,00	101,00	53,22	57,22	50,22	54,22	105	100,5	99

Table 13 Summary of the simulated amplitude of vibrations at the receivers, compared with Standards (DIN 4150-3) – construction works

Note: the column "category 2 long-short duration (dB)" contains the figures for Long AND Short vibration because for category buildings, according to DIN 4150-3, these values are similar.

CONCLUSIONS AND RECOMMENDATIONS ON VIBRATION CAUSED BY NEW ROAD CONSTRUCTION WORKS

The analysis of the data reported in the above tables shows that, along the route, the level of vibration evaluated in terms of speed of vibrations, is lower than the thresholds assigned by the UNI 9916 / ISO 4866 for residential buildings: for that **the expected level of vibrations caused by the new road construction will not result in any danger of damages to the considered buildings**.

As for the annexes to the buildings, even though the modeling showed no risk of damage to the Annexes of the resulting from road construction (assuming no other vibration-generating equipment or method than included in the detailed design for the project will be used in practice) – the Annexes, mostly built originally with disregard of essential engineering practices, are in poor shape. Because of this, it cannot be excluded that other than **road construction-related** vibration (e.g. seismic activity, some further modification of annexes done by the inhabitants of the flats, other construction activity or soil works in the area, or a combination of these) results in damaging or even collapse of some of the annexes, in which case, the inhabitants of the buildings still could claim that the cause of the damage has been the construction of the road. Even assuming, no such claims would be made or proved, the Annexes are not safe for the inhabitants since the time of their construction and this safety problem should be addressed.

Subsequently, based on the above conclusions, the following measures are strongly recommended:

1. **Limiting vibration levels and monitoring contractor compliance**: The modeling has been performed conservatively (at maximum impact levels for worst case scenarios) and the conclusions and recommendations are provided conservatively as well despite some safety margin allowed by this conservative approach. The modelling has been conducted while inputting the vibration data for the equipment, construction method and road and construction yard alignment clearly specified in the detailed engineering design documents prepared by Dohwa. The above conclusions are valid only in case no other method or equipment generating vibration than specified by Dohwa is applied.

   Subsequently, it is mandatory to:

   a. Instruct the Contractor to follow strictly, under a legal liability, the construction method and equipment list, and respect the boundaries of the construction yard during construction works. The contractor should further seek the approval of the client (MDF) of any need of modifying construction method, using equipment not specified in the detailed design documents or exceed the boundaries of the construction yard.

b. According to good international practices in the similar cases, perform, ongoing permanent supervision of the construction works to establish compliance of the contractor with conditions specified in point “a.” above. The supervision mechanism should include the tools of immediate identification of the problem and the authority of the supervisor agent to halt works, record the non-compliance and issue a mandatory corrective action instruction to the contractor.

2. **Reinforcing the Annexes**: Even though modelling showed no risk of damage to the annexes, due to the condition of Annexes determined by their faulty design, practical difficulties related to establishing that the road-related activities have not been the cause of a damage, and most importantly, lack of safety of the Annexes at any time since the day of their construction – it is recommended to reinforce the Annexes. The engineering design of reinforcement works reported under the assignment of NEP Srl. can be used in implementing reinforcements. The suggested method is effective, least expensive and possible to implement in the shortest period of time.

3. **Technical monitoring campaign**: Furthermore, given the legal sensitivity and the background of the case, again, based on best international practices, it is strongly recommended to conduct a proper technical monitoring campaign for the client (MDF) to possess a legally undisputable record of vibration levels / impacts vis a vis any claims by the residents or to establish legal responsibility of the contractor in case of need. Draft monitoring plan reported under the assignment of NEP Srl. can be used in planning and implementing such campaign.

5. VIBRATION COMING FROM THE OPERATION OF THE NEW ROAD

As reported above, the maximum values of peak velocity (mm/s) measured 3.65m from the edge of the road (Tab.10) is 1.45mm/s.

One of the requirements of the Additional Assignment 2 was to, whenever methodologically possible, input field data rather than other methodologically credible assumptions in modeling and analysis in order to validate the analysis and conclusions of the previous impact investigation. To meet this requirement, first, vibration reference values provided in guiding methodological sources were retrieved (source: **Traffic vibrations in buildings**. Osama Hunaidi. National Research Council of Canada. ISSN 1206-1220 Construction Technology Update No. 39. June 2000). Secondly, and most importantly, several measurements of the amplitude of vibrations induced by the existing road (Task 1 of the Scope of this assignment) have been performed, as below reported. Comparison of the two showed that the field measurements (referred in the tables below as Dynamic Vibration) were almost two times higher than figures in methodological reference sources. Consequently, following overall conservative approach, the higher figures of velocity of vibration were inputted in modeling road operation impacts.

ACQUISITION OF VIBRATION MEASUREMENTS

Data are acquired according to the following standards:

- SO/FDIS 4866 – "Mechanical vibration and shock, Vibration of fixed structures, Guidelines for the measurement of vibrations and evaluation of their effects on structures".

Sensors were installed near the cross section of the existing Urban Road and in correspondence of the foundation of Building #10 (Fig.11).

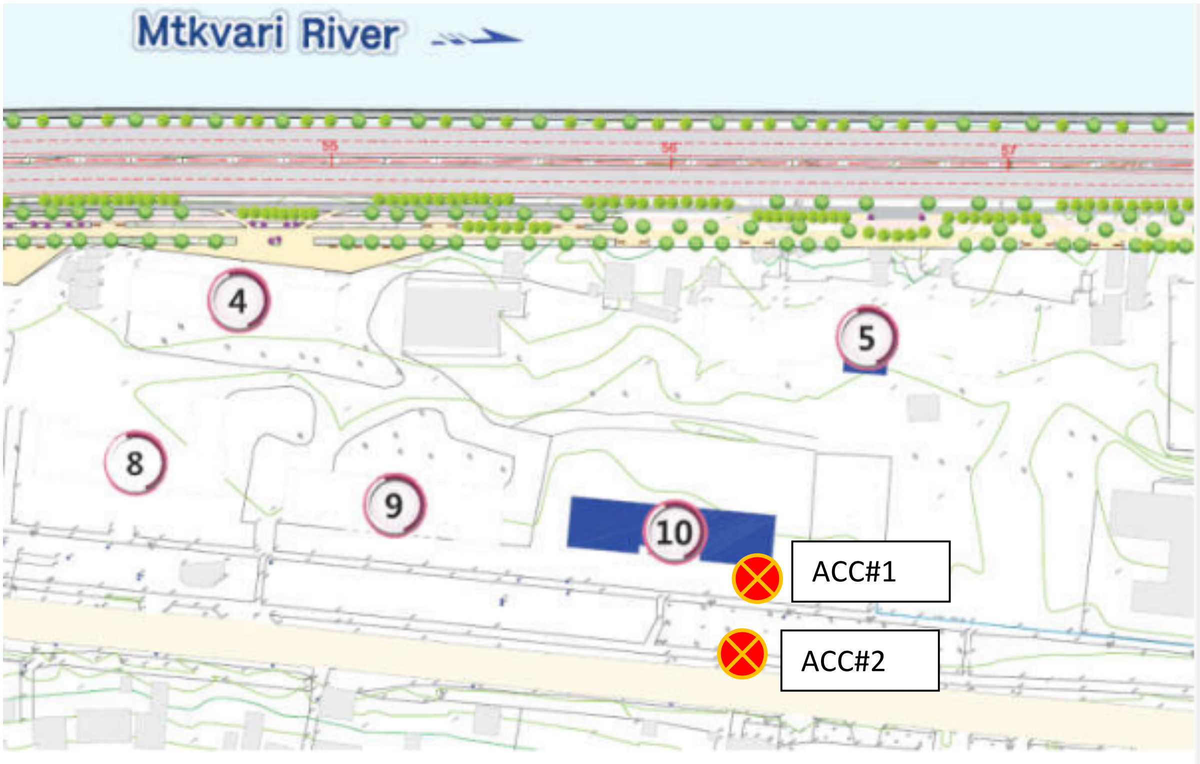


Figure 11 Layout of accelerometers placed for measurements of traffic-induced vibrations

Sensor n.1 (ACC#1) is placed in proximity of Building#10, and Sensor n.2 (ACC#2) is placed near the existing Road, 3.5m from the road edge and 27m far from ACC#1.

