VIBRATION INDUCED BY A METRO LINE: FROM PRELIMINARY ASSESSMENT TO EXPERIMENTAL VALIDATION

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The vibration impact assessment of a subway line in a major city urban environment represents a fundamental step in the design process. The results expressed in terms of expected level of vibration and ground-borne noise induced in the buildings by the train passages may lead to the adoption of impact mitigation measures. Considering that the budget for the realization of the subway line is usually consolidated during the initial phases of the project, the vibration impact assessment is usually carried out on numerical simulations (calibrated on measurement conducted in other contexts) and/or literature data, to be verified in the following phases of design.

This paper is aimed at describing the approach to the vibration impact assessment pursued for the design of the extension of the new driverless automatic system of Metro 5 (M5) line in Milan. During the Tender Design (TD), carried out by Metropolitana Milanese (MM) with the support of Studio Geotecnico Italiano (SGI), the preliminary vibration assessment was based on the measurement of the source carried out along other metro lines in Milan, while the evaluation of the vibration attenuation from the tunnel to the surface level and the structural response of buildings were conducted by means of empirical relationships calibrated or verified on literature data.

The preliminary assessment of the vibration path was thus improved during the Detailed Design (DD) by ALSTOM and SGI by means of a specific campaign of measurements which comprised an updating of the source measurement (this time conducted along a stretch of the same Metro 5 line already operational), the attenuation in the soil (by using specifically an artificial source of vibration) and the assessment of the structural response of representative buildings carried out with environmental sources of vibration (city trains, tramway).

The results obtained from the analyses of the experimental data gathered during the DD substantially confirmed the assumptions made during the TD regarding the entire vibration path. The choices made in terms of localization of the mitigation measures (mass-spring concrete slabs) along the subway line were also confirmed.
1. Introduction

The studied M5 subway line in Milan is a driverless automatic railway infrastructure running from Bignami Station (located in the northern part of the town) to San Siro Stadium Station (eastern of the town center). The stretch of interest runs from the San Siro Stadium to Garibaldi FS; the total extension is 7.076 km for a total of 10 stations, crossing a densely populated area of Milan. For this reason a thorough evaluation of the vibrational impact conducted during the Tender Design was considered as mandatory. While the preliminary phase of the project dates back to April 2007, the development of the TD began in December 2007, being the activation scheduled for year 2015 in time for the opening of EXPO 2015.

Along the studied line, two different types of track were foreseen in the tender design phase by following the same approach adopted for the first stretch of Metro 5 already operational from Garibaldi FS to Bignami stations, i.e.: direct fixation track type named "Milano Modificato", and a floating slab track named "Milano Massivo". The identification of the type of track along the line was carried out accordingly to performance requirements, with particular focus on vibrations reduction. In particular, the "Milano Massivo" track type was foreseen where the line passes right underneath buildings, or not far away from sensitive receivers (i.e. buildings where particular activities are carried out, as surgery intervention or high precision mechanical laboratories). The vibrational impact assessment in the tender phase combined a literature survey and the use of experimental data gathered in other projects. Considering all the uncertainties related to a vibrational levels assessment, a review of the results obtained in the TD was deemed as advisable in the following phases of design. Thus, the forecasts made in the TD were validated through an articulated vibration survey carried out during the detailed phase which included the measurements of the source signals, the evaluation of the transfer function between tunnel and surface-free field and the response of the building (including the groundborne noise assessment).

2. Vibration impact assessment during the tender design

The study of the vibration induced by a train transit in the buildings located above the line requires the solution of the following three sub-problems:

- source problem, i.e. the definition of the physical mechanism responsible for the generation of vibrations induced by the transit of trains and the evaluation of the vibration level at a short distance from the track;
- propagation problem, i.e. the study of propagation of vibration from the source to the building;
- structural response, evaluation of the modification to the vibration signal induced by the building components (i.e. foundations, load bearing structure, including infill walls, and floor plates).

