# Vibrations due to a test train at variable speeds in a deep bored tunnel embedded in London clay

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**Abstract**

This paper reports on the results of in situ vibration measurements that have been performed within the frame of the CONVURT project at a site in Regent's Park on the Bakerloo line of London Underground during 35 passages of a test train at a speed between 20 and 50 km/h. Vibration measurements have been performed on the axle boxes of the test train, in the tunnel (on the rails, the sleepers, the invert and the lining) and in the free field, both on the surface and at a depth of 15 m. Measurements have also been made on several floors of two buildings in a row of Regency Houses at a distance of 70 m from the tunnel. Prior to these vibration measurements, the dynamic soil characteristics have been determined by in situ and laboratory testing. Rail and wheel roughness have been measured and the track characteristics have been determined by rail receptance and wave decay measurements. Time histories and frequency spectra of the measured velocities are discussed and the variation of the peak particle velocity and the frequency content as a function of the train speed and the distance to the tunnel is elaborated.

## 1 Introduction

The main objective of this paper is to describe the results of in situ vibration measurements at a site in Regent's Park on the Bakerloo Line of London Underground during 35 passages of a test train at a speed between 20 and 50 km/h [1]. The tunnel is a deep bored segmented tunnel with a cast iron lining and a single track, embedded in London clay at a depth of 28 m. These tests are complementary to previous in situ tests obtained within the frame of the CONVURT project [2] at a site in Cité Universitaire in Paris on the RER B line of RATP, where a shallow cut-and-cover tunnel with two ballasted tracks is embedded in sandy soil.

Vibration measurements have been performed on the axle boxes of the test train [3], on the track (rails and sleepers) [4], on the tunnel invert and wall [4] and in the free field, both on the surface and at a depth of 15 m where tri-axial accelerometers have been installed in a seismic cone [1, 5]. Measurements have also been made on several floors of two buildings in a row of Regency houses at a distance of 70 m from the tunnel [1].

Prior to these vibration measurements, the dynamic soil characteristics have been determined by in situ tests (CPT, SCPT, SASW) and by laboratory testing on undisturbed samples (bender element test, free torsion pendulum test) [5, 6]. Rail and wheel roughness have been measured, while the track characteristics have been determined by rail receptance measurements [4].

Time histories and frequency spectra of the velocity during the passage of the test train at varying speed are discussed in detail. In particular, the variation of the peak particle velocity (PPV) and the frequency content as a function of the train speed and the distance to the tunnel is elaborated. Furthermore, it is demonstrated how the vibrations are attenuated at the basement of the building and propagate into the building. The results of these vibration measurements are presently used to validate the modular numerical prediction models that are developed within the frame of the project.

## 2 Characteristics of the site

The measurement site in Regent's Park in London is surrounded by a lake in the north and by the Outer Circle on the south (figure 1). The north- and south-bound Bakerloo lines are crossing the site at a depth of 28 m. A row of Regency houses is built along York Terrace West, parallel to the Outer Circle, at a distance of about 70 m from the Bakerloo line tunnels.

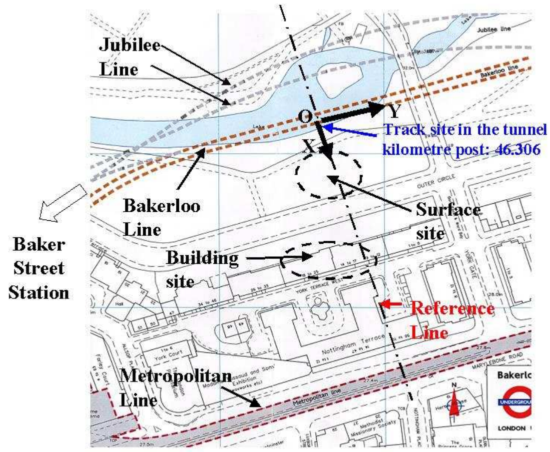



Figure 1: Plan of the measurement site.

