CONVURT PROJECT - EXPERIMENTAL RESULTS OF FREE FIELD AND STRUCTURAL VIBRATIONS DUE TO UNDERGROUND RAILWAY TRAFFIC

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Abstract

The present paper gives an overview of the results obtained from in situ vibration measurements performed within the frame of the EC-Growth Project CONVURT (”The control of vibration from underground rail traffic”) at the sites of the Cité Universitaire campus in Paris on the RER B line of RATP and of Regent’s Park in London on the Bakerloo and Jubilee lines of London Underground. Tests were carried out to determine the track and the soil characteristics, the transfer functions between the track and the free field and the track and the building, as well as the free field and the building response during the passage of a test train and service trains at variable speed. These results will be used for the validation of the numerical models which are being developed within the frame of the project.

INTRODUCTION

The passage of a train in a tunnel generates vibrations which propagate through the surrounding soil and cause vibrations and re-radiated noise in adjacent structures. The amplitude of the vibrations depends on various factors such as the vehicle characteristics, the train speed, the rail and wheel roughness, the properties of the tunnel, the propagation of waves through the soil and the properties of the structures.

Within the frame of the EC-Growth project CONVURT (”The control of vibration from underground railway traffic”), a modular numerical prediction tool is developed to predict vibration and re-radiated noise in adjacent buildings generated by the passages of metro trains in tunnels for both newly built and existing situations. The model will be validated by means of elaborate in situ measurements at the sites of Cité Universitaire in Paris and Regent’s Park in London.

The site in Paris is located in Cité Universitaire campus between stations Cité Universitaire and Gentilly. The site in London is situated in Regent’s Park between stations Regent’s Park and Baker Street. These two sites are highly complimentary. The metro tunnel on the line RER B at Cité Universitaire is a masonry cut-and-cover tunnel with two tracks at a shallow depth of about 9.3 m below the free surface. The tunnel is embedded in a soil composed of Beauchamp sand, marl and gravel layers. The deep bored single track metro tunnels on the Bakerloo line and Jubilee line at Regent's Park have cast iron lining and precast concrete lining respectively. The Bakerloo line tunnel is situated at a depth of 28.5 m below the ground surface The tunnels are embedded in typical London clay.

In May 2002, several in situ measurements were carried out in Cité Universitaire campus with a test train running at varying speed and service trains on the track, on the tunnel invert, in the free field and in a 5-storey student dormitory 'Maison du Mexique' situated in close proximity to the tunnel. In May 2003, similar measurements have been performed in Regent's Park and in a building on York Terrace West situated at a distance of about 70 m from the tunnel.

At both the sites, wheel-rail unevenness, rail receptance, sleeper receptance and wave decay rate along the rail have been measured independently to determine the dynamic characteristics of the track. The axle box vibrations were measured to assess the force at the contact point. A Spectral Analysis of Surface Waves (SASW) test has been performed to obtain the thickness and the dynamic characteristics of the soil layers. The building vibrations were also measured at both the sites. Furthermore, transfer functions between the track and the free field and the track and the building have been determined using a hammer impact on the rail head at Cité Universitaire site. A seismic cone penetration test has been carried out in Regent's Park site to estimate the shear stiffness of the soil and the wave speed.

The main objective of this paper is to describe the results of the in situ vibration measurements performed at the two sites mentioned above. The data obtained from the measurements in London are currently under investigation. Results are presented in terms of the time history and the frequency content of the velocity, the variation of the peak particle velocity and the frequency content as a function of the train speed and the distance to the tunnel in the free field. Furthermore, it is demonstrated how the vibrations in the building are attenuated at the foundation level and vary over the height of the building and on the eigenfrequencies of the floors and the walls. These experimental results are used for the purpose of validation of the numerical model.

MEASUREMENTS IN PARIS

An overview of the results of the measurements performed in Paris are described in this section.

Parameter identification

Tunnel and track characteristics. The metro tunnel on the line RER B at Cité Universitaire is a masonry cut-and-cover tunnel with two tracks at a shallow depth of about 9.3 m below the free surface and a width of 11.9 m (figure 1). The slab thickness is 0.6 m at the top and 0.4 m at the bottom, while the side wall thickness is 1.5 m.

