EXPERIMENTAL MEASUREMENTS AND NUMERICAL SIMULATIONS OF UNDERGROUND RAILWAY GROUND-BORNE VIBRATIONS.

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ABSTRACT

Underground metro networks can provide an effective solution to transport demand problems within a sustainable development framework although they can be characterised by high environmental impact. Railway induced ground-borne vibrations affect both surface and underground lines and are often claimed to be liable for cosmetic damages and for nuisance in buildings nearby. The approach to the problem usually implies the in-depth study of the three main phases in which the phenomenon can be split: the generation due to the dynamic interaction between the rolling stock and the railway superstructure, the propagation through the tunnel lining and the surrounding soils, the assessment of the impact on the 'sensitive subjects'.

In this paper, preliminary results following an extensive research that has been carried out on this subject within the VINCES project are presented. An experimental campaign has been performed on two test sites where Light and Heavy Rail Transit systems are operating. The experimental measurements have been carefully processed in order to extract representative vibration amplitudes and to calibrate a prediction model of vibration generation. This latter takes into account the PSD of rail defects, the mechanical and inertial properties of the vehicle as well as of the railway track. The propagation was simulated by 2D numerical modelling, accounting for soil properties derived from accurate geotechnical and geophysical investigations. In both cases, a reasonably good agreement between numerical simulations and experimental data has been observed.

Keywords: vibrations, underground railways, geophysical test, monitoring, numerical simulations.

1. INTRODUCTION

Rail transit technologies may offer an effective solution to the increasing transport demand but, sometimes exhibit critical environmental issues in planning, design and operational stages. Noise and vibration induced by railway traffic play a key role in the Environmental Impact Assessment (EIA) procedures; this aspect can be further emphasised in urban areas, where the density of 'sensitive subjects' (humans, structures, services) is undoubtedly high. However, no widespread practice there exists for the prediction, control and assessment of the vibration effects, while the case histories are in increasing number, often because of loyal conflicts between damaged communities and the constructors or the railway companies.

A rational prediction and performance methodology can be developed in three stages [AIELLO & SILVESTRI 2004]: first the source emission has to be characterised through rational or empirical methods, accounting for the properties of railway vehicles and superstructure; thereafter, the ground propagation of the wave field must be described by suitable attenuation laws or numerical simulations; finally, safety, serviceability or comfort of the sensitive subjects must be assessed, comparing the computed or measured vibration amplitudes to the limiting thresholds [SKIPP 1998].

The paper shows the main results obtained by the authors in the framework program of the research project VINCES (Vibrations in Civil Engineering Structures). The purpose was to calibrate methods of numerical prediction and experimental characterization of the vibrations induced by underground railway lines. To this purpose, collection of experimental data on representative test-sites and numerical simulations of vibration generation and propagation phenomena have been carried out.

The test-sites were selected along underground railways lines operating in Turin and Naples, representative of light (LRT) and heavy (HRT) railway transit systems, respectively. These two case studies are also different for the tunnel structure (pre-cast and cast-in–place), depth of the track surface (17.0 and 40.0 m) and nature of the subsoil (alluvial and pyroclastic soils). In both cases, soil properties have been accurately evaluated through geotechnical and geophysical investigations.

Amplitude and frequency content of vibrations generated by the train transit in the vicinity of the railway track (Turin), in depth (Naples) and at surface (both) have been measured and analysed by means of signal processing procedures. Finally, numerical modelling of the source and of ground propagation of the vibrations induced by the train passages were carried out by dynamic analyses. The numerical data were then compared to the experimental records to assess the performance of the analytical models adopted.

2. TRANSIT TECHNOLOGIES EXAMINED

The underground Line 1 in Naples was conceived since mid '70's in order to reduce the transport problems in the urban area and to allow a fast connection with city suburbs; only in 1993, however, the first section was opened to the public. The whole line, operated by the MetroNapoli company, develops along a 13 km long winding path, with steep gradients (with a maximum slope of almost 5.5%) imposed by topographic restraints. It consists of a dual tunnel layout joining in a single section approaching each one of the 14 stations, and was almost everywhere excavated in a volcanic tuff formation overlaid by granular pyroclastic soils [DE SANCTIS et al. 2006].

The railway superstructure (Figure 1a) is a slab track system without sleepers, directly connected to the tunnel invert. The rail is fastened to the tunnel floor through a resilient system similar to that used in Milan metro line. The railpad spacing is 0.75 m, whereas the rail type is a UIC60. The rolling stock (see Figure 1a), developed by FIREMA Trasporti, is composed by a 35.680 m long dual car, assembled up to a three units train. Each car body is connected through the secondary suspension system to two rail bogies that, in turn, are connected through the primary suspension system to a tandem wheel layout. The relevant technical data are reported in [AIELLO et al, 2007].