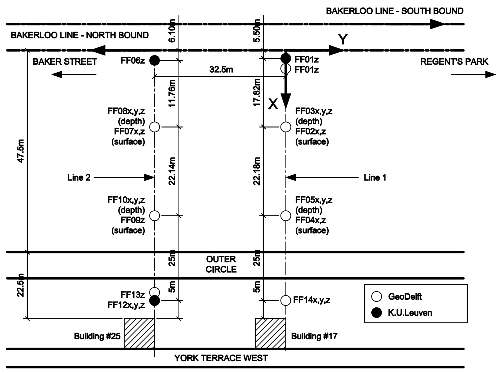



Figure 2: Measurement setup in the free field.

A right handed Cartesian frame of reference is defined with the origin at the free surface at kilometre post 46.306 of the north-bound Bakerloo line (which is about 200 m east of Baker Street station), the $x$-axis perpendicular to the tunnel axis, the longitudinal $y$-axis in the direction of the tunnel and the $z$-axis pointing upwards. Vibration measurements have been made along the reference line 1 that corresponds to the $x$-axis ($y = 0$) and along line 2 which is parallel to line 1 and located at $y = -32.5\,\mathrm{m}$ (figure 2), during operating hours of service trains and during the night for 35 passages of an instrumented test train in the north-bound Bakerloo line tunnel at a speed between 20 and 50 km/h. During service hours, trains running on the Bakerloo line could easily be differentiated from trains on the north-bound and south-bound Jubilee line and on the Metropolitan line (figure 1), as they give rise to the highest level of vibration, even in the buildings on York Terrace West that are relatively close to the shallow cut-and-cover tunnel of the Metropolitan line.

This paper only reports on the results of the latter vibration measurements, that have been performed on the axle boxes of the test train, on the track, on the tunnel invert and wall, in the free field and in two buildings at 17 and 25 York Terrace West (figure 2). The characteristics of the tunnel, the track, the train, the soil and the building are first reviewed.

### 2.1 *Tunnel characteristics*

The tunnel on the Bakerloo line is a deep bored tunnel with a cast iron lining and a single track, embedded in London clay at a depth of about 28 m below the surface. The tunnel has an internal radius of 1.83 m and a wall thickness of 0.022 m. There are six longitudinal stiffeners on the internal periphery of the tunnel and a circumferential stiffener at an interval of 0.508 m in the longitudinal direction, resulting in a periodic structure (figure 3).

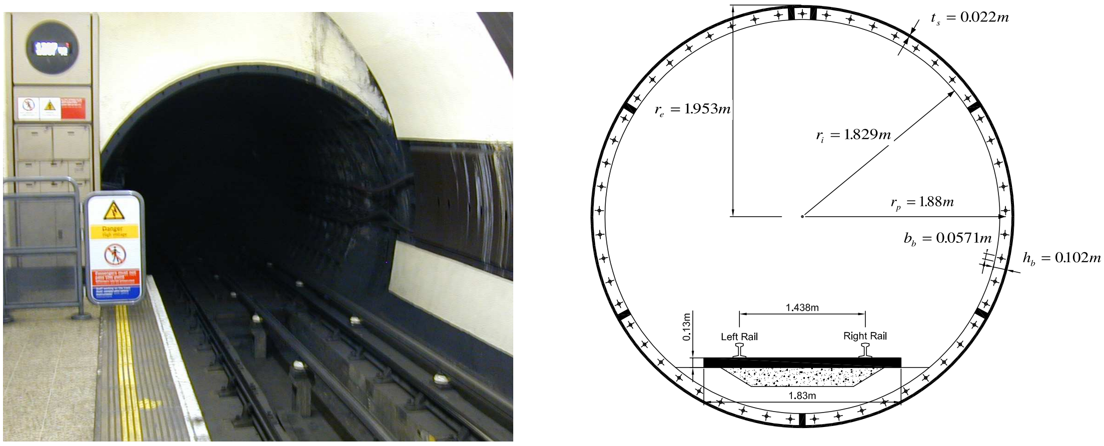



Figure 3: Cross section of the Bakerloo line metro tunnel at Baker Street station.