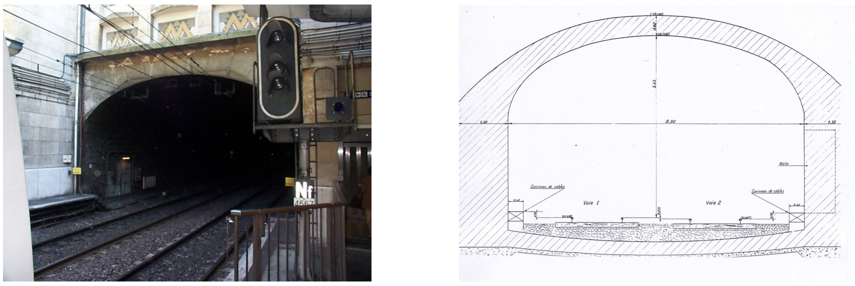


Fig. 1. Cross section of the metro tunnel on the line RER B of RATP at Cité Universitaire, Paris.

Two classical ballast tracks supported on mono-block concrete sleepers are running in the tunnel. The UIC60 rails are supported by grooved rubber pads with a thickness of 9 mm and are resting on mono-block concrete sleepers (VXP U61) with a mass of 200 kg. The sleeper distance is 0.6 m. The thickness of the ballast layer is 0.4 m.

The direct rail receptance, measured with a static pre-load and a small dynamic force amplitude, [1] shows a first resonance around 80-90 Hz, from which a ballast stiffness per unit area of $100\,\text{MN/m}^3$ and a loss factor of 0.80 can be estimated. The second resonance frequency around 600 Hz allows to derive a dynamic rail pad stiffness of about $375\,\text{MN/m}$ and a loss factor of 0.50. The pinned-pinned frequency of the rail is about 1200 Hz, which is a common value for tracks with a UIC60 rail and a sleeper distance of 0.60 m. Wave decay rates of the rail confirm the values of the track's natural frequencies.

Each sleeper has a length of 2.27 m, a width of 0.29 m and a thickness of 0.14 m. Modal analysis is performed to identify the first mode shapes and natural frequencies [1]. The first mode is a transverse rocking mode at 65 Hz with a modal loss factor of about 0.60, while the first bending mode is identified at 110 Hz with a modal loss factor of about 0.30.

Rail and wheel roughness. The rail roughness has been measured by a measurement team of SNCF using the Muller BBM technique at two sections, over a length of 10 m at the free field site and a length of 3 m near the building. The range of wavelengths measured between 0.01 m and 0.25 m partially covers the range of wavelengths between 0.1 m and 1.0 m which are relevant for ground borne vibrations.

The wheel roughness has been measured on the 8 wheels of two consecutive bogies, which are considered as the reference bogies on the test train, using LVDT sensors. Six parallel lines have been measured on each wheel. From a global point of view, the rail roughness is much higher than the wheel roughness in the wavelength domain of interest. During the test runs, 6 vertical accelerometers are mounted on the axle boxes in order to assess the total wheel/rail roughness level for long wavelengths.

Characteristics of the rolling stock. The test train (type MI79) consists of four coaches. The number of coaches in a service train is either four or eight. Each coach has two bogies with two axles. The front and the rear coaches have a length of 26.08 m. The length of an intermediate coach is 26.00 m. The total length of the test train is 104.16 m, while its mass is equal to 205000 kg. The bogie distance and the axle distance on a bogie are 18.5 m and 2.4 m, respectively, for all coaches.

Prior to the in situ vibration measurements, modal analysis of the wheelset has been performed to determine the first natural frequencies and mode shapes of the axle that can influence the excitation at the contact point. The cross receptance between the axle box and the contact point with the rail has also been measured to validate the prediction of the contact force in the excitation model.

Dynamic soil characteristics. Historical borings show that the soil stratigraphy at the test site has four distinct layers. The top layer is 1.6 m thick fill material underlain by a 3.2 m thick Beauchamp sand layer. Below this, there is a stiffer layer of 7.8 m marl and gravel followed by layer of chalk.

A SASW test has been performed in order to determine the thickness and the dynamic characteristics of the shallow soil layers [4]. The tests have been performed on two measurement lines, one line perpendicular to the tunnel and one line parallel to the tunnel and demonstrate the presence of a thin layer of approximately 1.7 m and a shear wave velocity $C_s = 123\,\text{m/s}$ and a stiffer layer with a thickness of 3.0 m and $C_s = 278\,\text{m/s}$ on top of a half-space with $C_s = 329\,\text{m/s}$.