The LRT system in Turin is the first example of rubber-tired metro adopted in Italy (Figure 1b); the design was initiated in 1995, and the construction started at the end of 2000 [CARRIERI et al. 2004]. Turin Metro line 1 is presently 7.2 km long with 11 stations; in 2007 further 2.2 km with 4 more stations will be opened. The main stretch of Line 1 proceeds straightaway along Francia Avenue with an average slope of 1%. The cross-section is a single tunnel, with a pre-cast reinforced concrete discrete lining, dug by an Earth Pressure Balanced TBM. The subsoil is characterized by alluvial sediments composed by gravel, sand and pebbles in a silty matrix, with a variable degree of cementation. The Light Automated Vehicle (VAL) system adopted by GTT (the Turin Transport Company) was developed by Siemens Transportation Systems, and represents the first fully automated light metro, without a driver or on-board attendant. The latest generation of VAL, the 208 system, employs rubber-tired vehicles running on steel plates whereas guidance is provided by horizontally fitted tyres, in front of and behind the driving axles The layout of the typical rolling stock (Figure 1b) includes 2 permanent married cars. Each car body is connected through the suspension system to four pneumatic tires. The railway superstructure is also a ballastless track system with a special H cross-section steel beam rail that is directly connected to the tunnel floor through a discrete resilient system 1 m spaced.

By comparing the different technical data [AIELLO et al, 2007], it can be easily highlighted that, although the maximum axle load of the two transit systems is almost the same, the overall weight of the VAL vehicle is about one half that pertaining to the conventional HRT. In addition, the dynamic wheel-rail contact force in the Turin LRT system is likely to be lower, because of the pneumatic tire. Therefore, a minor vibration level induced by VAL system should be expected.

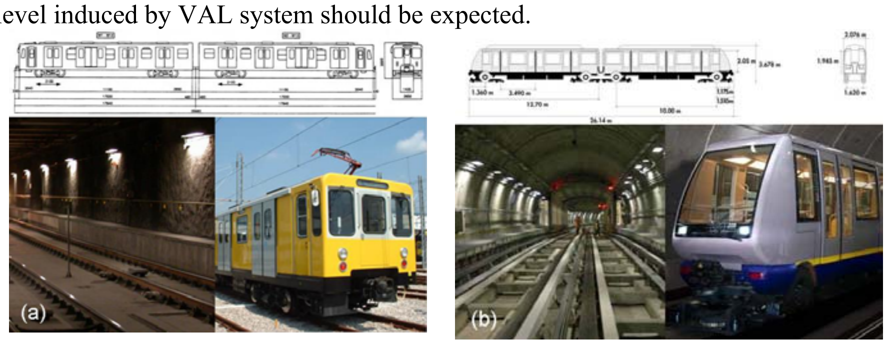


Figure 1 Naples' HRT system (a), Turin LRT system (b).

3. DESCRIPTION OF TEST SITES

The test site along Line 1 of Turin Metro is located along Francia Avenue between Rivoli and Racconigi stations, where the horizontal distance of tunnel axis is about 20 m away from the closest buildings (Figure 2). The site was selected because of the presence of a nearby downcast, which could facilitate the deployment of cables down to the tunnel and the connection between the instruments installed along the line and the surface monitoring system. The physical and mechanical properties of the subsoil were derived by geotechnical and geophysical reports for underground tunnel design supplied by GTT following refraction and surface wave (MASW) tests carried out by Turin Polytechnic [CROVA et al. 2003]. The subsoil is characterized by stiff fluvial deposits of gravels and sands, weakly and randomly cemented, with shear wave velocity, V_S, around 750 m/s. This formation is overlaid by a cohesionless layer of sand and gravel, featured by V_S around 350 m/s; the uppermost layer is constituted by silt and sandy clay, with V_S of 330 m/s. The values of the soil unit weight γ were attributed on the basis of laboratory tests data.

The HRT experimental records at Naples were taken in the courtyard of a historic building of the 17th century. The left tunnel of the underground railway runs uphill between Vanvitelli and Cilea stations, along a curve section more than 30 m below the ground level, and it is completely excavated inside the tuff formation. A layered subsoil model has been derived on the basis of laboratory and field tests, including Standard Penetration (SPT), Cone Penetration (CPT), and Down-Hole (DH) tests,, carried out along three verticals located in the courtyard of the building (Figure 3). The subsoil consists of a first series of finer soils (ash and pozzolana), with total thickness of 8 m and average shear wave velocity, V_S , about 200 m/s; a second series of coarse-grained materials (mainly pumice and lapillus), with thickness about 11 m and average $V_S \approx 440$ m/s; a 13 m thick formation of cohesionless to weakly cemented pozzolana, with average V_S around 360 m/s, resting on the yellow Neapolitan tuff. Some soil properties, such as tuff V_S (about 800 m/s), were derived by literature [RIPPA et al. 1983] [VINALE 1988].