### 2.2 *Track characteristics*

The track in the tunnel is of the conventional London Underground type. It is a non-ballasted concrete slab track with Bull head rail supported on hard Jarrah wooden sleeper via cast iron chairs. The sleeper distance is 0.9 m. Both ends of a sleeper are concreted into the concrete invert. The space between the sleepers is filled with shingle which does not support the sleepers but allows for a safe evacuation of the trains in case of emergency. The rails are not supported by rail pads and the resilience is mainly provided by the local resilience of the timber sleeper, which has a stiffness of approximately 70 kN/mm. Rail receptance measurements have revealed a pinned-pinned frequency of the rail at 380 Hz [4].

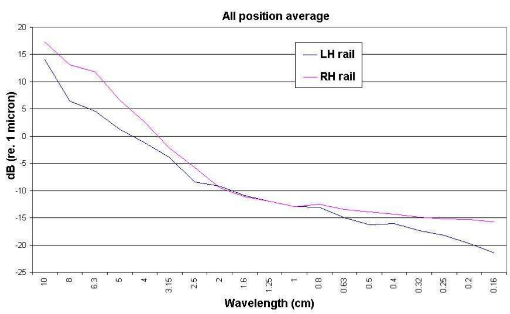



Figure 4: Average rail roughness spectra along the reference section.

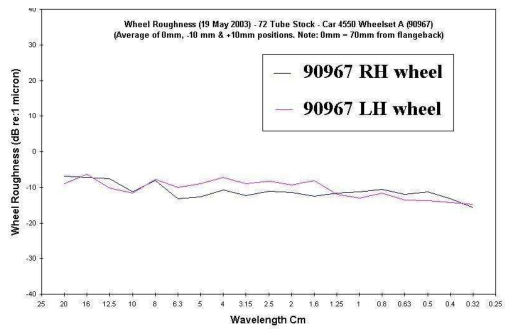



Figure 5: Wheel roughness spectra on a wheelset of the trailer car.

The rails have joints in the vicinity of the reference section. Rail roughness has been measured on both rails by London Underground's noise and vibration team. Figure 4 shows the average rail roughness spectra of both rails measured along the reference section. Wavelengths vary between 0.0016 m and 0.10 m, which are relatively short and only allow to assess roughness induced vibrations above 55 and 138 Hz at train speeds of 20 and 50 km/h, respectively.

### *2.3 Characteristics of the test train*

The test train consists of seven carriages: a motor car, followed by a trailer car, two non-driving motor cars, two trailer cars and a motor car. The length of a motor car is 16.09 m, while the length of a trailer car is 15.98 m. The bogie and axle distance on all cars are equal to 10.34 m and 1.91 m, respectively.

Roughness has been measured on five wheels of three wheelsets of a trailer car and one wheel on a non-driving motor car. Figure 5 shows the wheel roughness measured on both wheels on a wheelset of the trailer car. Recorded wavelengths vary between 0.0032 m and 0.20 m and generate vibrations above 27 and 69 Hz at train speeds of 20 and 50 km/h, respectively.

### *2.4 Dynamic soil characteristics*

Historical borings and geological maps of London show that the average thickness of the London clay layer at the site is 40 m.

GeoDelft has performed cone penetration tests (CPT) at the points FF02, FF04 and FF09 in the free field (figure 2) upto a depth of 21 m [5]. The soil is clay over the entire depth. A shallow top layer with a thickness of 4 to 6 m is not very homogeneous with inclusions of sand and gravel and varying cone resistance. The deep layer is very homogeneous with a cone resistance gradually increasing from 2 MPa at 6 m depth to 3.8 MPa at 21 m depth.

