APPENDIX I

Modeling of Vibration generated by tunneling activities in the calcarenitic formations along the tunnel TUN-4006 of F4 section

1. GENERAL APPROACH IN ANALYSIS

This report refers to the study carried out in order to estimate and evaluate the critical environmental issues, in terms of vibration, which will be generated by the construction of the new highway and the related tunneling activities in the carbonatic and volcanic formation formations.

The goal is to estimate of vibration levels during Road construction generated by those processes involving the use of all the categories of machinery (Bull Dozers, Motor Graders, Wheel Excavator, Wheel Loader, Vibro Roller, Tandem Roller, Roller Tire, Pneumatic Hammer, Dump Truck) necessary to complete the work. In particular, the analysis to evaluate the level of vibrations in nearby houses has been carried out by the following steps:

- Estimating/determining the vibration levels expected in the buildings as a result of the construction works of the new road, using a forecasting model based reference data sets;
- Verifying the reliability of simulated values by comparison with the permissible limits posed by international reference standards;
- Identification of monitoring during construction and post-operam and mitigation measures (if necessary).

2. FRAMEWORK OF IMPACT PROBLEMS AND PROVIDED ACTIVITIES

Vibration problems during the construction phase are the result of the direct emission of vibrations generated by the working activities and by the emission of low frequency noise, as represented in term of cause-effect in Table 1.

Problems	Principal causal factors	Potential effects
Vibration	Demolition of rock banks with jackhammers, sledgehammers Excavations by mechanical means Carryovers by mechanical means Compaction embankment substrates made with vibro-rollers or rollers Transit of heavy vehicles (Dump Truck, Concrete Mixer Truck,…)	Vibrations transmitted from the ground to the structural elements of buildings, with the emission of noise through solids
Low frequency noise emission	Machines in the construction site	Vibrations structural elements (windows and furniture's) with emission of noise in correspondence of the resonance frequencies

Table 1 - Causal factors and potential impacts

In general, the aspects influencing the level of vibro-acoustic noise in receptor buildings are mainly the following (see Table 2):

Factor	Mode of influence
Nature and characteristics of the soil	vibrations are more expected in the presence of rigid subsoil and rock
Distance between plano-altitude of construction sites and building foundations	vibrations tend to decay by the distance from their source according to an exponential curve
Features of the foundations of buildings	The loss of energy of vibration due to the coupling with foundation is greater in case of high-bearing foundations,– i.e. bigger is the bearing capacity of foundation more vibration energy of can be absorbed. The coupling losses also depend on the type of foundation
Structural characteristics of the buildings	vibrations inside the building are lower with the increasing mass of the building

Table 2: Factors and Modes of Influence in Vibration Transmission

3. ANALYSIS OF POTENTIAL ADVERSE EFFECTS

To produce a significant effect, the sources of vibration must be in proximity of to the buildings and according to the scientific literature no more than a few tens of meters.The effects of vibrations in buildings can range from a nuisance to exposed people, to architectural or structural damage.

Vibration sources such as construction activities can cause discomfort to the residents of buildings and in some cases could be of possible of potential damage to structures, especially in the presence of particularly critical structural conformation and/or use).

In general structural damage to the building caused by vibration phenomena are extremely rare and almost generally generated by the contribution of other factors. Other forms of damage, defined “threshold level", is the one that without compromising the structural safety of the buildings, can cause a reduction of the value or the use. The damage threshold takes the form of cracks in the plaster, enhancements of existing cracks, damage of architectural elements.

4. REFERENCE STANDARDS

There are several technical standards, which constitute a useful reference for the evaluation of the disturbance and damages caused by vibration phenomena.

For the disturbance to people, the main references are:

- ISO 2631 / Part 2 "Evaluation of human exposure to whole-body vibration ",
- UNI 9614 regulation "Measurement of vibrations in buildings and evaluation criteria of the disorder."

For damage to the buildings the main references are:

- UNI 9916 "Criteria for measuring and assessing the effects of vibration on buildings",
- DIN 4150 and BS 7385.

The above standards provides a guide for the selection of appropriate methods of measurement, data processing and evaluation of the vibratory phenomena for the evaluation of the effects of vibration on buildings (risk of structural damage), with reference to their structural response and architectural integrity.