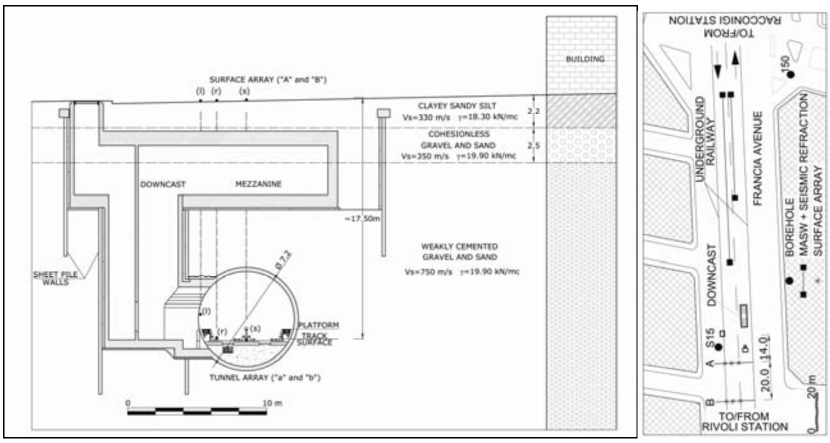


Figure 2 Test site in Turin: cross section (left), plan view (right)

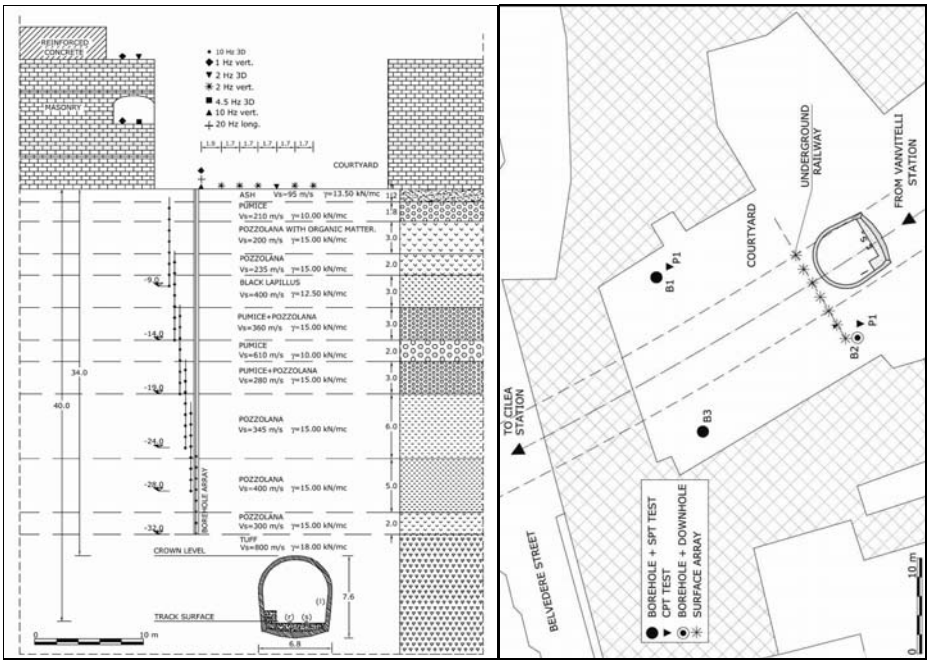


Figure 3 Test site in Naples: cross section (left), plan view (right).

4. MEASUREMENTS AND PROCESSING

The experimental measurements at the test sites were carried out joining the human and technical resources of the Laboratory of Soil Dynamics of University of Calabria and the Applied Geophysical Laboratory of Turin Polytechnic. In both cases the instrumental networks consisted of vertical and horizontal velocimeters with variable frequency response. All of them were firmly connected to the ground or to the structural parts and wired to a multi-channel digital acquisition system. High sensitivity velocimeters and high dynamic digital recorders (up to 24 bit) were used to allow the acquisition of good quality low-amplitude signals in a noisy environment.

The train-induced vibrations were recorded in seasonal periods and at times suitable to minimize troubles and noise due to surface urban traffic and anthropic activities. Nevertheless, most of the records presented unfavourable signal-to-noise (S/N) ratio, particularly at ground surface; hence, one of the major tasks of data processing was the retrieval of useful and significant signals. Therefore, a careful processing procedure was implemented in Matlab® [AIELLO et al. 2006], in order to recognize the reliable records and to analyze their attributes in both time and frequency domains [OPPENHEIM et al. 1999]. The signals were processed by baseline correction, time windowing and band pass filtering, The resulting records were subsequently synthesized in terms of peak time amplitudes and Fast Fourier spectra [BENDAT et al. 1986] to select, after a statistical interpretation, those more meaningful for the numerical modelling.

