Evaluation of the Effects of Transit of Subway Trains on Noise and Vibration Levels in the surrounding Buildings

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Summary

The increasing use of urban subsoil for public facilities, like underground railways and roads, and the consequent emission of noise and vibrations in soil, rises a problem both for new buildings to be erected nearby, and for the existing ones, which need protection from vibrations, in order to preserve comfort for residents. Therefore, the evaluation of the effects of train and road traffic on ground-borne noise and the propagation of vibrations through soil and foundation structures, up to residential stories, becomes a strategic issue to avoid complains from final customers and eventually impairing commercial appeal and value of the building.

Special–purpose software to be applied for this kind of problems must account for continuum modelization for soil, truss/beam elements for the structures, a dynamic time-domain approach, a realistic damping modelization in soil, energy dissipation at artificial boundaries, and user interface suitable to assign input and retrieve output as vibration power-spectra or accelerograms at any location in soil and in the building.

Currently available state-of-the-art software is applied as described in this paper to a case history in Milan, in order to demonstrate, the possibility of evaluating the ground-borne noise and vibrations generated by a subway train in an old cut-and-cover tunnel, and their effects on the buried stories of a new building (parking lot) to be erected very close to the tunnel.

The proposed approach allows for the determination of the vibration spectra at the base of the columns of the above-grade residential building, as an input for the design of dumpers to be possibly applied at the basis of the columns; the output from this analysis can be directly used as input (base motion spectra) to an elastic FEM model of the building, for a conventional forced-vibration modal analysis, in order to assess the level of expected noise due to the traffic of subway trains at any location.

Keywords: tunnel, vibrations, soil, modelling, noise, ground, disturbance, basement, residential

1. Urban Context and Scope of the Study

The necessity of evaluating the effects of ground-borne noise and vibrations on buildings arises mainly in densely built urban contexts, where new residential facilities have to deal with pre-existent buried structure, like motorway or railway tunnels. But, also, this kind of study may be needed where soil vibrations generated by industrial machinery (e.g., dye metal forming) may have detrimental effects on neighbouring facilities where high-precision production is carried out, like numerical-control operating machines, microelectronics, etc.

The analysis method proposed here has been set up and tested on a case history of the former type, with the aim of validating the design of a residential building from the standpoint of comfort.

In the context of one of the largest building site active in 2009 in Milan, site measurements were carried out in advance, by specialized consultants, of vibrations induced at soil surface by the transit of subway trains, in the frequency range 1 – 80 Hz.

The soil surface measurements were plotted as noise power spectra and directly compared with the perception threshold and with allowable limits for residential use.

However, the effects of the new building on the vibration levels require the development of a specific mathematical model to be assessed. In general, the effects of the new buildings on wave and noise propagation are the following:

- a change in soil stiffness, caused by below-grade structures (building basement)
- reflected waves generated at the soil-structure interface below foundation
- reflected waves at the soil – structure interface, at the side close to the tunnel, where vibration is generated
- a change in frequency contents in vibrations that will be transmitted to the above-grade structures (residential).

Noise spectrum at residential floors will therefore be substantially different from the spectrum measured at soil surface or at the tunnel wall.

The scope of the present study is to examine and evaluate such effects.

2. The Method

A method has been defined for estimating this dynamic soil-structure interaction, and the changes in wave propagation through soil and underground structures. This method, detailed in the following sections, includes a simultaneous modelling of soil and structures, and therefore does not allow for a complete, refined modelling of the building, which will be rather represented in an approximate way, in its main features. The results of this complete modelling, rather than being used as final predictions of vibration levels in the building, are to be applied as input to a detailed model of the building alone (e.g.as vibration input at the base of columns), for a traditional mode superposition linear elastic analysis, not described in this paper.

The dynamic analysis considered here allows for two-dimensional, plane-strain, plane-stress or axisymmetric, fully dynamic analysis. The calculation is based on the explicit finite difference scheme to solve the full equations of motion, using lumped gridpoint masses derived from the real density of surrounding zones. This formulation can be coupled to the finite element model of structural parts, thus permitting analysis of soil-structure interaction brought about by ground shaking. The dynamic feature can also be coupled to the groundwater flow model. This allows, for example, analyses involving time-dependent pore pressure change associated with liquefaction (although, this subject is not considered in this paper).