In situ measurements in the tunnel and in the free field

Transfer functions. The transfer functions between the track and the free field have been measured due to a large hammer ($m = 5.3\,\text{kg}$) excitation on the rail head of the high rail of track 1 (figure 2) [3].

Passage of a test train at variable speed. Vibration measurements have been performed on the track, on the tunnel invert and in the free field due to the passage of a test train in the southbound direction towards Gentilly at speed varying between 40 km/h to 80 km/h [2]. Figure 2

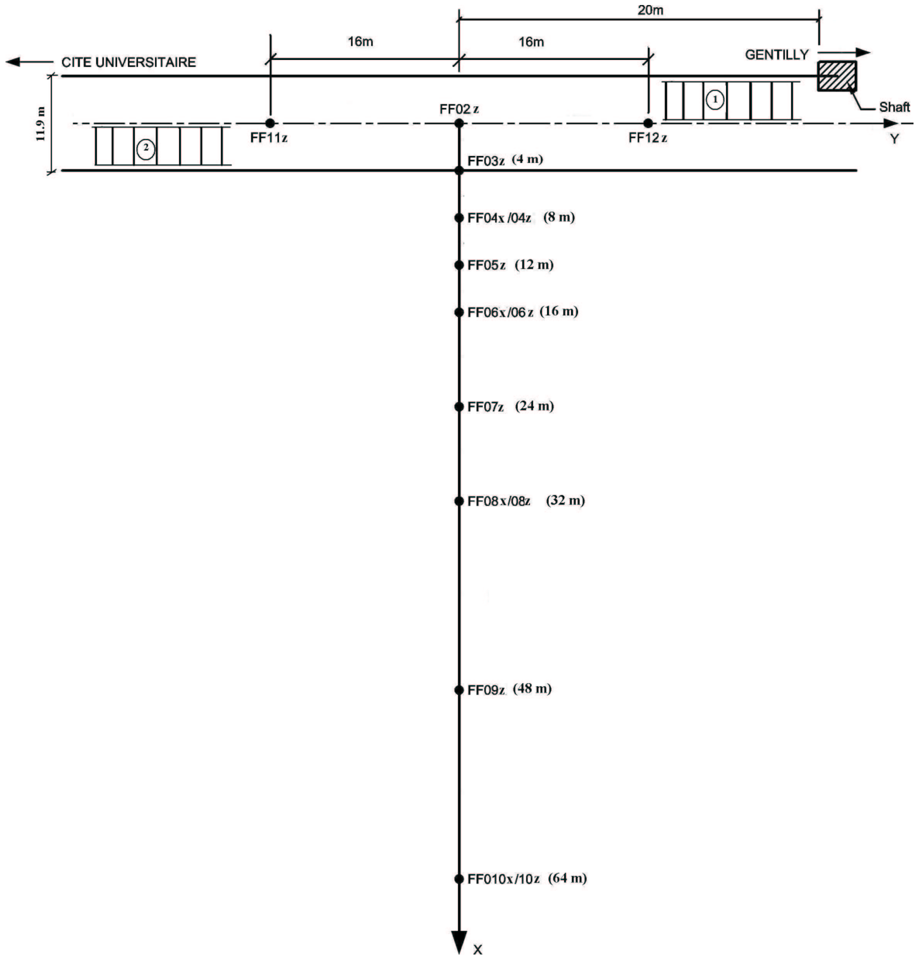
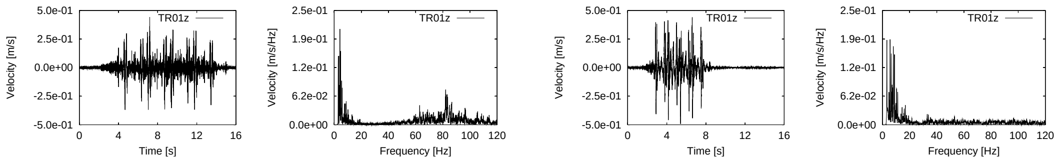


Fig. 2. Location of the measurement points in free field at Cité Universitaire campus.

shows the position of accelerometers in the free field.