4.1 Turin LRT

The measurements were carried out in January 2006, during the endurance testing of the underground system scheduled by GTT before the line opening at the night time under the supervision of technical staff of GTT. Two monitoring sections, 20 m spaced (see locations in Figure 2) were instrumented by arrays of velocimeters. installed in the tunnel (arrays a, b) and at the ground level (arrays A, B). A further array of velocimeters was placed close to the downcast to assess for structure transmission of vibration to the surface. 17 active channels wired to sensors located in the tunnel and 29 to those along the surface arrays have been employed. Three-component velocimeters were installed in the tunnel to record the vertical, transversal and longitudinal components of the vibration close to the rail (r), at the centre line on the slab (s), and at about mid-height of the lining (l); the surface sensors were placed at corresponding positions (Figure 2).

Figure 4 shows, for each measurement section, the peak velocity amplitudes (v_{max}) obtained after the analysis of time domain filtered signals, relevant to the most favourable four records in terms of S/N. The very small values recorded at the rail level (0.004 cm/s on the average), become about ten times smaller (around 0.0005 cm/s!) at the ground surface; nevertheless, a good repeatability was observed. For both sections, the amplitudes recorded at the source are greater for the vertical and transversal components, while the surface peak values do not show significant differences among the three components. Statistical compatibility tests [AIELLO et al. 2006] have been carried out in order to detect the most representative time record to be used as kinematic input for the numerical simulations.

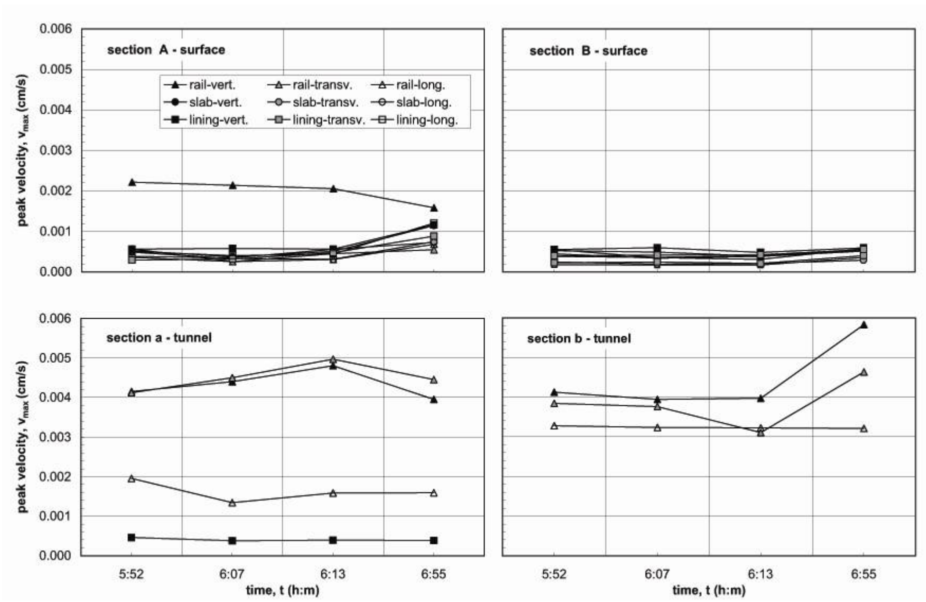


Figure 4 Turin LRT: peak velocity amplitudes of selected records.

4.2 Naples HRT

In 1996, two series of vibration records were committed by the management of MetroNapoli to the TecnoIn Company, in order to verify the effectiveness of a grinding of the rails, aimed to reduce the railway vibrations. The records were taken by 4.5 Hz 3D velocimeters placed close to the rail, in the middle of the slab and on the lining. The instrumented tunnel section was located few hundreds of meters away from the selected test site, along a rather steep and curved stretch. Most significant records were selected following a statistical screening according to criteria similar to those above mentioned. Vibration records showed peak amplitudes as high as 5 cm/s for the transversal component, about three order of magnitude higher than the corresponding values recorded at the LRT test site in Turin (see Figure 4) thus confirming the expected higher vibration level generated by the HRT with respect to the LRT.

In the first day of August 2006, a surface velocimeters network was installed at two building storeys and along a horizontal array in the courtyard, in a transversal direction with respect to the tunnel axis, as shown in Figure 3. Moreover, a vertical array was deployed in the cased hole previously used for the DH test, spaced about 9m away from the tunnel axis. Since 11 a.m. to 9 p.m. a set of 27 train passages was recorded. The records taken at surface and on the building were characterized by low S/N, caused by the background noise generated by urban activity. The borehole records (see Figure 5) resulted much less affected by noise, but were characterised by variable vibration levels according to the passenger traffic, train speed and transit intervals. Records taken at shallowest measuring points of the borehole array were discarded because of increase of environmental noise. Looking at the most reliable deep records in Figure 5, it can be seen that the peak amplitudes of all the components are progressively attenuated with distance from the source, but at some depths local amplifications can be distinguished, apparently referable to the stratigraphic discontinuities.