The physical quantities used to quantify the effects of vibration on humans and on building structures are described below.

Induced Vibratory phenomena are the motions of structures (in this case building and constructions) at frequencies ranging from 1 to and 80 Hz. The characterization is carried out in terms of effective average value (RMS) of the speed (in mm/s) or the acceleration (in mm/s2). Speed is usually used to evaluate the effects of vibrations on buildings, and acceleration (weighted) to assess the human perception.

Measurement, are normally done by accelerometers, providing the level of acceleration, or "geophones", providing a signal proportional to the speed.

Converting the acceleration values “a” to the corresponding values of speed “v”, can be done , having the frequency, “f”, by the relation: v = a / 2 π f .

According to the noise analysis, both speed values and acceleration are evaluated on the scale of dB, by the relations:

$$L_{acc} = 20\log\frac{a}{a_0}$$ **where** $$a_0 = 0.001\,{}^{mm}\!/\!_{s^2}$$ **= 10^{-6} m/s^2**

$$L_{vel} = 20\log\frac{v}{v_0}$$ **where** $$v_0 = 1\cdot 10^{-6}\,{}^{mm}\!/\!_{s}$$

DESTINATION OF USE	LEVEL (dBpa)		ACCELERATION (mm/s^2)		VELOCITY (mm/s)	
	Z Axis	XY Axes	Long.	Crossing	Long.	Crossing

Critical areas	74	71	5.0	3.6	0,10	0,28
Residential buildings (night)	77	74	7.0	5.0	0,14	0,40
Residential buildings (day)	80	77	10.0	7.2	0,20	0,56
Offices	85	83	20.0	14.4	0,40	1,10
Factories	92	89	40.0	28.8	0,80	2,20

Table 3: Values and limit levels of acceleration in weight of vibration disturbance (UNI 9614 – DIN 4150-2).

Category	Types of constructions	Velocity of vibration in mm/s *			
		Measurement at the foundation			Measurement at the last floor
		Frequency ranges (Hz)			Various frequencies
		< 10	10 ÷ 50	50 ÷ 100 **	
1	Buildings used for commercial purposes, industrial buildings and similar	20	20 ÷ 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
** Frequencies greater of 100 Hz should be referred to this column

Table 4: Reference values for the speed of vibration to evaluate the action of short duration vibrations on buildings (UNI 9916 – DIN 4150-3)

5. POTENTIAL IMPACT ON BUILDINGS

The present study has the goal to estimate the induced vibrations in the buildings during the construction phase and the evaluation in terms of disturbance to people (UNI 9614, DIN 4150-2) and damage to buildings (UNI 9916, DIN 4150-3). The following lists the procedural steps followed:

1. Identification of the potentially impacted buildings and evaluation of their distance from the construction sites of the new Road.
2. Analysis of the highway project in correspondence of settlements and buildings Analysis of the geotechnical characteristics of the foundation soils and bedrock
3. List of construction machines used in the construction of the highway in correspondence areas of interest. Analysis of about the vibrations spectra generated by the used construction machines.
4. Estimation of surface vibration levels using, in order to evaluate the attenuation due to the propagation of waves in the ground, the formulations proposed in the literature (for example Dong-Soo Kim, Jin-Sun Lee and GP Wilson).
5. Analysis literature data concerning the propagation of vibrations to the interior of buildings, in order to obtain transfer relationships of acceleration levels between exterior and interior building for various types of buildings.
6. Estimate of inside buildings vibration by application of the transfer function evaluation of vibration levels inside buildings by comparison with the limits set by the regulations.
7. Identification of critical points and possible mitigation actions.

6. EMISSION SPECTRA OF THE WORKSITE MACHINERY AND EQUIPMENTS

The vibration emissions in the construction phase are widely variable in relation to the type of equipment/operating machinery employed, to the context of use and to the operator. In this study we were used both data source bibliographic either data directly acquired through measures carried out in construction of large works in Italy.

As regards the bibliographic data, it was in particular used the volume LH Watkins - "Environmental impact of roads and traffic" - Appl. Science Publ., which represents a set of experimental data on the emission of vibrations by various types of construction machines, used in road construction.