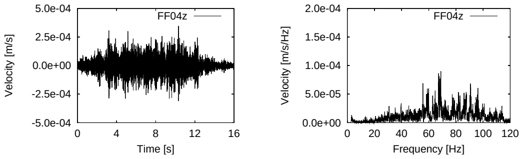
Figure 3 shows the time history and frequency content of the vertical velocity of the rail above a sleeper for the passage of the test train at speed of 40 km/h and 80 km/h, respectively. The passage of all axles can clearly be observed. At 40 km/h, the bogie passage frequency is $f_b = v/L_b = 0.606\,\text{Hz}$, while the axle passage frequency is equal to $f_a = v/L_a = 4.67\,\text{Hz}$. Figure 4



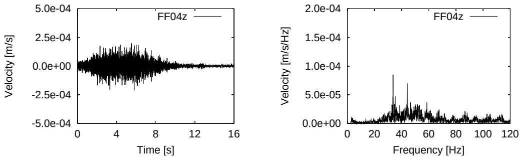
a. $v = 40$ *km/h.* *b.* $v = 80$ *km/h.*

Fig. 3. Time history and frequency content of the vertical velocity of the rail at a sleeper position during the passage of a test train at a speed (a) $v = 40\,\text{km/h}$ and (b) $v = 80\,\text{km/h}$.

shows the time history and frequency content of the vertical velocity at 8 m from the longitudinal axis of the tunnel during the passage of the test train on track 1 at 40 and 80 km/h. Similar results are shown in figure 5 at a distance of 32 m from the tunnel. The passage of individual axles can no longer be distinguished, even in the near field at 8 m. The peak particle velocity (PPV) at 8 m from the tunnel is about 0.3 mm/s and only weakly depends on the speed of the train. At 32 m from the tunnel, the PPV is about 0.1 mm/s. The frequency content is situated between 0 and 100 Hz at 8 m and shifts to lower values of frequency upto 60 Hz at 32 m from the tunnel. The excitation in this frequency range is mainly due to dynamic excitation as the wheels travel on an uneven rail.

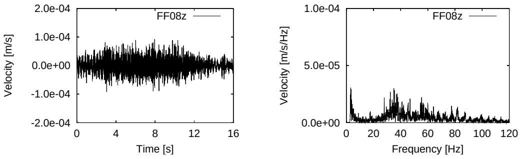


a. $v = 40$ *km/h.*

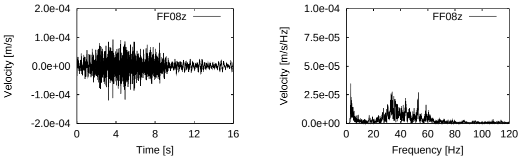


b. $v = 80$ *km/h.*

Fig. 4. Time history (left) and frequency content (right) of the free field vertical velocity at 8 m from the longitudinal axis of the tunnel during the passage of a test train.



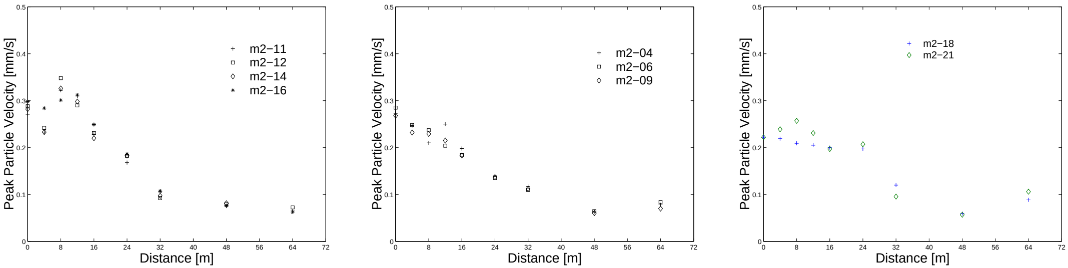
a. $v = 40$ *km/h.*



b. $v = 80$ *km/h.*

Fig. 5. Time history (left) and frequency content (right) of the free field vertical velocity at 32 m from the longitudinal axis of the tunnel during the passage of a test train.