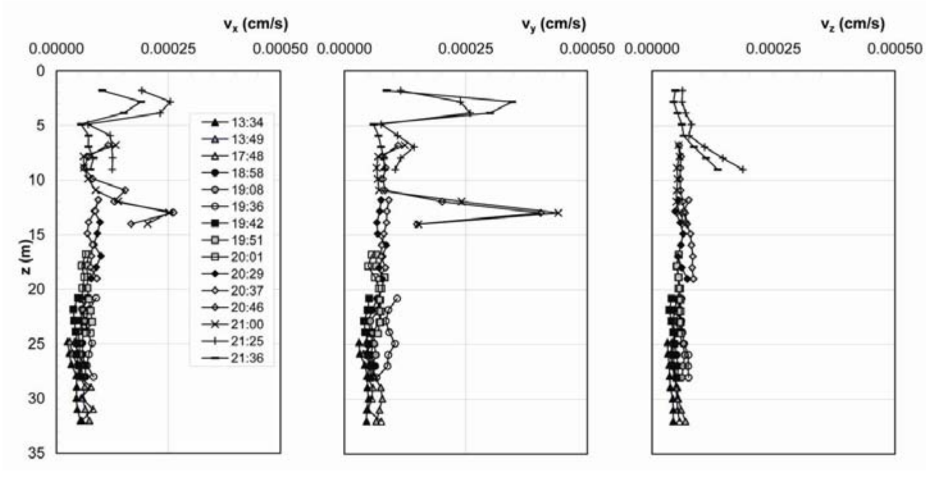


Figure 5 Naples HRT: peak amplitudes of horizontal and vertical velocity components recorded at different times along the borehole array.

5. MODELLING OF THE VIBRATION SOURCE

The vibration induced by railway traffic is generated by the dynamic interaction between the vehicle and the railway superstructure that, in turn, is affected by the unevenness of the surfaces coming into contact and the irregularities of vehicle motion [PANAGIN, 1990][CRISPINO et al. 2003]. The Power Spectral Density (PSD) of vertical interaction force between the wheel and the rail can be analytically expressed as a function of the circular frequency, ω, through the following equation [ESVELD, 2001][WU & THOMPSON. 2000]:

$$G_F(\omega) = \left|1/\left(H_V(\omega) - H_R(\omega) - H_W(\omega)\right)\right|^2 \cdot G_D(\omega) \qquad \text{(Eq. 1)}$$

where $H_V(\omega)$, $H_R(\omega)$ and $H_W(\omega)$ are the vehicle, rail and wheel vertical receptances respectively, while $G_D(\omega)$ is the PSD of vertical rail defects. In detail, wheel receptance, $H_W(\omega)$, can be estimated as the reciprocal of the Hertzian stiffness at the wheel-rail interface, K_H, whereas vehicle receptance, $H_V(\omega)$, can be approximately expressed as:

$$H_V(\omega) = 1/(M_W \omega^2) \qquad \text{(Eq. 2)}$$

where M_W is the wheel mass, in kg, while , assuming a Winkler beam on a visco-elastic foundation as rail model, the rail receptance, $H_R(\omega)$, can be expressed as follows:

$$H_R(\omega) = \frac{1}{2 \cdot (4EI)^{0.25} \cdot \left(e^{i \cdot \tan^{-1}\left(\frac{\omega \cdot c}{k_R - \omega^2 \mu}\right)} \cdot \sqrt{\left(k_R - \omega^2 \mu\right)^2 + \omega^2 c^2} \right)^{0.75}} \qquad \text{(Eq. 3)}$$

where: E is the steel Young's modulus; I is the inertia moment of the rail cross-section; k_R is the vertical beam stiffness per unit length; c is the vertical beam damping coefficient per unit length; μ is the beam mass per unit length; i is the imaginary unit. Once the PSD of vertical interaction force has been obtained, the time history of the rail displacement may be obtained, by superimposing the deflection generated by the dynamic interaction force to that induced by the static loads. Since the dynamic phenomenon can be assumed as stationary in a moving frame of reference, the dynamic reciprocity Betti-Rayleigh theorem can be invoked and the displacement time history can be evaluated assuming the interaction force (static + dynamic component) fixed on the rail, and the observer moving towards it with a velocity equal to that of train.