Figure 12 ACC#2 – existing Road

Equipment

A wired sensor network composed of the following elements was used:

- piezoelectric sensors (Integrated Electronic Piezoelectric - IEPE) KS48C-MMF with voltage sensitivity of 1V/g and measurement range of ±6g. (calibration certificates dated about 40 days before the test)

		KB12	KB12VD	KS48C	
Output		Charge	IEPE	IEPE	
Piezo Design		Bender	Bender	Shear	
Charge Sensitivity	B_{qa}	6500±20%	-	-	pC/g
Voltage Sensitivity	B_{ua}	-	10 000±10%[1]	10 000±5%[1]	mV/g
Range	A_{+} / a_{-}	±3	±0,6	±6	g
Destruction limit	a_{max}	200	200	1000	g
Linear Frequency Range	$f_{3\,dB}$ $f_{10\%}$ $f_{5\%}$	260 160 130	0,08.. 260 0,16.. 160 0,25.. 130	0,1 .. 4000 0,2 .. 2600 0,3 .. 2000	Hz Hz Hz
Resonant Frequency	f_r	>0,35(+15dB)	>0,35(+15dB)	>7 (+25dB)	kHz
Noise Densities	0,1Hz a_{n1} 1 Hz a_{n2} 10 Hz a_{n3} 100Hz a_{n4}	- - - -	0,3 0,06 0,03	1 0,6 0,1 0,06	µg/√Hz µg/√Hz µg/√Hz µg/√Hz
Costant Current Supply	I_{const}	-	2 .. 20	2 .. 20	mA
Output impedance (I_{const} = 4mA)	r_{out}	-	< 130	<130	Ω
Operating Temperature Range	T_{min}/T_{max}	-20/80	-20/80	-20/120	°C
Temperature Transient Sensitivity	b_{at}	0,01	0,002	0,0005	ms^{-2}/K
Acoustic Noise Sensitivity	b_{ap}	0,1	0,1		ms^{-2}/kPa
Weight (no cable)	m	150/5,3	150/5,3	165/5,8	g/oz
Mounting Thread		M5/M10	M5/M10	M8	
Case Material		Alluminio	Alluminio	Acciaio INOX	

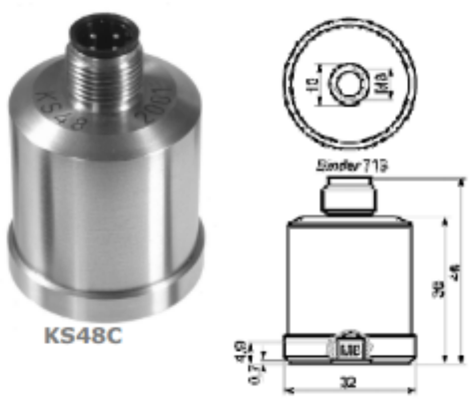


Figure 13 piezoelectric sensors KS48C-MMF

- digital recorder (DaTa500) composed by a 24-bit Digital Signal Processor (DSP), an analog anti-aliasing filter and a high-frequency acquisition range (0.2Hz to 200kHz).

Dati Tecnici Generali	
Numero Canali	8 Canali simultanei
Segnali Misurabili	Tensione, Ponte Intero (IEPE, Charge, Termocoppie e RTD /adattatore MSI
Risoluzione	24 bit
ADC tipo	Sigma - Delta
Frequenza Acquisizione	10 to 200 000 Hz 204.8 kS/s
Input Range	Voltage ±0,01 V, ±0,1 V, ±1 V, ±10 V,
	Voltage via adattatore MSI
	Ponte Intero ±10 mV/V, ±100 mV/V, ±1000 mV/V
	Half bridge
	IEPE—MSI adapter ±0,1 V, ±1 V, ±10
	Termocoppie (-200°C a 1000°C e da 0 a 6.5kOhm)
DC Accuracy	10V range: 0,1% del valore, +1 mV 1 V range: 0,1% del valore, +0,5 mV 100mV range: 0,1 del valore, +0.1 mV 10mV range: 0.1% del valore, +0.1 mV
Tensione Sensori	±5 V 0.1% @ 100mA, 12V@400mA per singolo canale
Protezione Sovraccarico	±0 70V

Caratteristiche Dinamiche	
Rumore Segnale @fs<1000Hz	< -100 dB
Crosstalk	< -100 dB
Ambiente di lavoro	
Temperatura Operativa	0 to 50 °C
Temperatura Storage	-20 to 70 °C
Umidità Relativa	10 to 90%
Vibrazione	MIL-STD 810F 516.5
Shock - Urto	MIL-STD 810F 516.5
Dimensioni	
Dimensioni	223 x 78 x 45mm
Peso	0,72 Kg
Consumi	
Consumo tipico	5 W
Massimo consumo sensori	6 W
Requisiti Sistema	
Interfaccia	USB 2.0
Sistema Operativo	Windows XP, Vista, 7
Sistema - Hardware	PC completo di software DeVsoft

Figure 14 Digital recorder (DaTa500)

- RG58 coaxial cables link from ccelerometers to recorder;
- M28 and M32 signal conditioners with frequency range of 0.1 to 100kHz and adjustable e gain.

	M28	M32
Input	IEPE—BNC connettore	
IEPE Sensors Alimentazione	Shear	
Indicazione Stato sensore	Tre Indicazioni LED: circuito aperto=off ; OK=giallo; Corto Circuito=rosso	
Guadagno	1 ± 0,5%	1 /10/100 ± 1% typ; ± 2% max
Livello Output	> ± 10_{pp} (in funzione del sensore)	> ± 10_{pp}
Rumore Output	< 1 μV_{eff} (2 .. 25kHz) < 1 μV_{rms} (2 .. 25kHz)	< 1 mV_{eff} (1 .. 50kHz) < 1 mV_{rms} (1 .. 50kHz)
Frequency Range (-3dB)	0,1 Hz .. 100 kHz	0,1 Hz .. 30kHz
Filtro Low Pass	-	Modello Plug-in serie FB2*
Tipologia Filtro	-	4 poli, butterWorth >70dB
Alimentazione	5 .. 26 VDC / 100mA	5 ..26 VDC / 200mA
Connettore Alimentazione	DIN 453232 circolare—bananaplug	
Range Temperatura	-10 .. 55 °C, 95% Umidità relativa	
Dimensioni	33x59x44 mm^3	56x59x44 mm^3
Peso	120g	170g
Accessori	2 banana plug filettati	
Accessori - Opzionali	FB2 Modulo Filtro Low Pass (30Hz) M28/32 DIN adattatore Barra DIN PS500 Alimentatore 500mA PS1600 Alimentatore 1,6A	

Assemblato M32—M28

Figure 15 M28 and M32 signal conditioners

Analysis of acquired Data

Data are acquired with at a sample rate of 1.000Hz. Time histories show the relevant peaks acquired caused by traffic-induced vibrations. Accelerations (mm/s^2) are integrated in order to obtain velocities (mm/s).