Such fully nonlinear analysis method (implemented in state-of-the-art codes such as FLAC, ref. [1], [2]) contrasts with the more commonly accepted "equivalent-linear" method used in earthquake engineering since many years (e.g., codes SHAKE, ref. [3] and FLUSH, ref [4]); although much more computer time-consuming for the calculation overhead involved, the fully nonlinear approach can provide more general and accurate response where soil non-linearity plays an important role.

2.1 Modelling Issues

In order to correctly represent wave propagation, two major issues have to be accomplished:

1. the dimensions of the continuum zone must be such that all relevant frequencies are correctly modelled: e.g., if the highest frequency considered is 80Hz, with a wave speed of 320 m/sec, the wavelength will be 4 m. The maximum size of a continuum zone (with linear displacement field in a zone and constant stress and strain shape functions) should not exceed 1/8th of the wavelength, that is 50 cm. Therefore, all the continuum modelled should include zones not larger than 50 cm.
2. in order to avoid an excessively long calculation time, artificial boundaries (usually, vertical sides and horizontal bottom) have to be introduced as close as possible to the soil region of

relevance. Rigid or compliant boundaries could be introduced, but any of the two would introduce artificial, unrealistic reflection of impacting waves. In order to avoid this, and correctly simulate wave propagation in the infinite medium, a special kind of viscous boundaries, known as “quiet” boundaries have to be introduced (see [5] and [6] for a discussion on the correctness and effectiveness of the formulation of quiet boundaries).

Usually other issues, like the definition of a stable integration timestep, are automatically addressed by the computer code.

Another important feature of this modelling method is that the actual history of soil and structures has to simulated, in a multi-step static analysis, in order to correctly simulate the stress state of soil and structures at the moment the dynamic input is given.

Also, in order to set up a realistic simulation, a back-analysis trying to reproduce field measurements should be run in advance, in order to calibrate soil damping, elastic moduli, etc., input excitation method, as briefly discussed in the following sections.

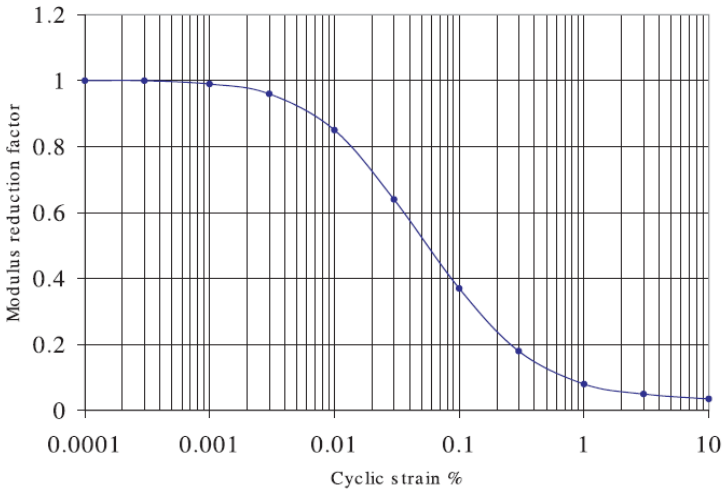

Fig. 1 - Modulus reduction curve for sand (Seed & Idriss 1970, [10] – “upper range”). See code SHAKE-91 (http://nisee.berkeley.edu/software/)

2.1 Elastic Moduli

It is well known that soil is not an elastic medium, and that its stiffness is affected by the level of strain.

Fig. 1 shows the well known relationship [10] between tangent shear modulus reduction factor (G/G_{max}) and level of shear strain during cyclic loading. It can be seen that, while during heavy shaking, e.g. caused by an earthquake, under level of strain of the order of magnitude of 0.1% to more than 1%, the reduction factor drops below 0.2; on the contrary, for low amplitude dynamic excitations, like those induced by train transit, the reduction factor will be considerably higher (0.8). Therefore, the value of G used in this kind of analysis could be 4 to 5 times larger than in earthquake analysis.