A preliminary attempt to validate the analytical model developed above was carried out, generating an artificial time history of vertical rail velocity at Naples HRT with parameter values derived from relevant technical data and literature [AIELLO et al. 2007], and comparing the predictions with the representative records of an 'after grinding' scenario. The following figure shows the output of the simulation (grey) compared to the experimental data (black) in the time and frequency domain. Prediction seems fairly good in time domain whereas in the frequency spectra only first low-frequency peak (at 5-10 Hz) mainly related to the vehicle axle's spacing, and high-frequency peak (at 80- 85 Hz), corresponding to the resonance of the wheel-rail system, seem to be reasonably reproduced. The reasons for the less satisfying prediction in the intermediate frequency range can be ascribed to inaccurate characterization of rail vertical defects, and to the simplified assumption of a rigid tunnel invert.

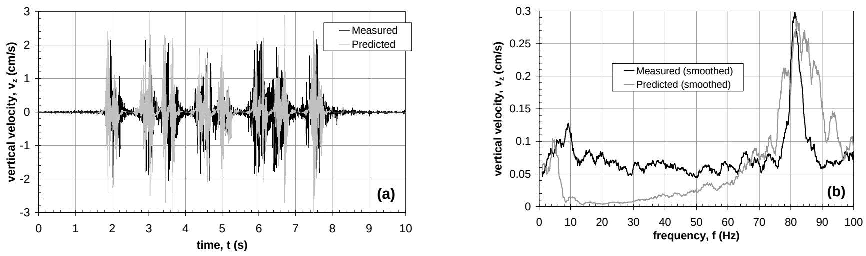


Figure 6 Comparison of predicted and measured rail vertical velocity in Naples' HRT system: time histories (a) and smoothed Fourier Spectra (b).

6. MODELLING OF THE VIBRATION PROPAGATION

The numerical simulations of the ground propagation of vibrations were carried out by the 2D finite differences code FLAC 5.0 [ITASCA 2005], referring to visco-elastic modelling of the layered subsoil profiles described in sections 3 for the test sites of Turin and Naples, respectively. The analysis domains, shown in Figure 7, were laterally surrounded by absorbing boundaries, while the nodes at the lower border were considered as quieted along both horizontal and vertical directions. Element size has been defined in order to yield an adequate resolution of the deformed shape due to each wavelength λ corresponding to the range of frequency present in the input signal. According to [LYSMER & KUHLEMEYER, 1969], if f_{max} is the maximum frequency of the Fourier spectra, and V_S is the shear wave propagation velocity in the material, the size d of the corresponding element must satisfy the condition:

$$d \leq \lambda_{\min} / k = V_S / (k f_{\max}) \qquad \text{(Eq. 6)}$$

where k is usually set higher than 6-8. The energy dissipation phenomena due to material damping were modelled through the well-known Rayleigh approach, i.e. considering the viscous damping matrix as linear combination of the mass and stiffness matrices . In the case of LRT-Turin, the damping values were directly determined after least square regression on the experimental dispersion curves D vs. f obtained from the MASW tests. For the case of HRT-Naples, the so-called double frequency approach was used, referring to literature experimental values obtained by resonant column tests on similar pyroclastic soils in the area of Naples [PAPA et al. 1988]. A 'kinematic input' was introduced in both numerical models, by applying the vertical and transversal components of the 'representative' velocity records in correspondence of the rails. The computed values of velocity amplitudes were picked at the nodes marked with black dots in Figure 7.

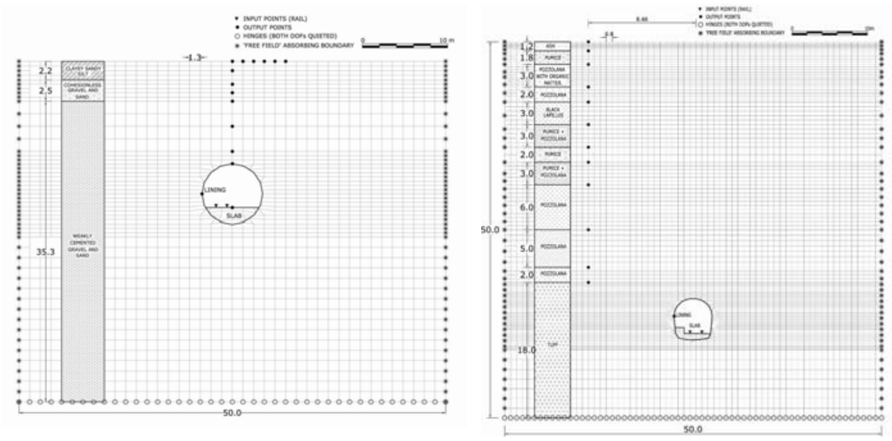
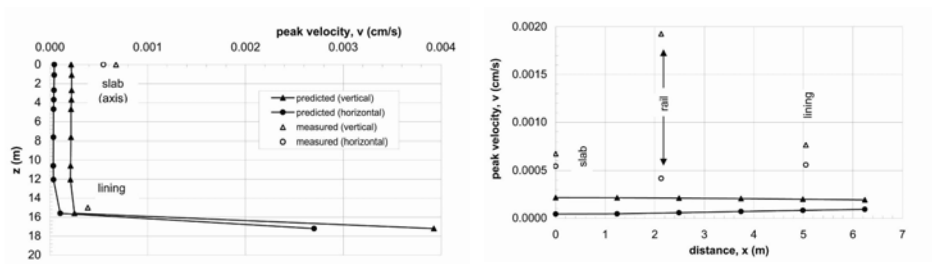