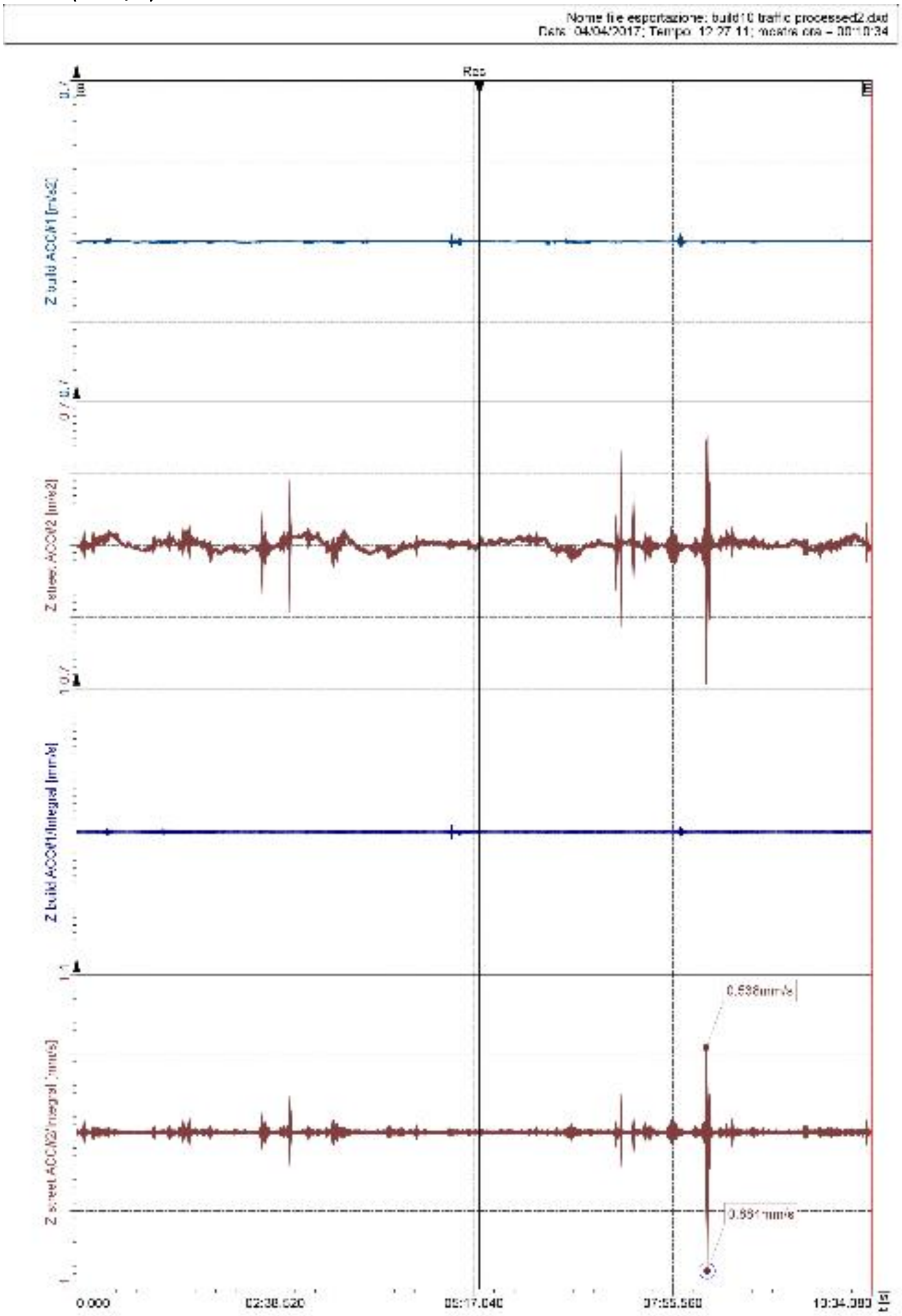


Figure 16 Time histories of traffic-induced vibrations

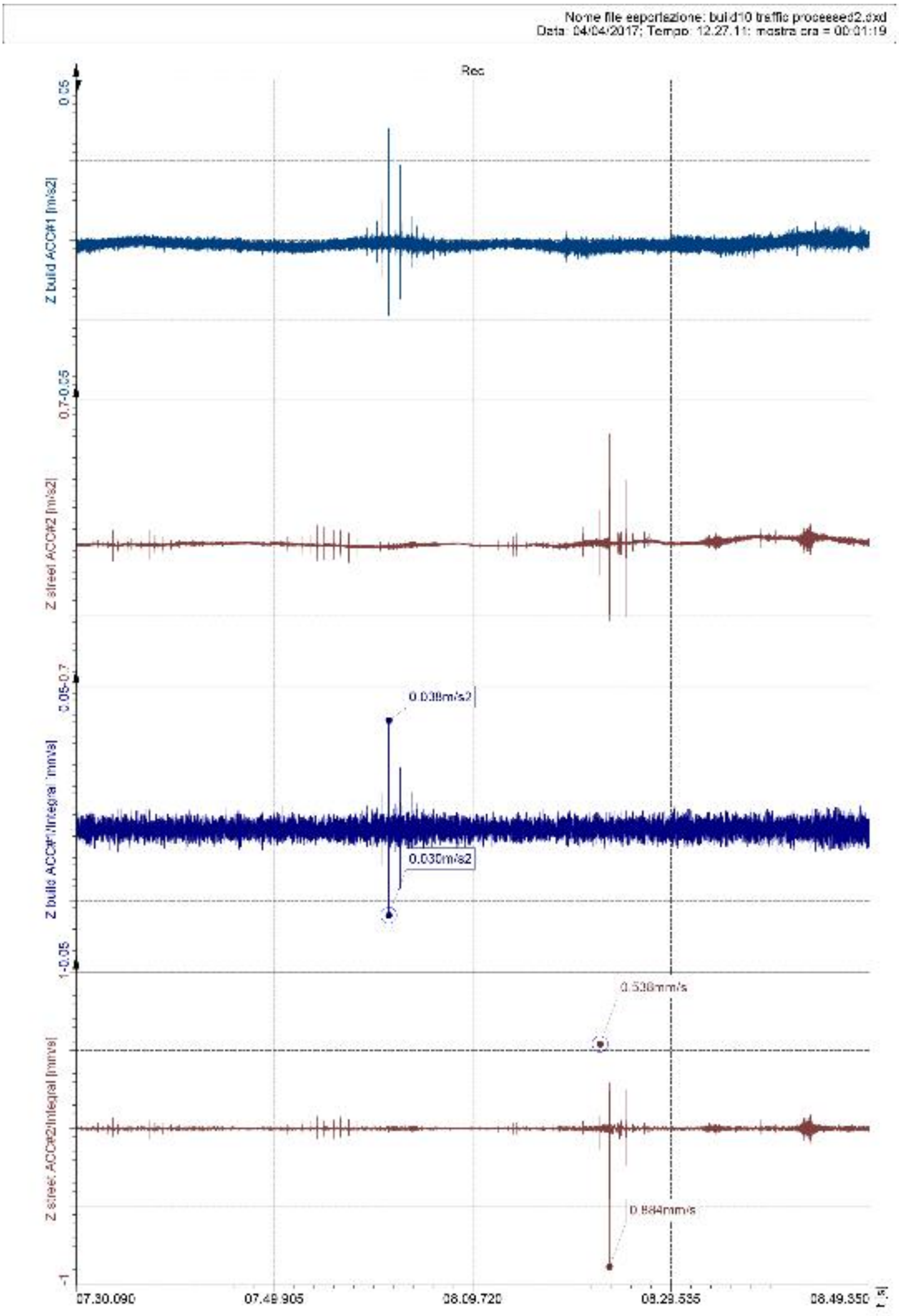


Figure 17 Time histories of traffic-induced vibrations

As a result the main velocity value is recorded at minute 8.25, with an amplitude of velocity equal to **0.884mm/s** in correspondence of the road (ACC#2).

For the calculation of traffic-induced vibrations, conservatively, the maxim values from methodological references - equal to **1.45mm/s** – have been taken.