On Table below is shown the acceleration levels in dB at various frequencies of certain construction machinery that have greatest impact (Hydraulic Hammer and Roller Compactor), measured at 5m and 2m away from the source of vibration.

Other machinery type Dozer, Motor Grader, Wheel Excavator, Wheel Loader, Dump Truck have lower levels of acceleration and therefore are not able to create vibrations that can exceed the limits set by the standard.

The frequency of vibration produced by equipment is expressed in Hz, and level of vibration is expressed in dB.

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 5: Levels of vibration of various machinery on respect of the frequency.

Notice that max amplitude of vibration occurs at frequencies range from 25 to 50 Hz. This frequencies range was considered in the analysis.

In Picture below are shown acceleration spectrums, of some machinery measured at 5m distance from the source of vibration in which it can be noted that the Hydraulic Hammer and the Drum Roller are machinery greatest impact, with acceleration levels emitted around 100dB for good part of the spectrum.

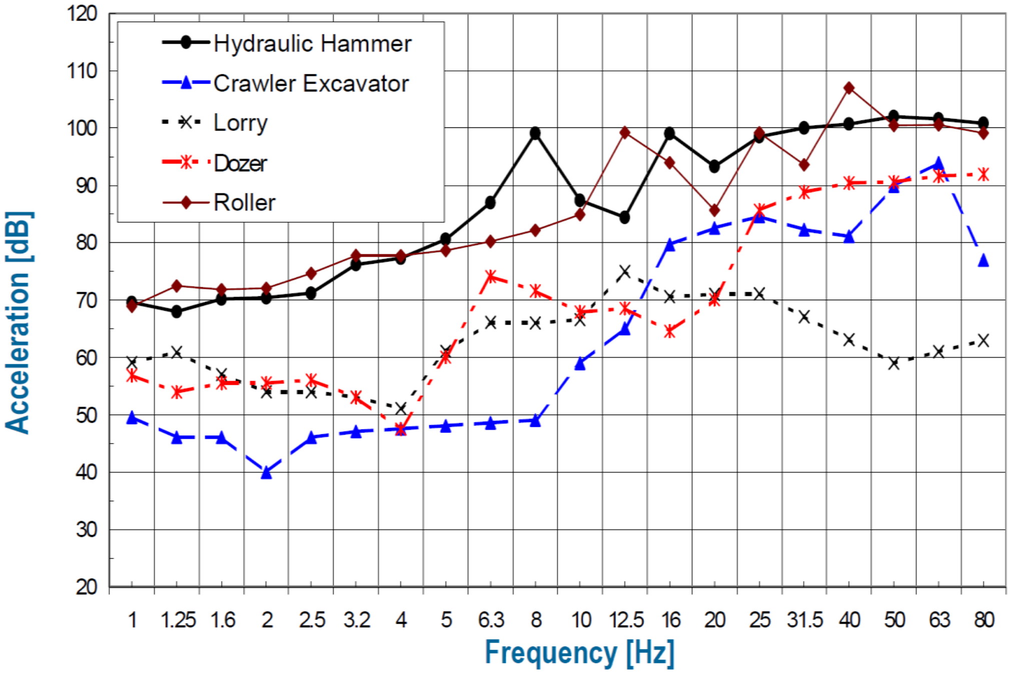

Figure 1: Acceleration spectrum of different machinery.

7. DYNAMIC CHARACTERISTICS OF SUBSOIL

Due to vertical in homogeneity of the subsoil, carbonatic and volcanic formations covered by a weathered/alterated material and alluvial soil, it can be assumed that important attenuations and modification of spectrum –toward lower frequencies- with will occur at the transition between the competent (hard) formation and the alterated layer/alluvia-vegetal soil where the shallow foundations of buildings are inserted.

The situation of the uppermost part of the subsoil – arable, alterated and alluvial- can be represented by the average values shown below, obtained by the geotechnical investigations and geophysical measurements.