2.2 Damping

For a dynamic analysis, the damping in the numerical simulation should reproduce in magnitude and form the energy losses in the natural system when subjected to a dynamic loading. In soil and rock, natural damping is mainly hysteretic (i.e., independent of frequency – see [7] and [8]). It is difficult to reproduce this type of damping numerically because of at least two problems (see [1]).

First, many simple hysteretic functions do not damp all components equally when several wave forms are superimposed. Second, hysteretic functions lead to path-dependence, which makes results difficult to interpret. However, if a constitutive model that contains an adequate representation of the hysteresis that occurs in a real material is found, then *no additional damping* would be necessary.

In the case history presented below, *Rayleigh damping* (see [9]) is used to provide a damping that is approximately frequency-independent over a restricted range of frequencies. Although Rayleigh damping embodies two viscous elements (in which the absorbed energy is dependent on frequency), the frequency-dependent effects are arranged to cancel out at the frequencies of interest.

2.3 Dynamic Input

Dynamic excitation can be given at any point in the model, both in form of a geometry constraint (displacement, velocity or acceleration histories) or of an external force (concentrated nodal force or surface stress or pressure at the model boundary).

The input excitation is defined with a base value and a time-history.

However, in most cases a time-history is not available; rather, acceleration spectra are given as a result of field measurements. An artificial accelerogram has therefore to be generated starting from the spectrum and applying random phase values to harmonic components.

In order to check the correctness of the adopted algorithm (usually implementing simple formulae available in literature), a back-analysis should be run, back-calculating the resulting spectrum at the dynamic input location and comparing it with the original input spectrum.

3. A Case History

3.1 The Project

Fig. 2 shows a plan view of the buildings; the underground railway is outlined in green. The two buildings shown have a common basement, which spans below the mall area between the two and includes the garage ramp in the bottom right corner of the picture.

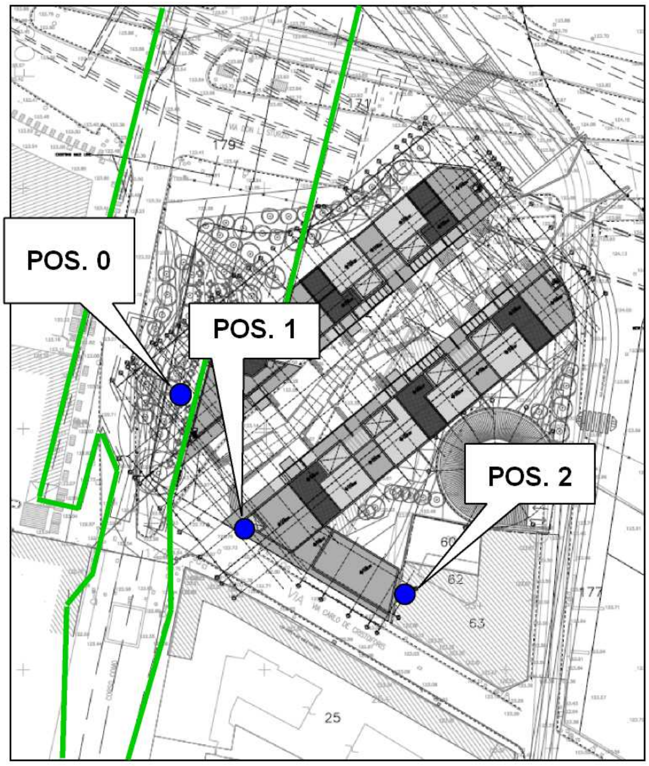

Fig. 2 – Plan view of the new buildings and of the existing tunnel (green outline)

All the basement is excavated by means of anchored diaphragm walls and steel pile along the perimeter; anchorages are typical post-tensioned steel wire strands bond to soil with cement grouting.

The metro railway tunnel was excavated in the sixties with a cut-and cover method. Both the station tunnel (wide part of the tunnel) and the line tunnel have rectangular sections, with r.c. diaphragm wall as vertical sides, a thick cover slab with r.c. high-depth beam, directly cast on soil before tunnel excavation, and a thin bottom slab.