Using three formulae above, the value is converted in a single rating scale in dB, witch correspond an acceleration level (dB) equal to **94dB** as reported below:

$$L_a = L_v - 29 = 20log\left[\frac{1.45}{10^{-6}}\right] - 29 = 94\text{dB}$$

This source value has been used for the calculations in order to obtain the simulated acceleration values in each receivers (Buildings).

ANALYSIS OF INDIVIDUAL BUILDINGS

Using the input described above, the amplitude of vibrations in the receivers (building) has been calculated.

Table 14 contains the levels of the amplitude of vibration caused by traffic during road operation and the thresholds imposed by the standards - for each building and its annex.

Building Code	Minimum Distance from the Road (m)	SOURCE		RECEIVER LEVEL VIBRATION		STRANDARD THRESHOLD DIN 4150-3 /9916. impact on buildings		
				main build	annex			
		TRAFFIC (dB)	Ref distance (X0) m	TRAFFIC	TRAFFIC	category 2 long - short duration (dB)	category 3 short duration (dB)	category 3 long duration (dB)
2	9	94,00	3,65	70,62	74,62	105	100,5	99
3	22	94,00	3,65	65,19	69,19	105	100,5	99
4	19	94,00	3,65	66,65	70,65	105	100,5	99
5a	27	94,00	3,65	62,94	66,94	105	100,5	99
5b	27	94,00	3,65	62,94	66,94	105	100,5	99
5c	27	94,00	3,65	62,94	66,94	105	100,5	99
6	30	94,00	3,65	61,66	65,66	105	100,5	99
7	52	94,00	3,65	51,27	55,27	105	100,5	99
8	57	94,00	3,65	49,51	53,51	105	100,5	99
9a	80	94,00	3,65	43,76	47,76	105	100,5	99
9b	80	94,00	3,65	43,76	47,76	105	100,5	99
10	87	94,00	3,65	41,48	45,48	105	100,5	99

Table 14 Summary of the simulated amplitude of vibrations at the receivers, compared with Standards (DIN 4150-3) - traffic

Note: the column "category 2 long-short duration (dB)" contains the figures for Long AND Short vibration because for category buildings, according to DIN 4150-3, these values are similar.

CONCLUSIONS AND RECOMMENDATIONS ON VIBRATION CAUSED BY NEW ROAD OPERATION

As expected, analysis of the data reported in the above tables show that the impact of vibration caused by traffic on the new road (evaluated in terms of speed of vibrations) is lower than the thresholds assigned by the UNI 9916 / ISO 4866 for residential buildings. Results of modelling impacts of **vibration caused by traffic load on the new road show no direct effect of damage either to core buildings or to the annexes**.

However, the factor of inherent structural weakness of the Annexes, and the future post-commissioning works of maintenance of the new road (as the measures that reduce the vibration and at the same time are the source of vibration) should be factored in into drawing conclusions and recommendations.

Specifically, the following measures are strongly recommended:

1. **Reinforcing the Annexes (the same as voluntary additions)**: The same recommendation as made for the vibration impact caused by construction works – applies. Even though modelling showed no risk of damage to the annexes, due to the condition of Annexes determined by their faulty design, practical difficulties related to establishing that the road-related activities have not been the cause of a damage, and most importantly, lack of safety of the Annexes at any time since the day of their construction – it is recommended to reinforce the Annexes. The engineering design of reinforcement works reported under the assignment of NEP Srl. can be used in implementing reinforcements. The suggested method is effective, least expensive and possible to implement in the shortest period of time.

2. **Preventing increased vibration resulting from the road surface deterioration:** With time, due to wear and other environmental factors, road surface develops defects, most of which (e.g. bumps) are the cause of vibration. The road surface quality should be regularly monitored to prevent and fix in timely and sustainable manner the defects that in turn cause increase in vibration caused by traffic load of the new road. Adequate resources should be allocated for maintenance of the Phonochala segment of the new road and all maintenance works should be conducted preventively or swiftly as the damage occurs.

3. **Technical Monitoring Campaign**: The campaign can be conducted periodically if not permanently and at least for the first 12-18 months after commissioning of the road which will allow to determine the pattern and decide on whether further technical monitoring means are required. In addition, in case of discontinued technical monitoring, relevant

sensors can be set up and data recorded during the maintenance works to establish compliance of the maintenance contractors.

6. VIBRATION GENERATED THROUGH CONSTRUCTION OF THE NOISE MITIGATION STRUCTURES

NOISE MITIGATION MEASURES

This section reports the main features of the draft report "**Noise Modelling of Tbilisi-Rustavi Highway (section 2)**", dated April 29, 2017 and shared with DRC and 4EMME with the recommendation to be considered in the analysis as reflected in the scope of work for this assignment. This report evaluates the noise potentially generated from the proposed new segment of the Section 2, particularly its western portion where the buildings are closer and the noise levels could be a matter of concern.

The report proposes the four mitigation options below listed:

- **W** (**Noise wall with maximum height of 8 m**). In this two noise-absorbing barriers are recommended; a first one 6-m high, 988 m and a second one 8m high and 640m long (Fig.18). Despite their dimensions these barriers will not achieve complete abatement and will therefore require the relocation of 5 buildings.

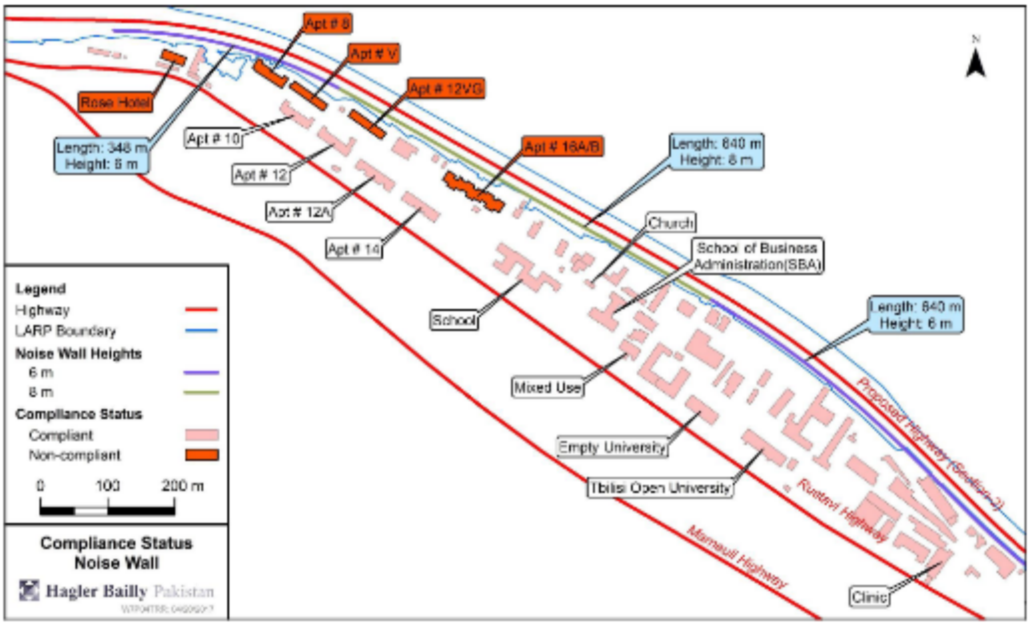


Figure 18 Layout and Compliance status for Noise Wall (Maximum height of 8m)

- **W'** (**Noise absorbing barrier with maximum height of 9 m**). In this solution three noise walls are recommended—one 6m high, 1,120m long, a second one 8m high and 240m long and a third one 9m high and 268m long (Fig. 19). These walls will not achieve reduce the noise to the threshold levels abatement and will therefore require the relocation of 4 buildings**.**