It is also important to consider the below formula and table showing the formula of attenuation and some typical damping parameters attenuation due to the absorption of the ground

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

Where: $\omega = 2\,\pi\,f$ is the pulsation wave (with f = frequency in Hz)

c is the speed of wave propagation in the soil in m / s

η is the absorption factor of the soil

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

Table 7: Values of the damping parameter as a function of the soil type

In the above expression the exponential term represents dissipation phenomena of mechanical energy, which is dependent on the frequency, on the propagation velocity and on the loss mean factor. This means that the high frequencies are extinguished after a short distance, while lower frequencies propagate at greater distances.

In particular for the overburden soil above the calcarenitic formation the level of acceleration at the distance “r” from a point source of energy is given by:

$$\square(\square) = \square_0 + 10\ \square\square\square\ (\square_0 / \square) - 8{,}69\ \square\ (\square - \square_0) \qquad \square\square$$

Where:

- L_0 is the reference level;
- d_0 is the reference distance for L_0;
- r is the distance from the source;

- α is the attenuation constant of the terrain.

The term relating to the dissipation of mechanical energy is obtained by the relationship $e^{-\alpha(r-d0)}$.

The values of "α" given from Rudder are the following:

TYPE OF TERRAIN	SHEAR-WAVE VELOCITY (m/s)	α x m
Moist clay	152	0,025-0,25
Alluvial deposit of clay	152	0,019-0,43
Wet clay	152	0,31-0,50
Deposits to ambient humidity	259	0,04-0,13
Dry sand	152-396	0,007-0,07
Compact sand with gravel	250	0,015-0,045
Gravel and deposit sand	250	0,023-0,053
Gritty sand saturated with water	110	0,09-0,3
Gritty sand saturated with ice water	110	0,05-0,17

Table 7: Values of the attenuation constant "α" for different kinds of soil and for the frequency of 15 Hz

The above values were obtained for the frequency f=15 Hz and for α = 2□□η / where "η" is the loss factor of the terrain and "c" is the speed of propagation by the transverse propagation mode.

8. TYPE OF EQUIPMENTS USED IN CONSTRUCTION AND TYPICAL EMISSION SPECTRA/ATTENUATION OF MACHINERIES AND BLASTING CHARGE

In the case of evaluation of the impact of vibration sources realized, simple analytical formulas allow an approximate calculation of the attenuation of the vibrations as a result of propagation in the soil.

In the scientific literature there are tables and diagrams allowing estimating the attenuation or amplification caused by the various structural components of buildings. By combining this information, it is possible, with some approximation (typically +/- 5 dB) to estimate the levels of vibration that will develop in potentially impacted buildings. Taking into account uncertainty above, it can still evaluate whether the planned source of vibration is potentially impacting, or if the same is certainly acceptable.

The vibration level at a receiver at a distance "x" from the point at which it is generated is equal to the level at the reference distance "x_0", minus the sum of the attenuations that occurring in the soil between "x_0" and "x":

$$\mathbf{L(x) = L(x_0) - \Sigma i A i}$$

The basic level $L(x_0)$ is generally derived from experimental measurements at distances between 2m and 25m. The components of attenuation and amplification of vibrations in the ground and on the building, introduced in the calculation model as average values, are:

- geometric attenuation, in relation to the type of source and wave;
- attenuation for internal dissipation of the soil;
- Attenuation due to obstacles or discontinuity of the ground.

The below table shows the decay diagram of the vibration velocity for certain types of machineries.