The tunnel has about 3m of soil covering, while the bottom slab is more ore less at the same depth of the new basement excavation.

A narrow strip of soil, less than 3m wide, separates the building diaphragm walls from the tunnel; a major concern therefore, was the possibility that vibrations induced by train transit could affect comfort in the new residences.

On the contrary, it was considered acceptable that vibrations could affect the basement, where only technical rooms and a car parking facility are foreseen.

Reduction of noise and vibration had therefore to be pursued by means (i) of insulation of the ground floor slab, and (ii) by introducing vibration insulators in all vertical structures springing from the ground level slab.

The scope of the special program of measurements and analyses, which the present study belongs to, was to assess the actual need for insulators. The program included:

- field recording of vibrations at soil surface at the specific site; the recordings were carried out after the diaphragm walls were cast, but prior to excavation, applying the sensors to the crown beam of the walls, in three positions, as shown in Fig. 2
- development a 3-d frame FE linear-elastic model of the building, to which the recorded excitation had to be applied, for a forced vibration mode superposition analysis; the surface recording was applied to one side of the basement, the closest to the tunnel, and this

assumption introduced a possible inaccuracy, neglecting soil-borne noise entering the basement from the bottom slab;

- the present study: a simplified FE model including soil, the tunnel and the building basement, with the main scope to validate the main assumptions on dynamic input.

3.2 Field Records

In Fig. 2, the three points where vibration records were taken are shown.

Three components were measured in each point, Z (Vertical), Y (horizontal, parallel to rails) and X (horizontal, transverse to rails).

In each position, several records were taken, each pertaining to the transit of a train. The results were superimposed in an acceleration spectrum, plotted in the frequency range 1 to 80 Hz.

The selected reference point for field measurement is POS. 0, the closest to the cross-section used in the numerical (plane strain) analysis. The spectra are shown in Fig. 3a (horizontal excitation) and 3b (vertical).

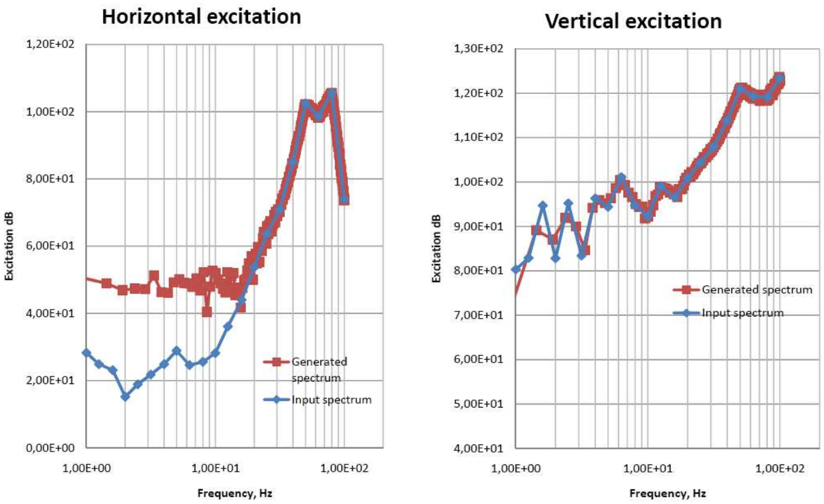

Fig. 3 – comparison of literature vibration spectra for train transit in tunnels (blue) and back-calculated spectra applied to the model (red) - a) horizontal b) vertical

3.3 Selection of the Source of Vibrations and Calibration of Input Excitation (Back-analysis)

Rather than directly applying the field measured spectra to the model at soil surface, literature excitation spectra recorded at the base slab of standard tunnels were considered, to be applied to the model, in the proper position, inside the tunnel.

The shown spectra were transformed into synthetic accelerograms, to be applied to the model, and the spectral content of the accelerograms was back-calculated. The blue lines in Fig. 3 are the input spectra, while the red lines represent the back-calculated spectra. An optimal coincidence can be observed, in the range 20 – 100 Hz.