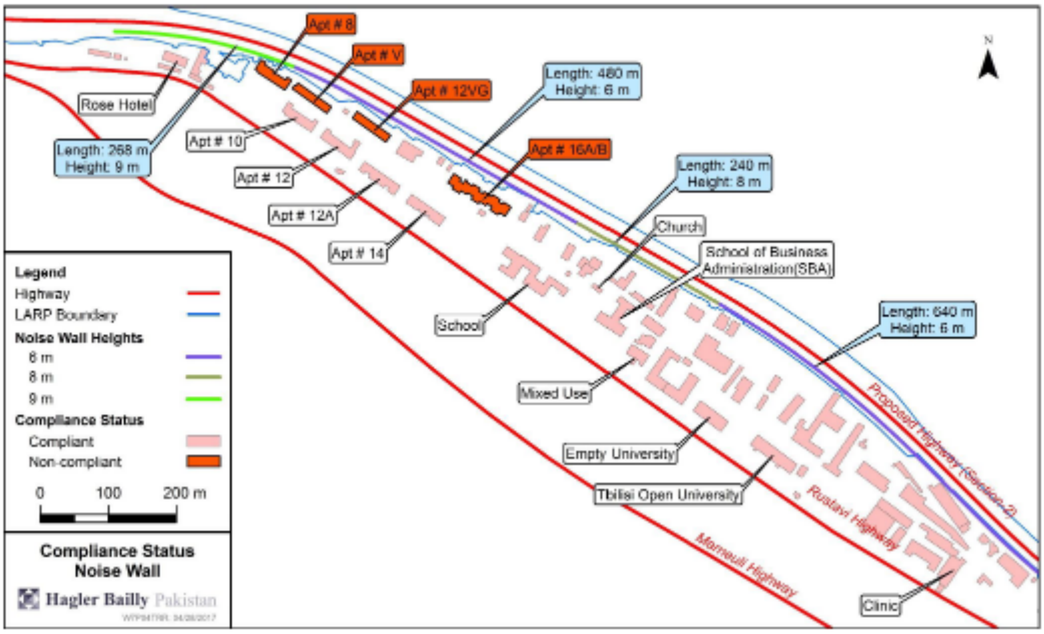


Figure 19 Layout and Compliance status for Noise Wall (Maximum height of 8m)

- **W + IRS** (**Noise wall with improved road surface**). In this solution a noise wall and improved road surface are recommended. The noise wall will be 5m high and 1,628m long (Fig.20). Despite its shorter length, about 26% less than previous options (noise wall only); it will be necessary to replace the standard asphalt with porous asphalt to reduce the noise at the source for a total length of 1.6 km.

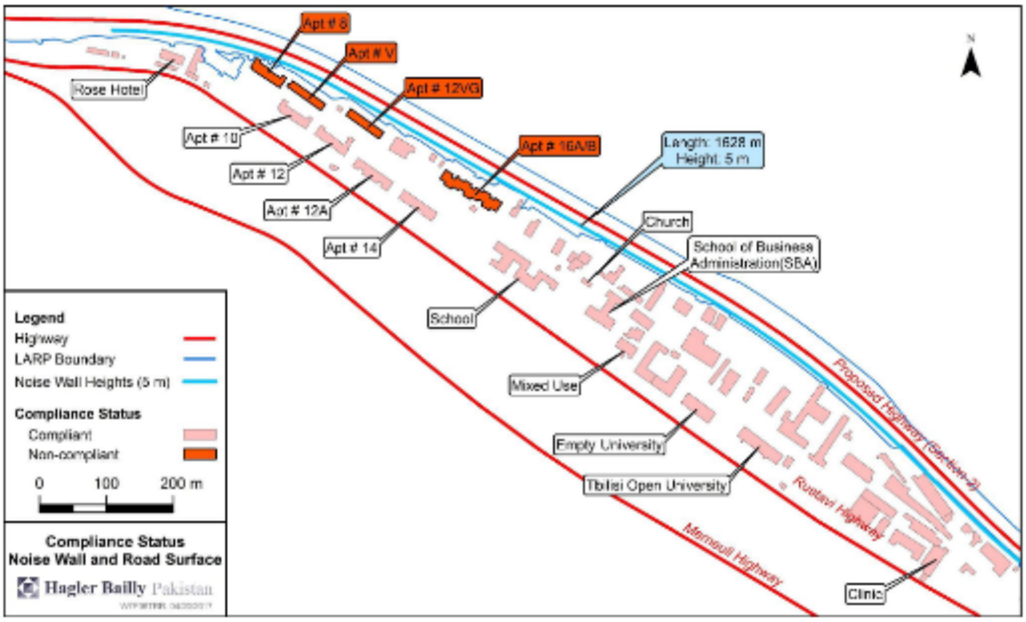


Figure 20 Layout and Compliance status for Noise Wall (Maximum height of 8m)

- **W + T** (**Noise wall with tunnel**). This last option requires the construction of one tunnel and a noise wall as shown in the below Fig.21. The tunnel will stretch for a length of 560m and will cover all lanes. Its height will be 5m, which is the same of the tunnel under the railway line. Two fulfill the goal of noise reduction two noise walls are also necessary: one 5m high, 880m long and a second 8m high and 188m long.

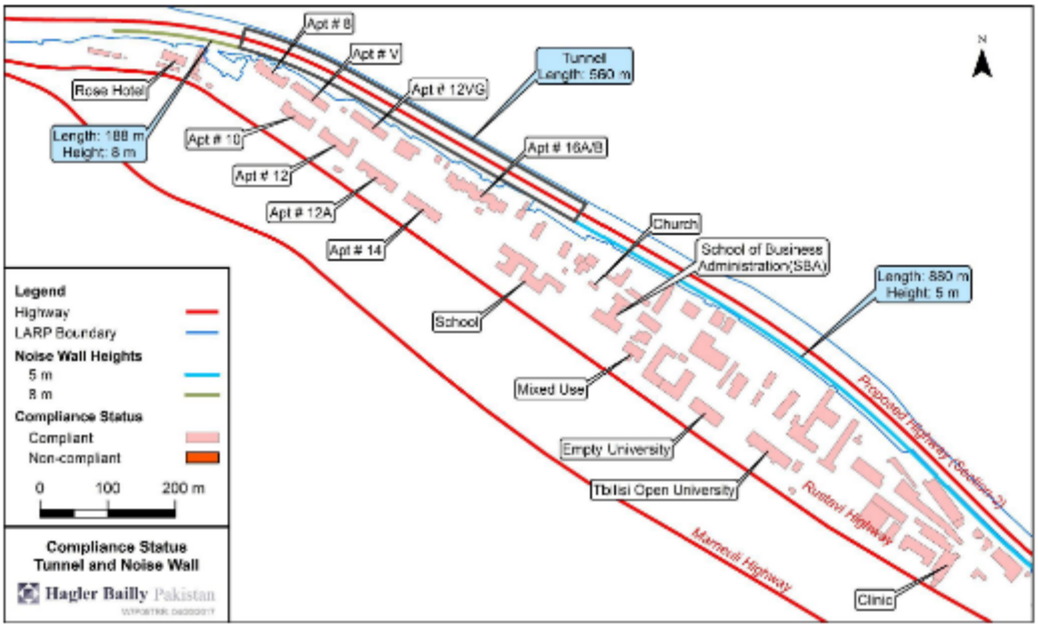


Figure 21 Layout and Compliance status for Noise Wall (Maximum height of 8m)

Examples of typical noise wall and noise tunnel are shown in Fig.22 and Fig.23.