Figure 7 2D dynamic FDM model for Turin LRT (left) and Naples HRT (right)

Figure 8 shows a comparison between the profiles of measured and computed transversal and vertical motion amplitudes at the LRT Turin test site. The plots report the peak velocity values respectively (a) along the vertical tunnel axis and (b) at the ground level, at increasing x distances from the centre line.

The vertical profiles in the first plot show that the numerical data are in a good agreement with the measurements at the lining level, and do not show a significant attenuation up to the surface. At ground level, the measured values appear still higher than those simulated. The second plot shows that at the ground level, the computed values of vertical velocity attenuate with distance, while the horizontal amplitude conversely increases with a specular trend. This seems to evidence a ‘screening’ effect of the tunnel with respect to the vibration propagation towards surface. Again, the numerical simulations appear still underestimating the experimental values. It must be observed, however, that such amplitudes are about two order of magnitudes lower than the threshold values prescribed by the most up-to-date standards: for instance, with reference to the worst case of vulnerable buildings and repeated loading, the Swiss Standards prescribe threshold levels of 0.15 to 0.3 cm/s according to the frequency range considered [SN 1992].

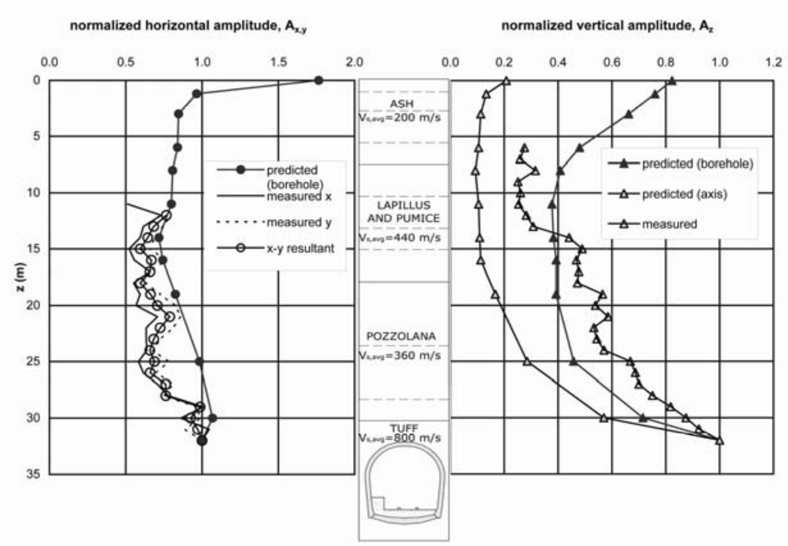


(a) **(b)**

Figure 8 LRT Turin: numerical vs experimental results along (a) vertical and (b) horizontal profiles.

The results relevant to the HRT test site in Naples are shown in Figure 9, again in terms of (a) vertical and (b) horizontal profiles. To scale out the effects of the different amplitude of the kinematic input motion assumed for the analyses with respect to that (unknown) corresponding to the experimental measurements, the data are expressed in terms of normalised profiles, i.e. of 'attenuation laws'. Therefore, the different records of the borehole array (shown in Figure 5) were first combined and normalized with respect to the average values recorded at the same depths. Summarizing, the plots in Figure 9 show the observed and simulated attenuation of the dimensionless horizontal and vertical velocity, $A_{x,y}$ and A_z, with respect to the value at the tunnel crown.

The experimental and numerical attenuation laws appear in a fair agreement for both components, at least up to the top of the coarse grained layer of lapillus and pumices; note that the computed values show a marked amplification across the shallow ash layers, with a resulting amplitude at surface about twice that at their base. Just like the measurements, the computed vertical component shows a more apparent decrease across the pozzolana layers; note that the attenuation along the middle axis profile is even more pronounced than along the borehole. This may be a further evidence of the geometrical 'screening' of waves induced by the tunnel body.



(a) (b)

Figure 9 LRT Turin: numerical and experimental results along (a) vertical and (b) horizontal profiles.