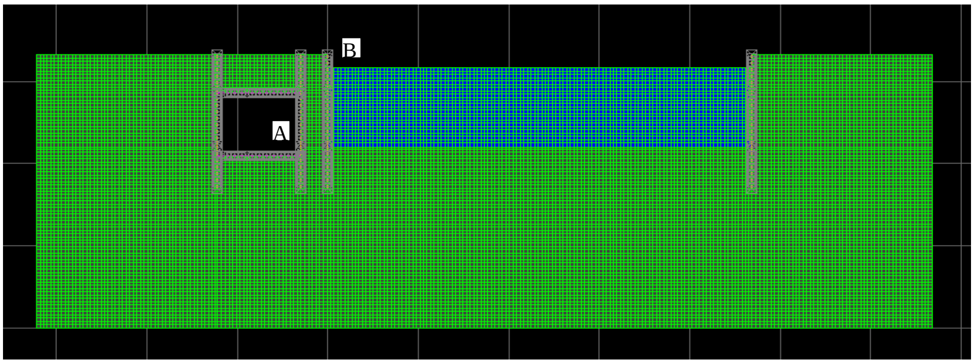

Fig. 4 – model grid, showing the tunnel structures, the new diaphragm walls (grey), future excavation soil (blue,) excitation point (A) and recording point (B)

Fig. 4 shows a plot of the model grid, in which the structures of the existing tunnel (left) and of the diaphragm walls of the new building are shown. Soil to be excavated for underground parking is shown in blue. Point A is where input excitation is given to the model, while point B represents the location where recordings were taken.

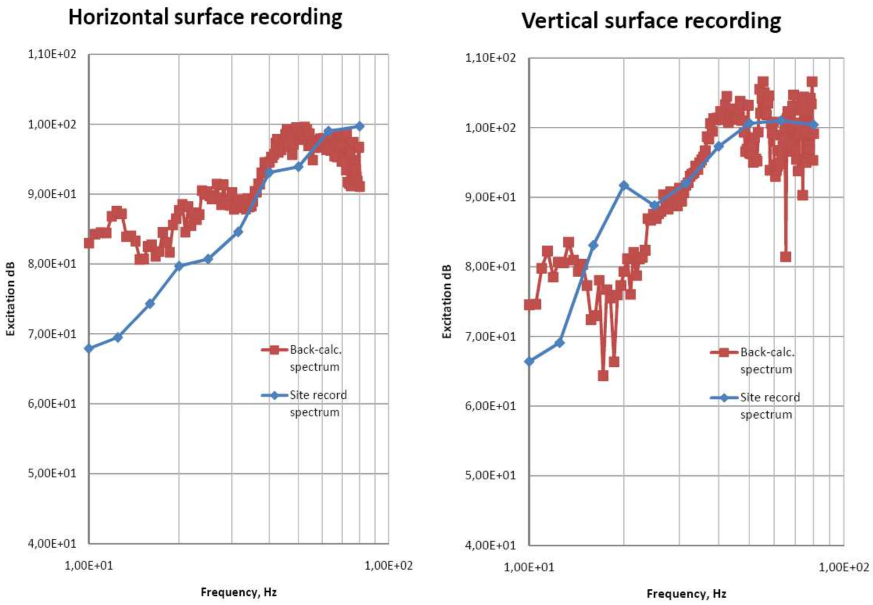

Fig. 5 – comparison of recorded vibration spectra at top of diaphragm wall (blue) and back-calculated spectra of the model (red) – a) horizontal, b) vertical

Fig. 5a, 5b show the comparison between recorded spectra at the top of the diaphragm wall and the back-calculated spectra obtained from the model. A substantial agreement can be observed, even if some discrepancies appear, mainly in the low frequency range.

Vibration induced in soil are influenced by the main features of the source, i.e., for our case, the type of train (weight, length, number of coaches, etc.), the track system (ballast or direct connection to base slab), the type and dimensions of the tunnel (shape, lining thickness). The accuracy of the simulation could therefore be improved adopting a more appropriate input spectrum, obtained, e.g. from actual recordings of a more similar type of train, track, or tunnel, which, however, was not available at the time. The obtained accuracy, however, was considered satisfactory for the scope of the study.