Undisturbed samples have been taken at the points FF02, FF04, FF07 and FF09 at a shallow depth of 4-6 m in the top layer and at depths of 6-7 m and 7-7.5 m in the deeper layer. Laboratory tests have been performed to classify the soil and determine the volumetric mass, particle distribution and Atterberg limits [5]. These tests confirm that the soil is clay with inclusions of sand, loam and gravel in the inhomogeneous top layer. The density is uniform in depth with a mean value of $1980\,\text{kg/m}^3$.

Bender element tests have been performed on undisturbed samples at several confining pressures [5], resulting in an average shear wave velocity of 124 m/s and a longitudinal wave velocity of 1604 m/s, corresponding to a saturated soil with a high Poisson's ratio of 0.497. A material damping ratio of 0.042 in the top layer and 0.039 in the second layer has been determined with free torsion pendulum tests [5].

Seismic Cone Penetration Tests (SCPT) at the points FF02, FF04 and FF09 upto a depth of 21 m confirmed the presence of a shallow stiffer layer with a thickness of 4 to 6 m and a shear wave velocity of 325 m/s on top of a homogeneous halfspace with an average shear wave velocity of 220 m/s [5]. The latter has the same order of magnitude as the value of 251 m/s reported by Bovey [7]. Spectral Analysis of Surface Waves (SASW) tests only revealed the presence of a homogeneous clay substratum with a shear wave velocity between 200 and 260 m/s [6].

### *2.5 Building characteristics*

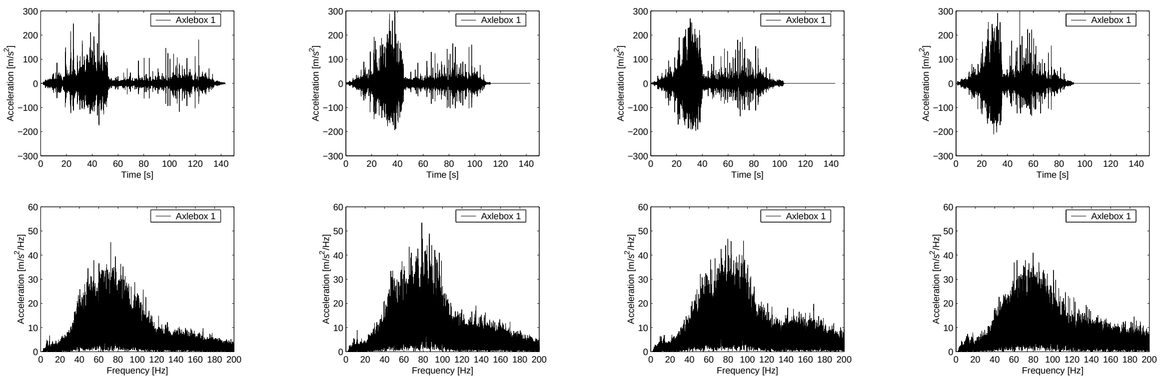
The buildings on number 17 and 25 York Terrace West are Regency houses with a repetitive structure parallel to the tunnel at a distance of about 70 m. Both buildings are reinforced concrete frame structures. The building on 25 York Terrace West is under renovation, involving important structural changes using steel columns and beams.

# 3 Experimental results

Figure 2 shows the location of the Bakerloo line tunnel, the measurement lines 1 and 2 in the free field and the buildings number 17 and 25 on York Terrace West. Detailed results are presented for the passage of the test train at four different speeds, while the variation of the peak particle velocity (PPV) with distance and train speed is summarized for all passages.

## *3.1 Axle box response*

Figure 6 shows the time history and frequency content of the acceleration of axle box 1 during the passage of the test train at four different speeds. Higher accelarations are noted when the wheel passes rail joints, but these peak values are not importantly influenced by the speed of the train. Further away from the rail joints, rail and wheel roughness are dominating the response and the acceleration does increase with train speed. The amplitude of the linear spectrum is dominated by frequencies between 20 and 120 Hz, that are related to relatively long wavelengths in the rail and wheel roughness spectra. Higher values around 80 Hz correspond to the resonance frequency of the track. Figure 7 shows a moderate dependency of the PPV on the axle boxes on the train speed, as the effect of rail joints masks the influence of rail and wheel roughness in the time window analyzed.