Figure 22 A Typical Transparent Noise Wall

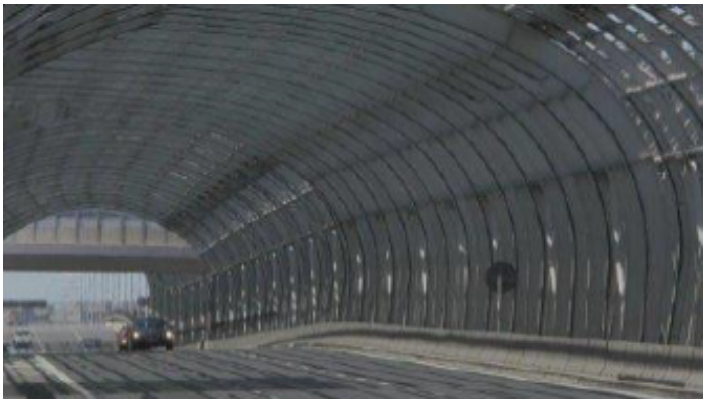


Figure 23 A Typical Tunnel Noise Barrier

Construction of noise mitigation structures suggested, regardless alternatives and their possible combinations, require anchoring and masonry structure to hold the columns of the barriers. The length and number of the columns will depending on the type and layout of these structures. The minimum distance between the noise barrier and the buildings as recommend in the noise modelling is in Table 15**.**

Building Code	Progressive Distance (m)	Minimum Distance from the Road (m)	Minimun Distance from the piles (noise mitigations) (m)
2	5Km + 300	9	6
3	5Km + 370	22	19
4	5Km + 470	19	16
5a	5Km + 660	27	24
5b	5Km + 660	27	24
5c	5Km + 660	27	24
6	5Km + 780	30	27
7	5Km + 370	52	49
8	5Km + 440	57	54
9a	5Km + 520	80	77
9b	5Km + 520	80	77
10	5Km + 600	87	84

Table 15 distances from the Road and foundations of noise mitigations (piles) to the buildings

International best practices for the construction of noise mitigation structures suggests there are two key methods and are:

a) **Precast Sound Walls** is selected for the sound walls due to cost or other considerations, **Drill Piling** is used to support the Precast Sound Walls – Field Installation Best Practices Manual, National Precast Concrete Association, USA (NCPA) - Annex 4 attached to this Report[1]. The best practices determined in this manual are in turn based on several relevant U.S. construction standards that are widely applied internationally as well. These standards are recommended to be referred to by the designer engineer of the noise mitigation structures and include:

- AASHTO R20 – Standard Practice Procedures for Measuring Highway Noise
- FHWA Highway Noise Barrier Design Handbook.
- NPCA Sound Wall Best Practices Manual
- NPCA Sound Wall Technical Brochure

For Backfill Placement and Compaction works, the Manual recommends “Compaction of the back ll shall be completed using lightweight compaction equipment so that the wall’s stability is not disrupted or compromised by vibration from operation of heavy equipment.

The other reference source for the noise mitigation structures is FHWA HIGHWAY NOISE BARRIER DESIGN HANDBOOK, U.S. Department of Transportation, Federal Highway Administration, FHWA-EP-00-005 DOT-VNTSC-FHWA-00-01, PB2000-105872. The Handbook outlines in detail the Types of Noise Barrier and their Acoustic Considerations; Noise Barrier Materials and Surface Treatments; as well as Structural, Drainage, Installation, Maintenance, Cost, Aesthetic, Effectiveness Assessment considerations and recommends approaches for the noise barrier design process. The Handbook considers, Concrete Slub Foundations (see Figure 24 below) as the proper and common solution[2].

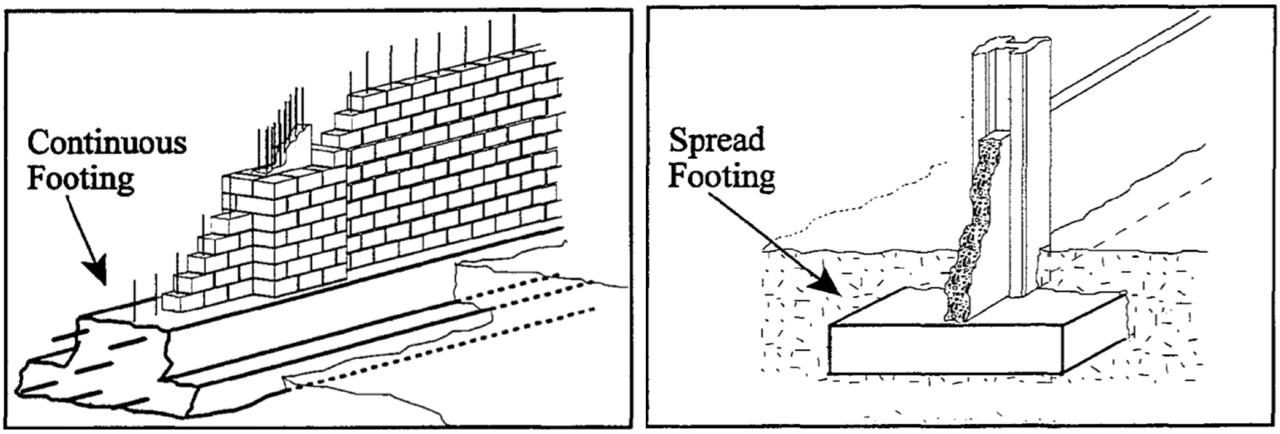


Figure 24: Examples of Concrete Slub Foundations with Continuous and Spread Footing.

[1] See Page 5 of the NCPA Manual.

[2] See FHWA Handbook, pages 4 and 13.

Construction of **Concrete Slub Foundations** requires shallow excavation works that do not require the use of heavy excavation machinery capable of producing vibration levels worth of considering.

Vibration impact due to piling: The data regarding vibration emissions of the equipment normally used in noise mitigation measures' construction is available in methodological reference sources – provided in Table 16 below. Construction vibration is generally assessed in terms of peak particle velocity (PPV). Table 16 gives typical vibration levels for representative types of equipment; as visible, the range of variation is very wide, but these tables provide a reasonable estimation for wide range of soil conditions. However, regardless the soil characterization parameters, it is clear that it is only the pile driver is capable of producing the vibration levels at the source of origination that is higher than the damage threshold of 105dB at the receiving point. As it is shown in Table 16, other equipment to be used cannot produce vibration impact equal or above damage threshold.

Equipment		PPV at 25 ft (in/sec)	Approximate L_v[†] at 25 ft
Pile Driver (impact)	upper range	1.518	112
	typical	0.644	104
Pile Driver (sonic)	upper range	0.734	105
	typical	0.170	93
Clam shovel drop (slurry wall)		0.202	94
Hydromill (slurry wall)	in soil	0.008	66
	in rock	0.017	75
Large bulldozer		0.089	87
Caisson drilling		0.089	87
Loaded trucks		0.076	86
Jackhammer		0.035	79
Small bulldozer		0.003	58

[†] RMS velocity in decibels (VdB) re 1 μinch/second

Table 16 vibration source levels for construction equipment – measured data (Source: Ground vibrations from impact pile driving during road construction, D.J. Martin, supplementary report 544, United Kingdom Department of the Environment, Department of Transport, 1980)

The data of vibration emissions of construction machinery are not available in machinery datasheets, for that it is a common and accepted practice to use the reference values reported in literature. As expected, pile driver impact produces the highest values of induced vibrations. The higher value of amplitude vibration (velocity) of the pile driver is equal to **1.518 in/sec**, which corresponds to **38.35 mm/s**.

The results of modeling of equipment vibration impacts at the receiver level of vibrations generated by pile driver for each building are provided in Table 17 below.

ANALYSIS OF INDIVIDUAL BUILDINGS

Table 17 is given below below for demonstration purpose only. The Table contains the data of modeling performed for comparison of vibration impact produced by drive piling (never considered or required for Phonichala area and not recommended in the Conclusions and Recommendations section below) with the vibration impact produced by a safe piling solution - drill piling.