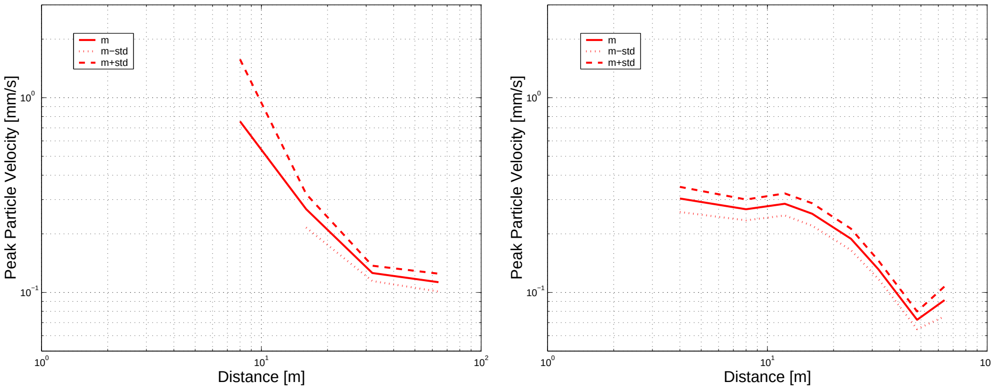
Figure 6 shows the variation of the vertical PPV in the free field as a function of the distance to the tunnel for different passages of the test train at a speed of 40 km/h and 80 km/h. The amplitude of the vertical vibrations decrease for increasing distance to the tunnel due to material and radiation damping in the soil. Although the number of train passages is too low to apply a statistical analysis, the variation of the response for different passages at the same train speed is moderate. In the range of train speeds considered, the PPV appears to be independent of the train speed.



a. $v = 40$ *km/h.* b. $v = 60$ *km/h.* c. $v = 80$ *km/h.*

Fig. 6. Vertical PPV as a function of the distance from the longitudinal axis of the tunnel for different passages of the test train at a speed (a) $v = 40$ km/h, (b) $v = 60$ km/h, and (c) $v = 80$ km/h.

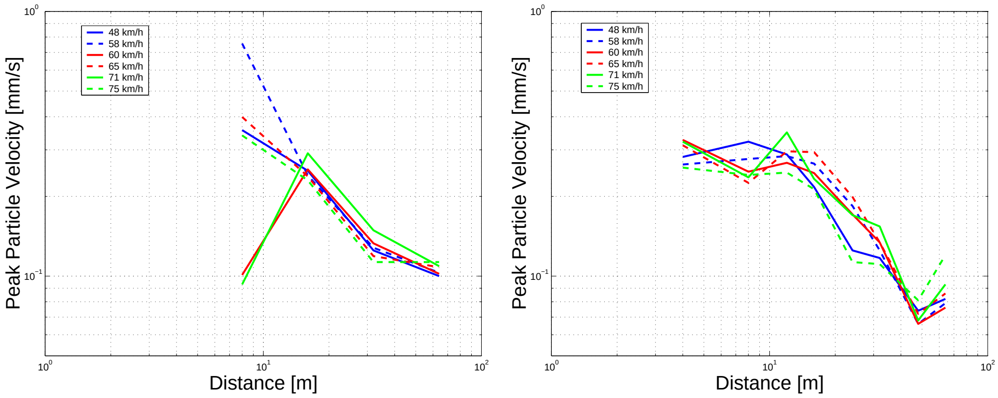
PPV due to passages of service trains at different operating speeds. A statistical analysis has been done to estimate the maximum deviation of PPV from the mean values. All data records of the service train passages are considered. Figure 7 shows the curves corresponding to the mean values of PPV within an envelope formed by two other curves corresponding to mean plus standard deviation and mean minus standard deviation. It is observed that the deviation of vertical PPV from the mean value at any distance from the track is small and uniform. However, the deviation of horizontal PPV from the mean value seems to be larger in the near field within 20 m from the track.



a. Horizontal component. *b. Vertical component.*

Fig. 7. Spatial variation of the mean and the standard variation of (a) the horizontal and (b) the vertical PPV for all train passages.

Figure 8 shows the changes in the values of the horizontal and the vertical PPV for a number of train speeds. It can be appreciated from this figure that the train speed has negligible influence upon PPV and the radiation damping in the soil decreases the response with increasing distance.



a. Horizontal component. *b. Vertical component.*

Fig. 8. Variation of (a) the horizontal and (b) the vertical PPV with distance for various speeds of service trains.

In situ measurements in the tunnel and in the building

Vibration measurements have been performed on the track, on the tunnel invert, in the free field and also at basement and at different floor levels of the 5-storey building ’Maison du Mexique’ due to the passage of service trains at variable speed [5].

Experimental setup. 25 accelerometers and 2 microphones are placed in the free field and in the building. The position of the accelerometers in the building is shown in figure 9.