*a. 23.86 km/h.* *b. 32.96 km/h.* *c. 38.88 km/h.* *d. 47.60 km/h.*

Figure 6: Time history (top) and frequency content (bottom) of the acceleration of axle box 1 for four speeds of the test train.

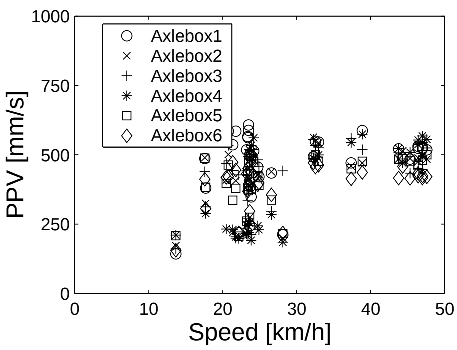



Figure 7: PPV on axle boxes vs train speed.

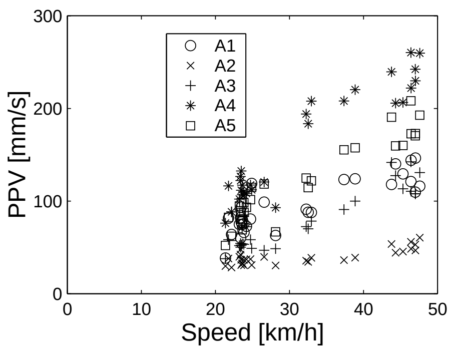



Figure 8: PPV of the rails vs train speed.

### 3.2 Response of the track and the tunnel

Figure 9 gives an overview of all accelerometers installed on the track, the tunnel invert and the tunnel wall. Figure 10 shows the time history and frequency content of the vertical velocity on the foot of the right rail in the reference section (A1) during the passage of the test train at four speeds. The contribution of each axle can clearly be distinguished, resulting in a quasi-discete spectrum at low frequencies governed by the boogie and axle distances and the train speed. Contributions in the frequency range above 20 Hz are associated with rail and wheel roughness. These results demonstrate that the PPV on the rail increases with train speed, which is confirmed by figure 8.

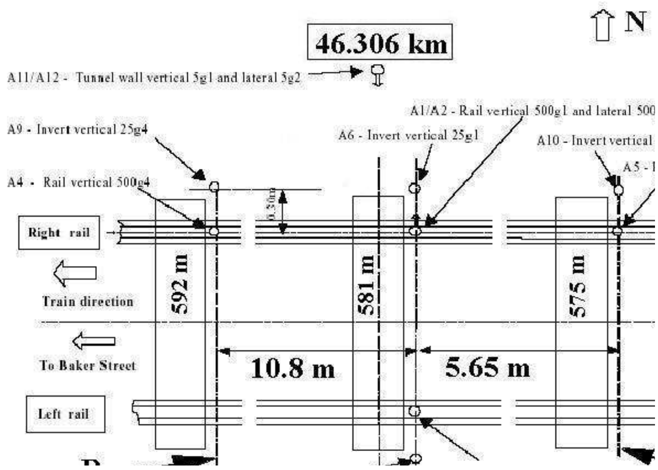
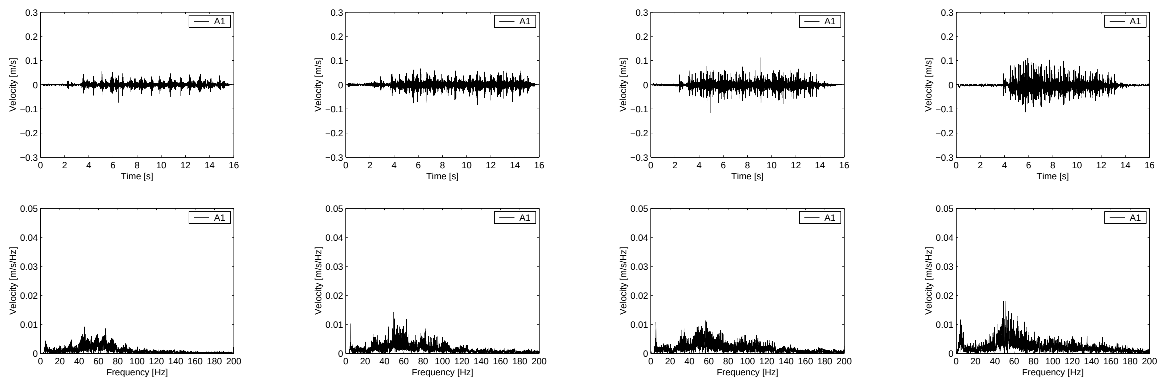