During the TD, once having identified the potentially impacted buildings along the track by a detailed survey, the vibration levels induced by the train pass-by were estimated by means of a prediction model based both on literature data and on measurements carried out in similar conditions in other projects. The vibrational levels at the ground floor of potentially critical buildings were evaluated by the characterization of the vibration source, taking into account the vibrations attenuation in a free field condition and the assessment of the attenuation/amplification effects at the receptors floors. Thus, the obtained levels were compared with the limits defined by applicable Standards to evaluate the vibration effect in terms of annoyance, establishing the necessity of remedial measures which consisted in the adoption of mass-spring concrete slabs tracks.
3. Vibration source

During TD, the vibration source was defined on the basis of high quality measurements carried out during the monitoring of the Metro 2 line in Milan between Famagosta and Abbiategrosso Stations, similar in terms of type of soil and tunnel structure/geometry but different with respect to the M5 line in terms of type of trains. Moreover, the data were collected during the passage of almost empty trains running at an average speed lower than reference design value (i.e. 50 Vs. 70 Km/h), along a track characterized by very low wear conditions. Thus, corrections based on literature data and on other measurements carried out along the Metro infrastructure in Milan (e.g. to consider the effects of an increased speed of transit and a higher mass of the train due to crowding and wearing conditions) were introduced to obtain a design source spectra which would have been representative for the real condition of the MM5 line in operational conditions.

In the DD, the source spectra introduced above were verified by vibrational measurements carried out in two sections located along the already operational M5 stretch. The choice of the measurements sites was carried out on the basis of criteria of similarity in terms of dynamic response characteristics of the ground, type of line track, type of train, railway operation, geometry and structure of the tunnels. Regarding the type of track in particular, the first section was characterized by the presence of “Milano Modificato” railway equipment, while the second one saw the presence of “Milano Massivo”, based on a floating slab track technology.

3.1 Effect of the train speed

The speed of a train may induce a significant effect on vibration. The dependence between vibration and train velocity generally expressed in literature through the use of different formulas. As an example, doubling the speed of transit, the vibration levels increase from 3 to 6 dB. During the DD, the literature formulations were compared to real measurements carried out in previous projects. For an increase of speed from 50 to 70Km/h, the increment in spectral ordinates resulted + 4 dB for frequency f < 25 Hz and + 2 dB for f > 25 Hz.

The supplementary activities conducted during the DD validated the above assumptions on the basis of the vibration source measurements conducted along the M5 line, at the section characterized by the Milano Modificato type of track. The spectra recorded were divided in two classes, depending on the recorded speed (lower or higher than 60Km/h). Through the analysis of data it has been observed an increase of spectral ordinates of: + 8 ÷ 10 dB (f<20Hz), +4 dB (20 <f<63 Hz) and + 0 dB for f> 63dB. Hence, the amplifications determined during the detailed design phase resulted as generally higher than those determined in the TD.

3.2 Effect of the wheel and rail corrugation

An inefficient maintenance of the wheels and rails program may induce significantly higher vibration levels into the surroundings. The additional vibration generated due to irregularities in the wheel-rail contact may increase the levels of 3-6 dB with respect to a reference smooth rail and wheel configuration, particularly at f> 30 Hz. During the TD, available data from previously conducted measurements allowed to define a correction for taking into account wearing rails. In the DD, two specific measurement sessions were carried out before and after the programmed track maintenance activities (track grinding) by preserving the same geometry of installation of the triaxial accelerometers adopted for the measurement of the source of vibration. By analyzing the recorded data, a remarkable reduction in the signal amplitude after the maintenance activities was observed. While at low frequencies the benefit of grinding is not so evident, the spectral peak moves towards lower frequencies after grinding (from 100Hz to 63Hz), leading to attenuation of 3-5dB (1<f<40Hz), 3-10dB (50<f<63Hz). For f > 80Hz, a negligible attenuation was observed. By considering that the source spectra were recorded on a well maintained track, the above attenuation were added to the source level in order to consider in the design a medium worn track.
3.3 Effect of the vehicle mass

The overcrowding of trains is recognized in literature to increase the emitted vibration levels. Again according to literature, a doubling of the load on the axles causes an increase of 2 - 4 dB in vibration levels, in the tunnel and on surface. In the TD, the train mass during the measurements of the source spectrum source was limited to 7.5t vs. a design value of 12.5t. Hence, by interpolation, it was considered reasonable to apply an average value of 2.5 dB in the prediction model. The source spectra measured during the detailed design phase did not show any substantial dependence to the load of trains (visually assessed on a scale from 1, empty train, to 10). Thus, no correction were applied to the measured spectra in order to account for an increased train weight.