Another source of approximation is the fact that the analysis was carried out in two dimensions, where the actual problem is intrinsically 3D, for at least two reasons:

- looking at Fig. 1, one can clearly see that, due to the angle formed by the axis of the tunnel and the axes of the building, any cross section adopted for the analysis would introduce an approximation; we have indeed studied a problem where the tunnel runs parallel to mayor building axis;

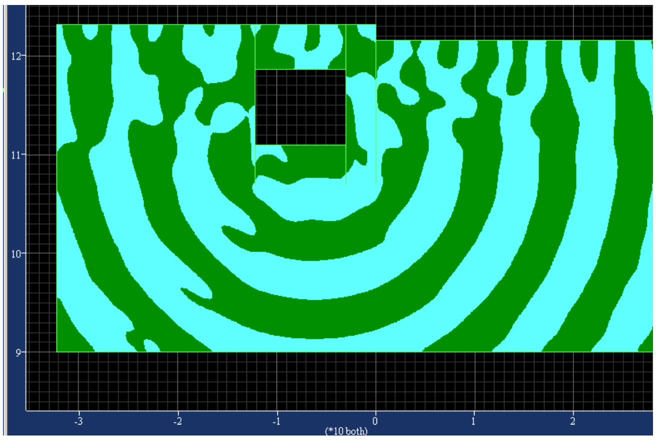

Fig. 6 – stress waves induced by a sinusoidal acceleration applied at the tunnel slab

- the vibration induced by train is a series of point-wise sources (one for each bogie of the train), each producing spherical waves, and moving at the train speed; the reproduction of this phenomenon in 2D introduces a further approximation: the train is seen as an infinitely long source of cylindrical waves. Fig. 6 tries to illustrate this concept. Stress waves induced by a sinusoidal wave are shown. Reflection at soil surface but not at model bottom is also evident.

3.4 Actual Case Study and Results

After this calibration phase, the prediction of the effects of the transit of trains on the new building was carried out, based on the same model shown above, where in place of the excavated soil the building structures were introduced. Fig. 7 shows the model representing the same cross section as above, but with the basement frame and foundation represented by means of beam elements.

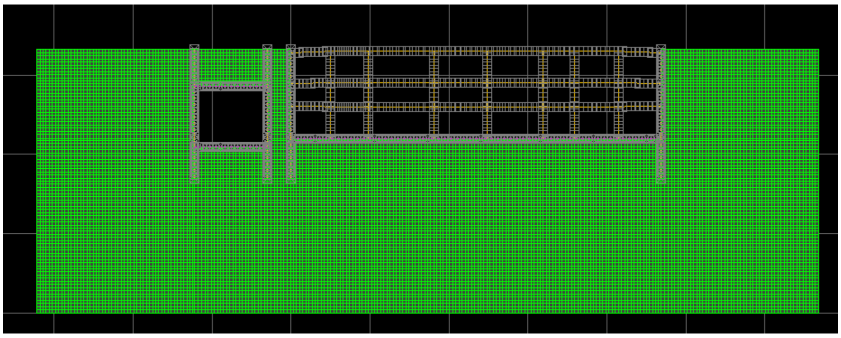

Fig. 7 – model grid, showing the tunnel and the new basement structures (grey)

The analysis method is still the same as above, but, rather than evaluating the vibration spectrum at the top of the existing diaphragm wall, floor response spectra can be evaluated at any point in the building basement and at the base of the columns supporting the above grade building.

However, it is interesting to observe the effects of the structures in the following Fig. 8, which compares the vertical acceleration spectra for the former case, calculated at the top of the tunnel diaphragm wall, (in which there was soil in place of the basement), outlined in red, and the new case (with the completed basement), blue line.