Building Code	Minimum Distance from the Road (m)	Minimum Distance from the piles (noise mitigation structures) (m)	SOURCE		RECEIVER LEVEL VIBRATION		STRANDARD THRESHOLD
					Main building	Building annex	
			PILE DRIVER (dB)	Ref distance (X0) (m)	DRIVEN PILES	DRIVEN PILES	DIN 4150-3 /9916. impact on buildings (dB)
2	9	6	123.00	7.62	114.00	118.00	105
3	22	19	123.00	7.62	109.93	113.93	105
4	19	16	123.00	7.62	111.49	115.49	105
5a	27	24	123.00	7.62	107.55	111.55	105
5b	27	24	123.00	7.62	107.55	111.55	105
5c	27	24	123.00	7.62	107.55	111.55	105
6	30	27	123.00	7.62	106.22	110.22	105
7	52	49	123.00	7.62	97.63	101.63	105
8	57	54	123.00	7.62	95.84	99.84	105
9a	80	77	123.00	7.62	88.02	92.02	105
9b	80	77	123.00	7.62	88.02	92.02	105
10	87	84	123.00	7.62	85.73	89.73	105

Table 17 Summary of the simulated amplitude of vibrations at the receivers, compared with Standards (DIN 4150-3) – pile driver

Pile drivers generate the maximum vibration levels, especially during the start-up and shut-down phases of the operation because of the various resonances that occur during vibratory pile driving. Maximum vibration occurs when the vibratory pile driver is operating at the resonance frequency of the soil-pile-driver system. The frequency depends on properties of the soil layers where the pile is driven.

As reported in Table 17, for many buildings, the simulated amplitude of vibrations induced in an unlikely case of using drive piles exceeds the thresholds by standards. in particular, had pile driving been used:

- Buildings 2, 3, 4, 5, 6 would have been particularly vulnerable to vibrations and, for those buildings, structural damage is expected.
- Buildings 7, 8, 9, 10 are sufficiently far for the source of vibration (over 49m), so structural damage even using pile drivers wouldn’t have been expected.

As indicated above, neither the nature of the subsoil in Phonichala area require resorting to pile driving, nor drive piling has been considered or recommended in any document or discussion regarding building noise mitigation structures in Phonichala area. The FHWA HIGHWAY NOISE BARRIER DESIGN HANDBOOK[3] makes a reference to Pile Driving (and respectively - drive piles) as a risky solution - the risk that was confirmed by the impact modelling simulation (Table 17).

b) Noise mitigation structures with light weight pre-manufactured components are made of composite/polymer materials. There are multiple options to choose from in this type of structures depending of the type of material of the structure sections, precise configuration of the structure component set, installation techniques, cost, visual transparency, specific noise absorption capacity etc. In case light-weight composite material noise mitigation structures are selected, in terms of vibration, the execution design engineer should carefully examine the type of foundations required.

An example for a light-weight mitigation structure – the structures “AIL Sound Walls” is attached below (Please, see ANNEX 6: AIL SOUND WALLS, Engineering Noise Mitigation Solutions). The reference source is a company brochure that shows the examples of possible solutions, installation techniques including footing (fundaments) and discusses the advantages of this option etc. Please, see Figure 25 below for example of pile mounting applied for light-weight noise barriers.

Important disclaimer: the brochure AIL SOUND WALLS contains the information about particular product provided by a particular company. The brochure is referred and attached to this Report solely for illustrative purpose as one of multiple examples and by no means the Consultant Team endorses or recommends this particular product or company for any further activity related to the future construction of noise mitigation structures in Phonichala.

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[3] **Precast Sound Walls – Field Installation Best Practices Manual**, National Precast Concrete Association, USA (NCPA).FHWA HIGHWAY NOISE BARRIER DESIGN HANDBOOK, U.S. Department of Transportation, Federal Highway Administration, FHWA-EP-00-005 DOT-VNTSC-FHWA-00-01, PB2000-105872.

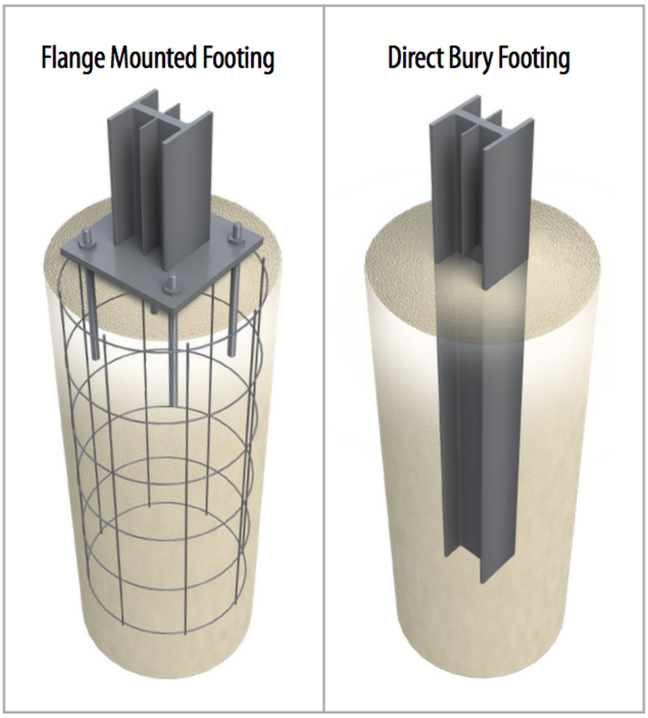

Figure 25: Examples of the footing (fundament) of a light-weight noise mitigation structure

The footing (shown in Fig 25) requires shallow piling as opposed to building concrete slub foundation discussed above.

Drill Piling (often also referred as Bore Piling) on the other hand is considered in international best practices as a safe solution in terms of vibration emissions, not to mention other advantages.

Using drilled piles provides several advantages:

- No casing installation required
- Little working space required
- Marginal distances to nearby buildings possible
- Low vibration and noise level
- No impact on ground water
- No unnecessary pile lenghts required
- No underground cavity formation

Bored piles cast in situ are made at a very low vibration levels and on practice, in the similar cases, it is assumed that the level of vibration produced by drill piling is negligible. It is recommended to use two different sizes of shaft diameters ranging from 40cm to 60cm. Higher values of diameters will require more noisy and heavy equipment that conservatively could generate considerable vibrations on the buildings.

International best practice reference sources provide no reference to vibration generated by drill piling and the manufacturers of drilling machines for piles (who for obvious reasons of legal liability are obliged to be guided by a set of regulations including those related to vibration impacts) declare zero vibration emissions for this type of drilling. Yet, conservatively, the modelling of drill pile impact to the Phonichala buildings was performed while factoring in drill piling vibration levels taken as equal to those produced by roller compactor. The results of modeling are provided in Table 18 below.

Building Code	Minimum Distance from the Road (m)	Minimun Distance from the piles (noise mitigations) (m)	SOURCE		RECEIVER LEVEL VIBRATION		STRANDARD THRESHOLD DIN 4150-3 /9916. impact on buildings		
					main build	annex			
			PILE (dB)	Ref distance (X0) m	PILES	PILES	category 2 long - short duration (dB)	category 3 short duration (dB)	category 3 long duration (dB)
2	9	6	104,00	7,62	95,00	99,00	105	100,5	99
3	22	19	104,00	7,62	90,93	94,93	105	100,5	99
4	19	16	104,00	7,62	92,49	96,49	105	100,5	99
5a	27	24	104,00	7,62	88,55	92,55	105	100,5	99
5b	27	24	104,00	7,62	88,55	92,55	105	100,5	99
5c	27	24	104,00	7,62	88,55	92,55	105	100,5	99
6	30	27	104,00	7,62	87,22	91,22	105	100,5	99
7	52	49	104,00	7,62	78,63	82,63	105	100,5	99
8	57	54	104,00	7,62	76,84	80,84	105	100,5	99
9a	80	77	104,00	7,62	69,02	73,02	105	100,5	99
9b	80	77	104,00	7,62	69,02	73,02	105	100,5	99
10	87	84	104,00	7,62	66,73	70,73	105	100,5	99

Table 18 Summary of the simulated amplitude of vibrations at the receivers, compared with Standards (DIN 4150-3) – pile drilling

Note: the column “category 2 long-short duration (dB)” contains the figures for Long AND Short vibration because for category buildings, according to DIN 4150-3, these values are similar.