4. Vibration attenuation from the tunnel to the surface

The assessment of the attenuation of the vibration levels from the source to the g.l., in free field conditions (i.e. not taking into account the interaction with the buildings), represented a fundamental phase of the study. Several are the approaches in literature aimed at solving this problem through numerical approaches. During the TD, the assessment of the attenuation was based on an empirical relationship calibrated on observations carried out in other projects, in similar conditions of soils and tunnel geometry and by literature:

$$\Delta L = K \log_{10} \left( \frac{R - R_0}{V} \right) f$$

where $\Delta L$ is the attenuation in dB between the tunnel and surface, $K$ is a parameter which depends on soil type and dynamic response, $(R - R_0)$ is the distance between the source and the receiver (i.e. the tunnel and the point located at the surface level), $V$ represents the velocity of propagation of shear waves in the ground and $f$ is the central octave frequency under consideration. Through the calibration of the $K$ parameter, equation (1) was matched to real observation reported in literature or previous project and therefore adopted for the design by varying the $(R - R_0)$ term as a function of the deepening of the M5 stretch of interest, to obtain the expected vibration spectra at ground level, in free field conditions.

During the DD, specific tests were carried out aimed at evaluating experimentally the transfer function of the vibration signal from the rail, through the tunnel structure, up to the ground level. Two representative locations along the stretch under construction were identified considering that:

- The soil profile do not change dramatically within the area of interest, with the prevalence of alluvial formations with values of shear wave velocities within the first 30m ranging from 250 to 350 m/s.
- The variation in depth of the Metro line along its entire course is rather limited (the track depth ranges from 15 to 30m).
- The tunnel and the corresponding area on the surface should have been fully accessible for the installation of the source and sensors.
- The area should have been characterized by very low background vibration levels.

On the basis of the above criteria, the first measurement location was located along the straight stretch that runs near the San Siro soccer stadium. The second location was identified within an area characterized by a high quality housing and commercial development (City Life Project), which may represent a critical location in terms of sensitivity to vibration induced by the M5 operation. The artificial vibration source employed (a 6 tons hydraulic vibrodyne, see Fig. 1, left) was mounted at the track location, and a vibration signal induced into the tunnel structure by targeting a reference load power spectrum (defined on the basis of measurements of the load induced below the sleeper by the passage of a reference metro train), i.e. the selected source was driven to apply a point load of the same amplitude of that induced by the passage of a real metro train. Triaxial accelerometers were installed in the tunnel (near the source, at the tunnel wall, along its length at 10 and
22m of distance), on ground level (at the tunnel projection and at 15-20m) and inside a building (in one of the two measurement sites). The vibrodyne was run in transient mode, reproducing the train passage, and the measurement conducted in all the accelerometers at the same time, preserving the phase of all signals.

The effects of a different geometry of the load (point load in the measurements conducted, line load in the real case) were checked by comparing the attenuation observed with the artificial source with that measurement conducted with a real train passage during the survey carried out for the evaluation of the vibration source along the operational stretch of M5. This comparison (Fig. 1, right) shows that the results of the attenuation measurement conducted with an artificial source were in acceptable agreement with those observed with a real source in similar conditions of tunnel, soil type, tunnel embedment.

![Image](image.png)

**Figure 1**: Left: hydraulic vibrodyne (source of vibration). Right: measured vibration attenuation from the tunnel to the ground level (vertical component).

### 5. Receiver response

The modifications that occur to the vibration signal in its propagation through the building structure are often seen in literature as the sum of the following contributions:

(a) Coupling between foundation and surrounding soil (path A-B in Fig. 2);
(b) Response of the vertical load-bearing structure of the building (B-C);
(c) Amplification induced by the floor plates from their boundaries to the centre of the room where the verification with respect to the Standard limits is usually carried out (C-D).

While in the TD the evaluation of the structural response was based on literature data supported by measurements conducted in other projects, in the DD the effect of the structure on the vibration level was studied by a specific campaign of measurements carried out in two representative buildings located along the stretch of M5 under study by measuring the vibration levels:

(a) outside the building, near the vibration source (underground railway, tramway);
(b) inside the building (1) at the foundation level, (2) at a lower floor and (3) the upper floor.