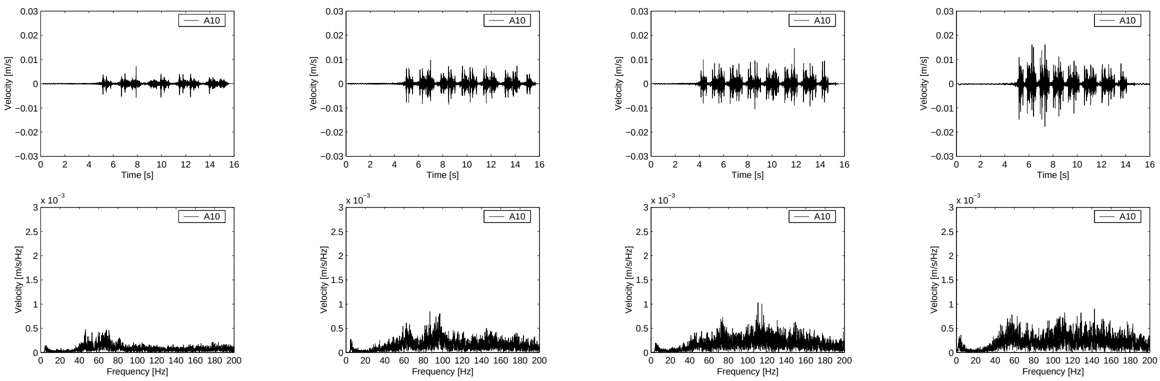

Figure 9: Measurement setup in the tunnel.




*a. 23.86 km/h.* *b. 32.96 km/h.* *c. 38.88 km/h.* *d. 47.60 km/h.*

Figure 10: Time history (top) and frequency content (bottom) of the vertical velocity of the foot of the right rail (A1) in the reference section for four speeds of the test train.

Similar observations can be made for the response of the tunnel invert and the tunnel wall. Figure 11 shows the time history and the frequency content of the vertical velocity on the tunnel invert in the reference section (A10), while figures 12 and 13 show the PPV on the all channels on the tunnel invert, the tunnel wall (A11) and the soil's surface (FF01z) as a function of the train speed.




*a. 23.86 km/h.* *b. 32.96 km/h.* *c. 38.88 km/h.* *d. 47.60 km/h.*

Figure 11: Time history (top) and frequency content (bottom) of the vertical velocity of the tunnel invert (A10) in the reference section for four speeds of the test train.

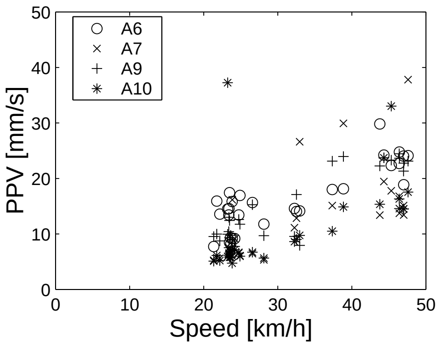



Figure 12: PPV on the tunnel invert vs train speed.