The results of conservative modeling given in Table 18 show that the impact of pile drilling at the receiving points is lower than damage threshold.

The maximum pile length that can be obtained is 16m and 8m respectively (Table19).

Pile diameter	40 cm	60 cm
Maximum pile length	16 m	8 m
Bearing Capacity*	300–500 kN	300–600 kN
Device	caterpillar	truck with crane
Daily output	8–10 piles	10–12 piles

* depending on the existing subsoil and the bond length

Table 19 – drilled piles – length and diameters usable

The maximum values of diameters that can be used during the construction of the noise wall and tunnel are given in Table 20.

Building Code	Minimum Distance from the Road (m)	Minimun Distance from the piles (noise mitigations) (m)	Type of Pile	Maximum diameter pile (Ø cm)
2	9	6	Drilled	60
3	22	19	Drilled	60
4	19	16	Drilled	60
5a	27	24	Drilled	60
5b	27	24	Drilled	60
5c	27	24	Drilled	60
6	30	27	Drilled	60
7	52	49	Drilled	80
8	57	54	Drilled	80
9a	80	77	Drilled	80
9b	80	77	Drilled	80
10	87	84	Drilled	80

Table 20 – type and diameters of piles recommended during the construction of noise mitigation structures

Although formally the calculations show that for Buildings 7, 8, 9, 10, the diameter of drilled piles can be incremented up to 80cm, because of the high distance between source-receivers (52m – 87m), still the limitation of 60 cm diameter shall apply because Buildings 7, 8, 9, 10 are located behind the other most impacted buildings.

CONCLUSIONS AND RECOMMENDATIONS ON VIBRATION GENERATED THROUGH CONSTRUCTION OF THE NOISE MITIGATION STRUCTURES

To summarize the analysis provided in this section, the following mandatory recommendations should be made:

1. **Pile drilling, as opposed to pile driving should be used** shall the execution design engineer choose a structure involving pile footing for noise mitigation structures (these could be light weight pre-manufactured components, as recoemmended by the Noise Modeling study). In such case, the diameter of piles shall be limited to 60 cm diameter for the full length of the mitigation structure alignment in front of buildings in focus.

2. **Reinforcing the Annexes (the same as voluntary additions)**: The same recommendation as made for the vibration impact caused by construction works and road operation – applies. Even though modelling showed no risk of damage to the annexes, due to the condition of Annexes determined by their faulty design, practical difficulties related to establishing that the road-related activities have not been the cause of a damage, and most importantly, lack of safety of the Annexes at any time since the day of their construction – it is recommended to reinforce the Annexes. The engineering design of reinforcement works reported under the assignment of NEP Srl. can be used in implementing reinforcements. The suggested method is effective, least expensive and possible to implement in the shortest period of time.

Furthermore, similarly to the road construction and maintenance works:

3. **Monitoring for compliance**: The mitigation measures construction works should be carefully monitored for compliance with the set parameters. The supervision mechanism should include the tools of immediate identification of the problem and the authority of the supervisor agent to halt works, record the non-compliance and issue a mandatory corrective action instruction to the contractor.

Standards to be considered by the execution design engineer shall be guided by reference sources relevant to the selected type of structure and fundament - such as: Precast Sound Walls – Field Installation Best Practices Manual, National Precast Concrete Association, USA (NCPA), AASHTO, FHWA, NPCA references quoted thereby; and FHWA HIGHWAY NOISE BARRIER DESIGN HANDBOOK, U.S. Department of Transportation, Federal Highway Administration as well as other relevant guideline references quoted in the Handbook or similar internationally recognized standards.

7. SUMMARY TABLE OF ALL FINDINGS

For convenience, a summary of the results obtained by the numerical simulations are reported in Table 21.

Building Code	Minimum Distance from the Road (m)	VIBRATIONS CONSTRUCTION WORKS (dB)				VIBRATIONS OPERATION CONDITIONS (dB)		VIBRATIONS NOISE MITIGATION (dB)			STRANDARD THRESHOLD DIN 4150-3 /9916. impact on buildings		
		roller compactor		pneumatic hammer		traffic	traffic	piles		Maximum diameter DRILLED pile (Ø cm)			
		main building	annex	main building	annex	main building	main building	main building	main building		category 2 long - short duration (dB)	category 3 short duration (dB)	category 3 long duration (dB)
2	9	82,36	86,36	79,36	83,36	70,62	74,62	95,00	99,00	60	105	100,5	99
3	22	76,93	80,93	73,93	77,93	65,19	69,19	90,93	94,93	60	105	100,5	99
4	19	78,38	82,38	75,38	79,38	66,65	70,65	92,49	96,49	60	105	100,5	99
5a	27	74,67	78,67	71,67	75,67	62,94	66,94	88,55	92,55	60	105	100,5	99
5b	27	74,67	78,67	71,67	75,67	62,94	66,94	88,55	92,55	60	105	100,5	99
5c	27	74,67	78,67	71,67	75,67	62,94	66,94	88,55	92,55	60	105	100,5	99
6	30	73,40	77,40	70,40	74,40	61,66	65,66	87,22	91,22	60	105	100,5	99
7	52	63,00	67,00	60,00	64,00	51,27	55,27	78,63	82,63	80	105	100,5	99
8	57	61,24	65,24	58,24	62,24	49,51	53,51	76,84	80,84	80	105	100,5	99
9a	80	55,49	59,49	52,49	56,49	43,76	47,76	69,02	73,02	80	105	100,5	99
9b	80	55,49	59,49	52,49	56,49	43,76	47,76	69,02	73,02	80	105	100,5	99
10	87	53,22	57,22	50,22	54,22	41,48	45,48	66,73	70,73	80	105	100,5	99

Table 21 summary of vibrations induced by construction road, operation conditions and noise mitigation structures with drilled pile foundation

Note: the column “category 2 long-short duration (dB)” contains the figures for Long AND Short vibration because for category buildings, according to DIN 4150-3, these values are similar.

The results obtained by the numerical simulations are sufficiently lower than the thresholds assigned by the Standards for residential buildings (assuming mandatory recommendations for piling works during construction of noise mitigation structures are followed), considering the poor state of conservation of all buildings, in particular of the annexes, **a vibration monitoring during operation of the Urban Road and noise mitigation structures is recommended** as indicated in recommendations section above**.**

The aim of **vibration monitoring campaign** is checking the vibrational levels considering any critical conditions or changes in the situation before work and the operating conditions, in defined points.

The vibration monitoring ensures the adequate knowledge and control of the phenomenon of vibration, in relation to potential effects induced by construction works and road operation and maintenance.

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8. ANNEXES

ANNEX 1: Input data (entered in the model)

ANNEX 2: Raw data of measurements of vibration from present day road – separate attachment

ANNEX 3: Outputs of modeling (data tables)

ANNEX 4: Field Installation Best Practices Manual, National Precast Concrete Association, USA (NCPA).

ANNEX 5: FHWA HIGHWAY NOISE BARRIER DESIGN HANDBOOK, U**.S. Department of Transportation, Federal Highway Administration, FHWA-EP-00-005 DOT-VNTSC-FHWA-00-01, PB2000-105872.**

ANNEX 6: AIL SOUND WALLS, Engineering Noise Mitigation Solutions *(an example of international best practices)*