![Image](image2.png)

**Figure 2**: simplified model of structural response
All the measurements were carried out in empty apartments and, at each floor, one triaxial accelerometer were located near the vertical structure and one at the center of the room, in order to distinguish the signal amplification induced by the floor plates from the modification given by the travelling of the signal along the load bearing structure. A statistically representative set of signals were collected (> 10 for the case) and during the postprocessing phase the attenuation/amplification of the vibration levels induced in each of the paths of Fig. 2 was evaluated for both the buildings.

The soil-foundation coupling (A-B path in Fig. 2) is generally assumed as a purely dissipative term in the vibrational chain, as results of coupling losses between foundation elements and surrounding soil particles 11, 12. The results shown by the measurements conducted substantially confirmed the assumption made in the previous phase of design when the attenuation at the foundation level was conducted using empirical curves available in literature. As shown in Fig. 3, the attenuation ranges from 0 to 10 dB for f < 10Hz, is negligible in the range 10<f<50Hz, increasing at higher frequencies to 15-20dB.

According to the literature 11, 12, the vertical load-bearing structure may induce a (slight) attenuation effect in the vibrational signal, which was neglected in the Tender Design. The results obtained from the measurement conducted are in agreement with that assumption (i.e. no significant attenuation/amplification) for 1<f<10 Hz (Fig. 4). In the medium range, the resonance of the building structure play a significant role in amplifying the vibration levels (8<f<20Hz). In the higher portion of the spectrum, the trend of the observed attenuation is more erratic, with general amplifications observed at higher frequencies which was considered in the assessment of the vibration level at higher floors in the DD phase.

Again according to literature data, the assumptions made in the TD were based on literature 11, 12, assuming that the resonance of the floor plates can cause a significant amplification of the vibrations in the frequency range between 10 to 30 Hz. The frequency ranges may contain the peak of the spectrum of the vibration induced by the source, leading to resonances that can play a fundamental role in the vibration chain. The results obtained from the measurement conducted in the DD confirmed the assumptions (see Fig. 5).
6. **Ground-borne noise**

The annoyance induced by vibration related phenomena is a combination of two effects: the high frequency motion of contact surfaces and the low frequency sound pressure generated by the oscillation of the floor-pavement-roof-walls system, the latter effect generally denoted in literature with the term of ground-borne noise sup₃.

In the standard practice, the evaluation of ground-borne noise can be conducted by means of empirical relationships calibrated on experimental observations or literature data, which return the sound pressure level \( L_p(f_j) \) as a function of the vibration level \( L_a(f_j) \) as:

\[
L_p(f_j) = L_a(f_j) - 20 \cdot \log(f_j) + K
\]

being \( f_j \) the octave-band central frequency (Hz) and \( K \) a constant term which depends on the characteristic the room (materials, geometry, resonating objects etc.) to be determined on the basis of experimental data. During the TD, a value of \( K = 16 dB \) was considered as representative of a standard room on the base of the already cited literature.

In the DD, a series of measurements have been carried out in buildings characterised by low or high level of vibration induced by the passage of underground railways and metro lines. The instrumentation was composed by a triaxial accelerometer (frequency of acquisition set at 2KHz) and a sound level meter connected to a condenser microphone. Several realizations of the source were recorded and the data was interpreted in terms of vibration and acoustic levels induced. The results obtained led to an assessment of the value of the constant \( K \) in the range from 19 to 21.5dB, fairly higher than the value adopted in the TD. In Fig. 6, the measured data were interpreted in terms of \( L_p(f_j) \) as a function of \( L_a(f_j) \). It worth noting that red dots (data recorded in a low level of vibration environment) and the blue triangles (data recorded in a building characterized by very high level of vibration) can be reasonably connected by an interpolation line which can be used to obtain the level of groundborne noise starting from the overall value of acceleration as determined by vibration impact assessment.

7. **Conclusions**

Two different approaches were pursued for the vibrational impact assessment of a new Metro line for the Tender and Detailed phases of Design. During the Tender phase, a literature based approach was followed in order to obtain a first evaluation of the vibration levels which guided the design of the track. In the detailed phase of design, all the assumptions made in the previous phase were verified through an extensive experimental campaign carried out along the operative section of the M5 line. The results obtained by the analysis of the measured data substantially confirmed the assumption made on the base of the literature and previous knowledge.
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