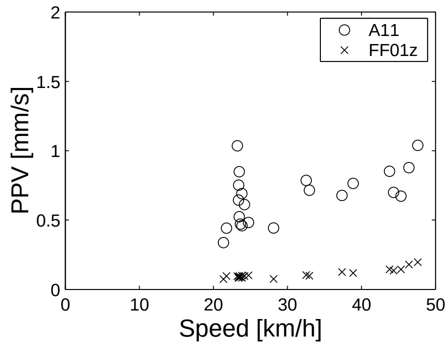
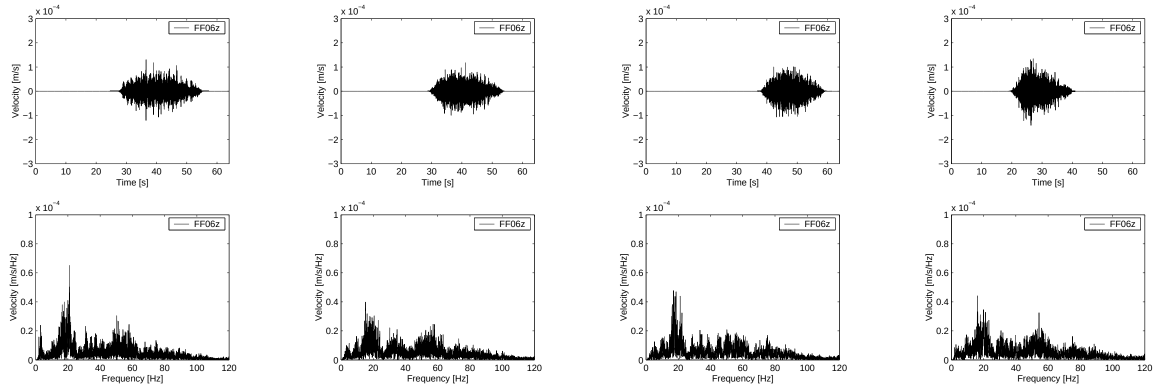



Figure 13: PPV on the tunnel wall and at the soil's surface vs train speed.

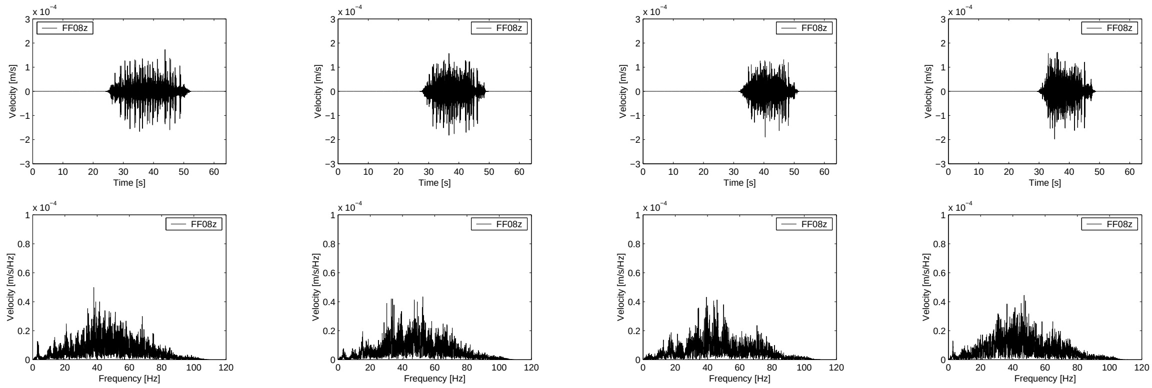



*a. 23.86 km/h.* *b. 32.96 km/h.* *c. 38.88 km/h.* *d. 47.60 km/h.*

Figure 14: Time history (top) and frequency content (bottom) of the vertical velocity at the point FF06z in the free field for four speeds of the test train.