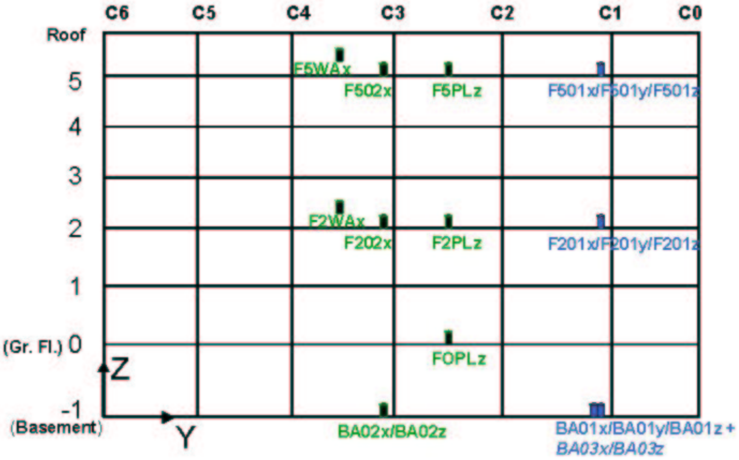


Fig. 9. Location of the measurement points in the building 'Maison du Mexique', Paris.

Passage of service trains. Figures 10 and 11 show the time history and the frequency content of the response in the free field and in different parts of the building during the passage of a service train with 4 carriages at 71.72 km/h in directions perpendicular (x) to the tunnel and in the vertical direction (z).

Figure 10 shows that the PPV in the vertical direction on the free field (FF02z) equals 0.583 mm/s. The response in the basement of the building is generally less than in the free field due to attenuation in the soil and dynamic soil-structure interaction effects. The PPV in the x-direction on the second floor (F201x) equals 0.113 mm/s and on the fifth floor (F501x) is 0.079 mm/s. There is a small decrease of the horizontal vibration amplitudes in stiff points over the height of the building. The vertical PPV on the second floor (F201z) equals 0.074 mm/s and is smaller than the PPV in the basement; this value slightly increases to 0.108 mm/s (F501z) on the fifth floor.

Figure 11 shows that the frequency content in the free field is mainly situated between 20 and 60 Hz. The frequency content of the second and fifth floors show an amplification at frequencies of about 2 Hz, which correspond to the lateral bending modes of the building. These values have been confirmed by finite element analysis. A resonance frequency of about 15 Hz can be seen for the slab on the fifth floor.

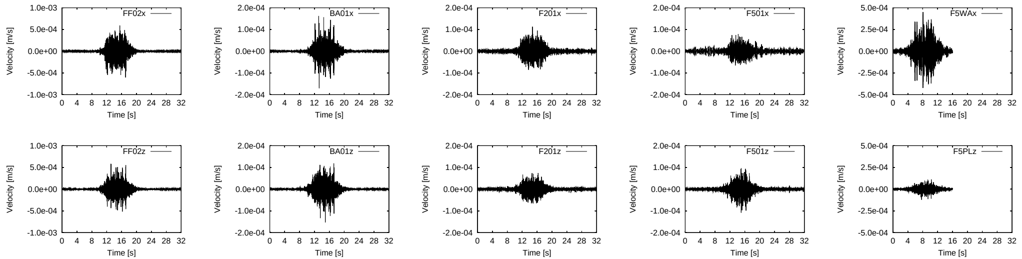
MEASUREMENTS IN LONDON

The data obtained from the measurements in London are currently investigated. An overview of the results obtained so far are described in this section.

Parameter identification

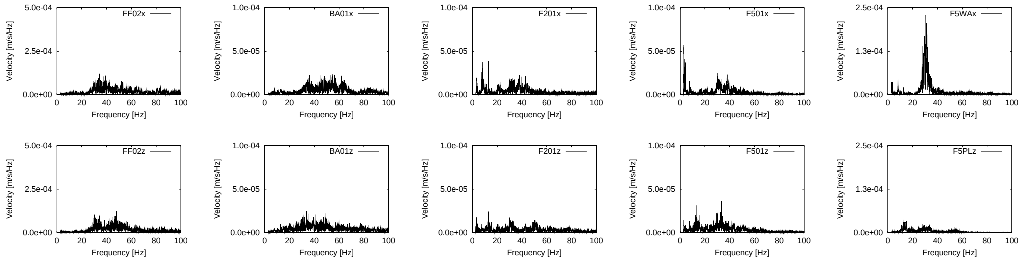
Tunnel and track characteristics. The metro tunnel on the Bakerloo line of LUL is a deep bored cylindrical cast iron tunnel with a single track at a depth of about 28.5 m below the free surface. It has an internal radius of 1.83 m and a shell thickness of 0.022 m. Figure 12 shows the Bakerloo line tunnel and the cross-section of the tunnel.