7. CONCLUSION

In this paper, preliminary results following an extensive research that has been carried out on underground railway traffic induced ground-borne vibrations are presented. An experimental campaign has been performed on two test sites where Light and Heavy Rail Transit systems are operating. The experimental measurements have been carefully processed, in order to extract representative vibration amplitudes and to calibrate rational models to simulate the vibration generation and propagation through the subsoil. In both cases, a reasonably good agreement between numerical simulations and experimental data has been observed. These and previous analyses [e.g. AIELLO & SILVESTRI 2004] executed insofar showed that, in the application of numerical tools for the simulations of the propagation wave field, particular attention should be paid to the sensitivity of the predictions to many factors affecting the output, namely: the boundary conditions, the mesh geometry and discretization, the dynamic integration procedures, the application of input signals at the source, the impedance contrasts between soft and stiff soil layers, and the definition of damping properties of all the materials.

REFERENCES

AIELLO, V. SILVESTRI, F. (2004) – “Vibrazioni prodotte da infrastrutture di trasporto in ambiente urbano: una proposta metodologica applicata ad un caso di studio” – *Proc. XXII National Conf. on Geotechnical Engineering*, AGI, Roma, (1).pp.15-22.

SKIPP, B. O. (1998) – “Ground vibration. Codes and standards” –*Ground dynamics and man-made processes*, Thomas Telford, London, pp. 29-41.

DE SANCTIS, L. MANDOLINI, A. VIGGIANI, G. (2006) – “Finite element analysis of the excavation of the new Garibaldi station of Napoli underground”. *Numerical modelling of Construction Processes in Geotechnical Engineering for Urban Environment*, Balkema Publishers, pp. 57-67.

AIELLO, V. BOIERO, D. D’APUZZO, M. SOCCO, V. SILVESTRI, F. (2007) – “Experimental and numerical analysis of vibrations induced by underground trains in urban environment” – *Structural Control and Health Monitoring*, Wiley, in press.

CARRIERI, G. CROVA, R. GRASSO, P. GUGLIELMETTI, V. (2004) – “Torino Metro Line 1, The tunnels excavation of the first section” – *Proc. International Congress on "Mechanized Tunnelling - Challenging Case History"*, GEAM, pp. 16-19.

CROVA, R. STROBBIA, C. SAMBUELLI, L. (2003) – “Indagini geofisiche per la caratterizzazione del sottosuolo interessato dalla costruenda metropolitana di Torino” –. *Proc. XXII GNGTS National Conference*.

RIPPA, F. VINALE, F. (1983) – “Effetti del terremoto del 23 novembre 1980 sul patrimonio edilizio di Napoli” – *Proc. XV National Conf. on Geotechnical Engineering*, AGI, Roma, pp. 193-206.

VINALE, F. (1988) – “Caratterizzazione del sottosuolo di un’area-campione di Napoli ai fini di una microzonazione sismica” – *Rivista Italiana di Geotecnica*, 22. pp.77-100.

AIELLO, V. BOIERO, D. SILVESTRI, F. SOCCO, L.V. (2006) – “Misure vibrometriche presso la Metropolitana Automatica di Torino”. *Technical Report*, GTT.

OPPENHEIM, A.V. SCHAFFER, R.W. BUCK, J.R. (1999) – *Discrete time signal processing*– Prentice Hall, Upper Saddle River.

BENDAT, J.S. PIERSOL, A.G. (1986) – *Random data: analysis and measurement procedures* – John Wiley & Sons, New York.

PANAGIN, R. (1990) – *La dinamica del veicolo ferroviario* –Levrotto e Bella, Torino: pp. 1-641.

CRISPINO, M. D’APUZZO, M. LAMBERTI, R. (2003) – “Development and experimental validation of a prediction model to assess railway induced vibrations” – *In 5th European Conference on Noise Control: EURONOISE 2003*, Naples.

ESVELD, C. (2001) – *Modern railway track: second edition* – MRT-Productions, Zaltbommel, The Netherlands, pp. 1-654.
WU, T.X. THOMPSON, D.J. (2000) – "Theoretical investigation of wheel/rail nonlinear interaction due to roughness excitation" – *Vehicle System Dynamics*, (34) pp. 261-282.
LYSMER, J. KUHLEMEYER, L. (1969) – "Finite dynamic model for infinite media" – *Journal of the Engineering Mechanics Division*, ASME, (95), pp. 859-877.
Nat. Conf. on Earthquake Engineering, ANIDIS, Roma.
PAPA, V. SILVESTRI, F. VINALE, F. (1988) – "Analisi delle proprietà di un tipico terreno piroclastico mediante prove dinamiche di taglio semplice" – *I National Symposium on Research in Geotechnical Engineering*, AGI, Roma, pp. 265-286.
SWISS NORM (1992) – "SN 640 312 a Erschütterungseinwirkungen auf Bauwerke" – *Schweizerische Normenvereinigung SNV*, Zürich.

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