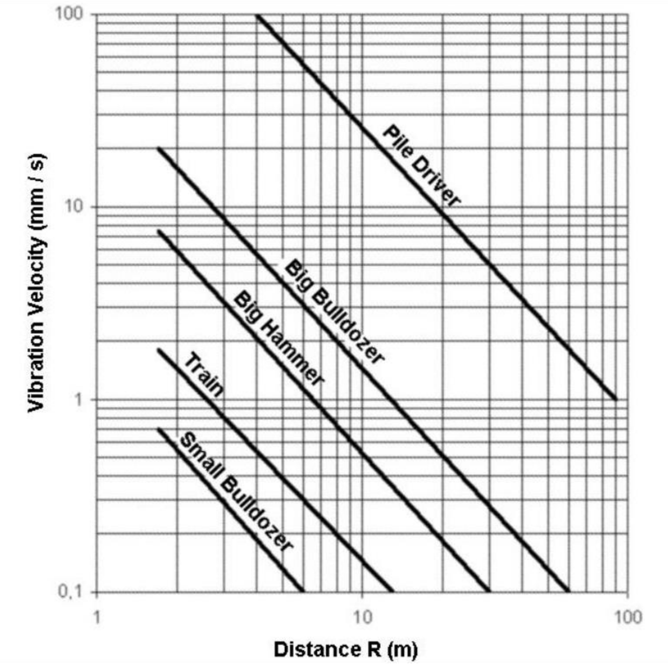

Figure 2: Decay curves of the vibration velocity

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 8: Values of attenuation due to radiation damping for various combinations of source location and type

Considering that, for a conservative estimation a concentrated source has to be estimated, the exponent "n" should be 0.5 for the surface waves (prevailing in the case of source placed on the surface), and "n" equal to 1 for the volume waves which are prevailing in the case of deep source such as in tunnels.
The assessment of attenuation or the amplification in the buildings structure must also be considered.

Various types of foundation systems can determine attenuations or amplifications, inside buildings compared to the levels on the ground.

In particular for the type of buildings which are prevalent in the area of the tunnels, it should be considered that these shallow and small foundations should determine a certain attenuation of the acceleration levels in the buildings for the fact that the interface soil-structure is not perfectly coupled and also small. For that the system soil-foundation will generate s dissipative phenomena. The attenuation caused by bad ground-foundation coupling is illustrated in Figure 3 for different categories of buildings. The category of large reinforced concrete buildings with continuous foundations can be associated to large buildings in masonry with continuous foundations which curve suggests an attenuation of 2 dB.

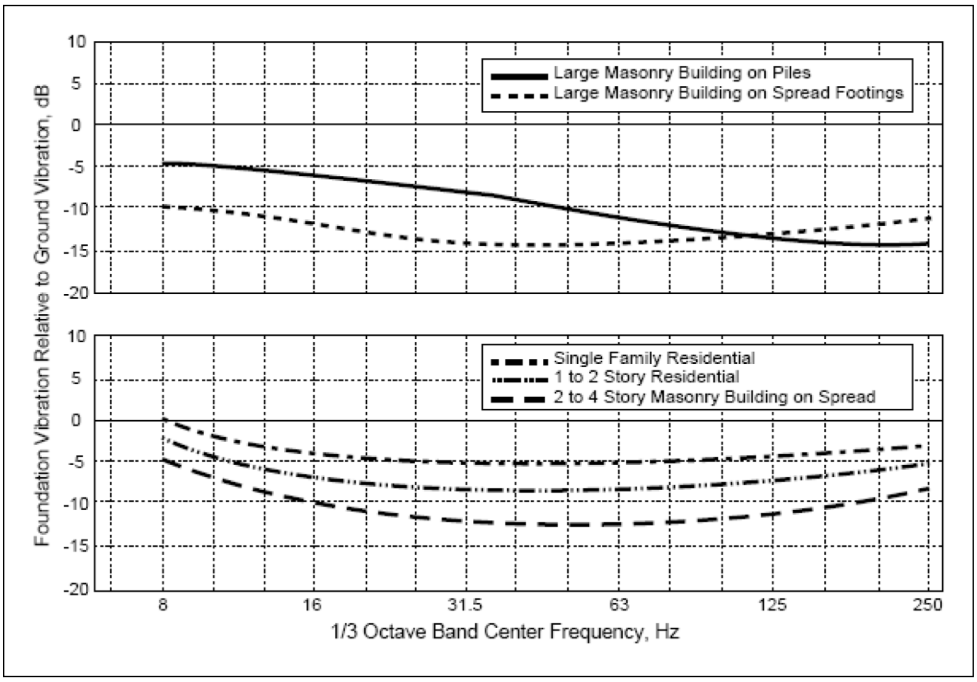

Figure 3 - Coupling losses for various types of buildings

The Table below shows the results at various frequencies of such interaction effects with the structures. In particular these are the standard parameters used in modeling and similar analysis.