The track in the metro tunnel is a non-ballasted concrete slab track with Bull head rail supported on hard wood sleeper via cast iron chairs every 0.95 m. The mass per unit length of the rail is 46 kg/m. The rail material is the same as that of UIC rails with nominal modulus of 210×10^9 N/m^2.



Free field. *Basement.* *Second floor.* *Fifth floor. (column)* *Fifth floor. (wall and slab)*

Fig. 10. Time history of the response in the free field and the building during the passage of a service train at 71.72 km/h in x (top) and z (bottom) directions.



Free field. *Basement.* *Second floor.* *Fifth floor. (column)* *Fifth floor. (wall and slab)*

Fig. 11. Frequency content of the response in the free field and in the building during the passage of a service train at 71.72 km/h in x (top) and z (bottom) directions.

a. The Bakerloo line tunnel. *a. Cross-section of the tunnel.*

Fig. 12. (a) The Bakerloo line tunnel at Regent's Park, London and (b) the cross-section of the tunnel.

No rail pad is present and the resilience is mainly provided by the local resilience of the timber sleeper. The sleeper has a varying stiffness depending on its moisture content but may be assumed to have a stiffness of about 70 kN/mm. The distance between any two adjacent sleepers is 0.915 m in the case of Bakerloo line.

Rail and wheel roughness. Rail and wheel roughness has been measured and the data are now being processed.

Characteristics of the rolling stock. Each of the service train and the test train consists of seven coaches. The first coach is a motor car followed by a trailer car. This trailer car is again connected to three non driving motor cars in series followed by two more trailer cars and one motor car at the end. Each motor car (driving and non-driving) is approximately 16.1 m long and each trailer car is about 15.98 m long. The distance from the one end of the car to the nearest wheel set is about 0.95 m. Hence, the total length of the train and the distance between the front and the rear wheel sets are about 112.34 m and 110.44 m respectively. The distances between the two adjacent axles and the two adjacent bogies are 1.91 m and 10.34 m respectively.

Each coach/car has two bogies and each bogie has two axles. In case of Bakerloo line trains, the bogie mass including wheel sets is 6690 kg for motor car and 4170 kg for trailer car, and the masses (tare) of the motor coach and the trailer coach are 15330 kg and 10600 kg respectively.

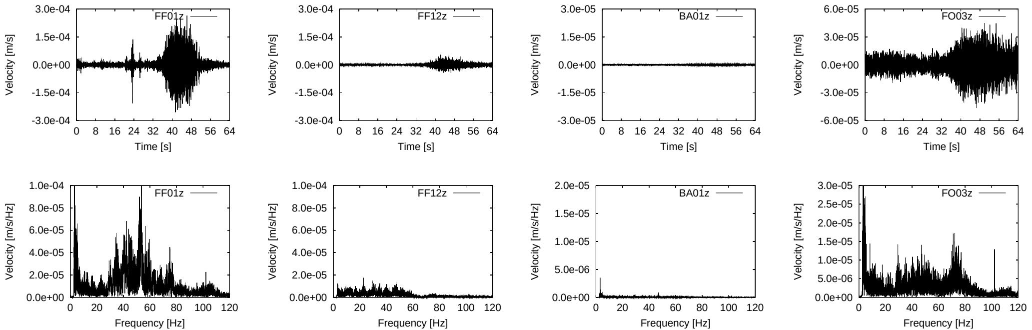
Dynamic soil characteristics. The tunnel is embedded in typical London clay. A SASW test has been performed in order to determine the thickness and the dynamic characteristics of the soil layers at the testing site. The tests have been performed on two measurement lines as done in case of Paris. The final results are yet to be obtained.

In situ measurements in the building

In situ measurements have been carried out on the track, in the tunnel, in the free field and in a building on York Terrace West situated at about 70 m from the tunnel and the data processing is continuing. The measurements mainly in the building corresponding to a test train passage at 39 km/h in the North bound Bakerloo line (towards Baker Street station) are presented in the following section.

Passage of a test train at 39 km/h. Figure 13 shows the time history and frequency content of the vertical velocity of the free field, the basement and the ground floor. The channel FF01z measures the vertical response (z-direction) in the free field on the tunnel and channel FF12z measures the vertical response in the free field (in the garden adjacent to the building) at about 5 m from the building. The channels BA01z and F003z are located in the basement and in the ground floor respectively to record the vertical responses.