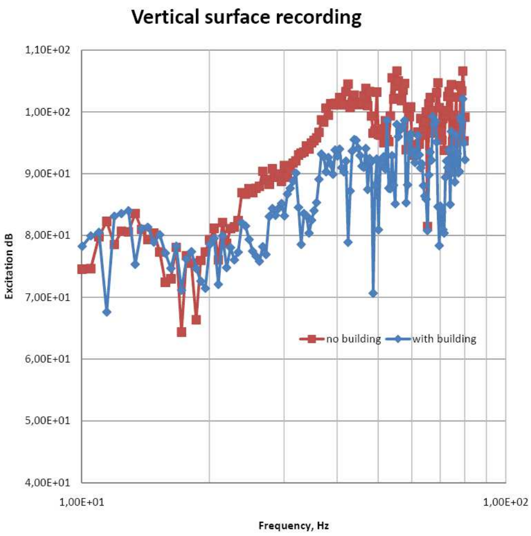

Fig. 8 – comparison of calculated spectra at top of diaphragm-wall before (red) and after (blue) the construction of the basement

A substantial reduction is observed in all frequencies between 25 and 80 Hz.

Fig. 9, instead, shows the floor response spectra at ground floor, for three beams, pertaining to the 2ns, 4th and 7th span (counted starting from the tunnel side). It can be seen that no appreciable reduction in vibration amplitude occurs in farther spans (e.g., 7th) with respects to spans near to the source (e.g., 2nd).

Finally, Fig. 10 represents the same comparison between several points in the base slab: here an appreciable reduction is observed in points far from the source (e.g. a point in the 7th span, pale blue line).

This apparent inconsistency can be explained observing that vibration of the base slab is substantially directly affected by soil vibration (which gradually decreases with distance from the source), while beam vibrations depend mainly on the base excitation of the frame, with very low damping (5%), and therefore tend to be of constant amplitude throughout the whole frame.

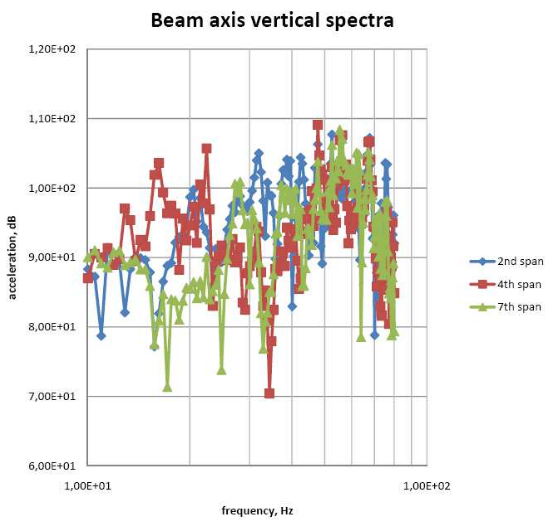

Fig. 9 – comparison of calculated vertical floor response spectra at the axis of the ground floor beams, for the 2nd, 4th and 7th span

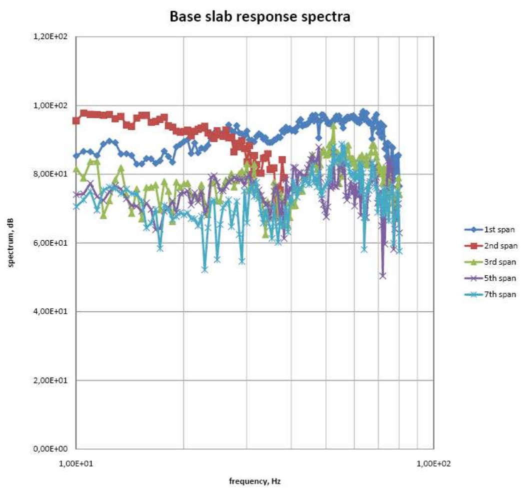

Fig. 10 – comparison of calculated vertical floor response spectra at some points in the base slab

4. Conclusions

The problem of vibrations and noise disturbance induced by train transit in urban tunnels on surrounding building is studied, by means of a FEM modelization in 2 dimensions. Data from literature are used as input excitation spectra and vibration values at typical locations are estimated, for a real-case study.

The presented method, based on a full-non linear dynamic modelization of soil and structures, is demonstrated to be capable to produce useful results for the design of vibration absorption systems, without incurring in heavy and expensive calculations; the proposed method is therefore applicable to practical cases, for medium to large scale projects, in order to assess the effective need for absorption systems when new buildings have to be erected near potential sources of vibration, like underground railway lines or motorway tunnels.

5. References

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