Band (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
Loss by coupling the soil-foundation (masonry building)	4.8	4.8	4.8	4.8	4.8	4.8	4.9	5.0	5.1	10	11	12	13	13	14	15	15	15	14	14
Loss by coupling the soil-foundation (concrete building)	3	3	3	3	3	3	3	3	3	8	9	10	11	11	12	13	13	13	12	12
Attenuation by propagation from floor to floor	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	3.0
Amplification of the horizontal elements	4.5	4.5	4.4	4.4	4.3	4.2	4.0	3.8	3.6	3.3	3.0	1	4.4	16.5	4	0.0	0.0	0.0	0.0	0.0

(dimension 4-5m)																				

Table 9: Reference parameters for the calculation of the interaction with structures

9. CALCULATION OF VIBRATIONS DURING EXCAVATION OF TUNNEL TUN-4006

Based the above considerations, and given the fact that the vibrations transmission to the ground is a side effect difficult to reduce, mostly during tunneling activities; the best approach is to consider the risk/disturbance for the population and buildings and to enforce the actions required for the mitigation of these effects.

In the studied case, the modeling does not point out levels of risk for standard buildings due to the excavation techniques and the attenuation provided by the cushion of alterated/weathered rock and arable/vegetal soil. in addition the type of foundations of the buildings, shallow and small, will determine an additional damping factor.

According to the recorded geomechanical parameters and stratigraphy for the computation of attenuation the following model should be considered:

- Tunneling technique: Roadheader from 7 to 10 m below the surface (as a conservative approach a TBM computation has been applied)
- Medium of propagation:

Calcarenites (N_1^2)at the source followed by:

2 meters of weathered calcarenites followed by

4 meters of alluvial soil (eQ) and 1 m of topsoil

For simplicity the topmost soil and the Alluvial deposits can be modelized as a single layer having a thickness of about 5 meters.

The sequence is characterized by an inversion of the VP and VS waves, suggesting a poor propagation of the energy in the upward direction

Layer n.	Lithology	Bed depth	Thickness	Waves velocity		Dynamic density	Poisson Modulus	Dynamic Elastic Modulus	Dynamic Shear Modulus	Dynamic Compressibility Volumetric Modulus	Dynamic Compressibility Edometric Modulus	Vp/Vs
				Vp	Vs	γ	ν	E_d	G_d	K_{dv}	K_{de}	
		(m)	(m)	(m/s)	(m/s)	(t/m³)	(-)	(kg/cm²)	(kg/cm²)	(kg/cm²)	(kg/cm²)	(-)
1	Soil	1	1	300	130	1,51	0,38	705	255	1017	1357	2,3
2	eQ	5	4	500	230	1,66	0,37	2400	879	2981	4153	2,2
3	Weathered N_1^2	7	2	1240	720	1,97	0,25	25493	10233	16707	30350	1,7
4	N_1^2	-	-	2340	1320	2,23	0,27	98299	38803	70204	121942	1,8

Table 10: Stratigraphy of the terrain starting for surface for tunnel TUN-4006 and relevant parameters

In a very conservative assumption it can be assumed that:

- The vibrations generated at the source will propagate with velocity of 10 mm/s (conservative source: big hammer and bulldozer);
- After travelling 2 meters into the weathered calcarenites, vibration at the boundary weathered calcarenite-alluvial soil are estimated at 7-8 mm/s. A strong backscattering is expected at this boundary due to the strong inversion of Vp and Vs velocity.
- After this points vibrations will be strongly attenuated by the travel into 5 meters of alluvial soil with poor geomechanical parameters. (Vs velocity decreased by 70%, Vp velocity decreased by 50%),
- The expected value at the surface will be 5-4 mm/s .
- At this point the coupling with the foundations will generate a further dumping effect whose amount depends on the type of foundation.

The results of calculations fit with the results provided in the scientific literature for tunnels done by TBM, which represents a stronger source of noise.

<u>For the above consideration an area of influence has to be considered with a distance from the source of 20 meters (total width about 75 meters) also in consideration of the poor quality of the building.</u>

For that it is recommended to proceed with photo-documentation of the state of the buildings, to avoid conflicts with the population and to set up a couple of monitoring stations to have reference data to provide in case of controversy (see figure 4).

Figure 4 – Area of influence and buildings potentially affected

1.