In figure 13, the time history shows that the maximum vertical velocity (about 0.3 mm/s) is recorded at channel FF01z on the tunnel top and is considerably less at the basement level due to soil-structure interaction effects.

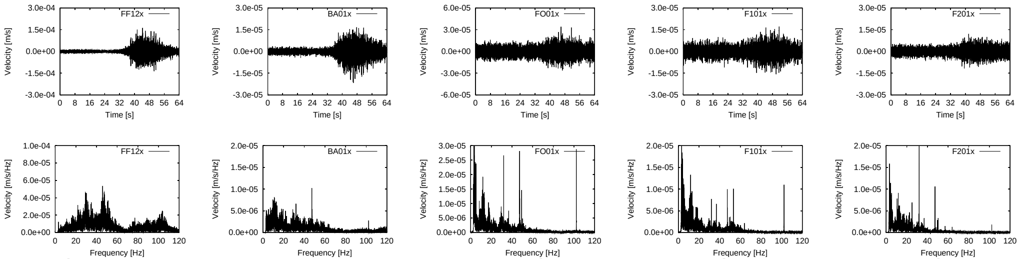


Tunnel top. (FF01z) *Free field (garden). (FF12z)* *Basement. (BA01z)* *Second floor. (FO03z)*

Fig. 13. Time history and frequency content of the vertical velocity on the tunnel, in the free field and in the building due to the passage of a test train at measured speed of 39 km/h.

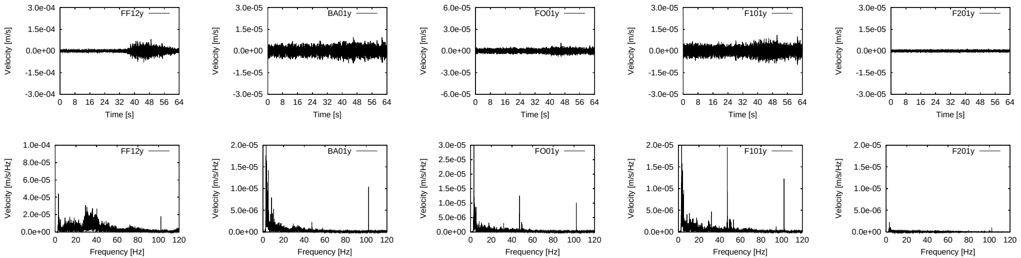
Figures 14 and 15 show the time history and frequency content of the horizontal velocity of the free field, the basement and the ground floor in a direction perpendicular (x) and parallel (y) to the tunnel. The channels FF12x/y, BA01x/y, FO01x/y, F101x/y and F201x/y are located in the free field (in the garden), in the basement, on the ground floor, on the first floor and on the second floor respectively and are measuring in x or y direction. The time history in these two figures demonstrates that the response on the first floor (FO01x and FO01y) has the same order of magnitude as the response in the basement (BA01x and BA01y). The responses, however, is slightly reduced on the upper floors (F101x, F101y, F201x and F201y) unlike building measurements in Paris where the response is slightly amplified in the upper floor.

The frequency content in figure 14 shows that the dominant frequency range lies between 0 and 60 Hz.



Free field (garden). (FF12x) *Basement. (BA01x)* *Ground floor. (FO01x)* *First floor. (F101x)* *Second floor. (F201x)*

Fig. 14. Time history and frequency content of the horizontal velocity (perpendicular to the tunnel) in the free field and in the building due to the passage of a test train at measured speed of 39 km/h.



Free field (garden). (FF12y) *Basement. (BA01y)* *Ground floor. (FO01y)* *First floor. (F101y)* *Second floor. (F201y)*

Fig. 15. Time history and frequency content of the horizontal velocity (parallel to the tunnel) in the free field and in the building due to the passage of a test train at measured speed of 39 km/h.

CONCLUSIONS

From the various types of in situ measurements performed on the RER B line of RATP at Cité Universitaire campus in Paris and Bakerloo line tunnel of LUL at Regent’s Park in London, the following conclusions can be drawn. The PPV decreases due to increasing distance from the tunnel and only weakly depends on the speed of the train. In free field , both the horizontal and vertical vibrations have the same order of magnitude and both components decrease for increasing distance to the tunnel due to material and radiation damping in the soil. Soil-structure interaction effects reduce the magnitude of the response in the basement compared to that on the tunnel or in the free field.

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