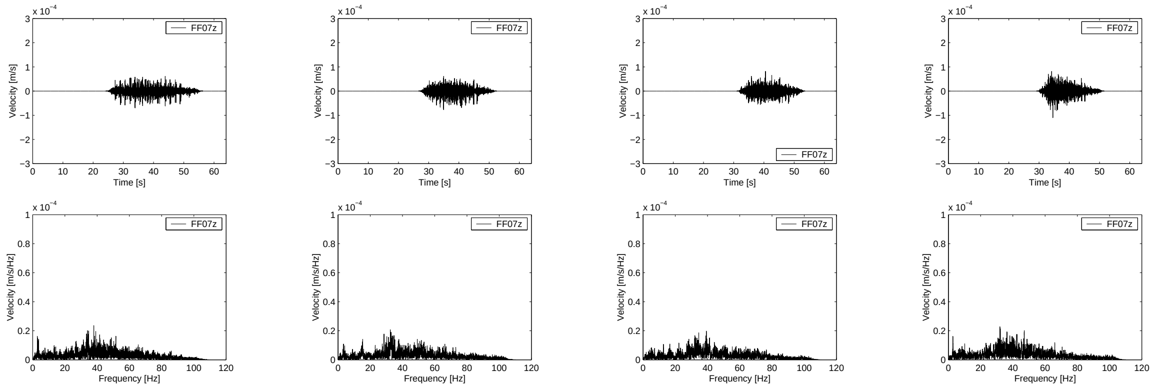
### *3.3 Response in the free field*

Figure 14 shows the time history and frequency content of the vertical velocity on the free surface on top of the tunnel on measurement line 2 (FF06z). The PPV is below 0.2 mm/s and the threshold for human perception and does not importantly depend on the train speed. The frequency content is mainly governed by wheel and rail roughness and is situated between 15 and 60 Hz for the lower train speeds and shifts upto 80 Hz at higher train speeds. Low frequency components associated with the passage of the individual axles can no longer be distinguished, while higher frequency components are attenuated by material damping in the soil.




*a. 23.86 km/h.* *b. 32.96 km/h.* *c. 38.88 km/h.* *d. 47.60 km/h.*

Figure 15: Time history (top) and frequency content (bottom) of the vertical velocity at the point FF08z in the free field for four speeds of the test train.




*a. 23.86 km/h.* *b. 32.96 km/h.* *c. 38.88 km/h.* *d. 47.60 km/h.*

Figure 16: Time history (top) and frequency content (bottom) of the vertical velocity at the point FF07z in the free field for four speeds of the test train.

Similar results are obtained in the point FF08z (figure 15), where a tri-axial accelerometer is installed in a seismic cone at a depth of 15 m below the surface, and in the point FF07z (figure 16) at the free surface. Both points are situated at a lateral distance of about 18 m from the tunnel (figure 2).

The moderate dependence of the PPV on the train speed is confirmed in figures 13, 17 and 18. Figure 13 compares the vertical PPV on the tunnel wall (A11) and in the free field immediately above the tunnel (FF01z) as a function of the train speed, showing a very weak dependency of the free field response on the train speed. Figures 17 and 18 show the variation of the horizontal and vertical PPV along measurement line 2 with the train speed.

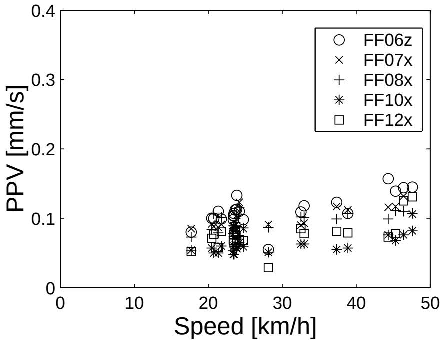



Figure 17: Free field PPV ($x$) vs train speed.

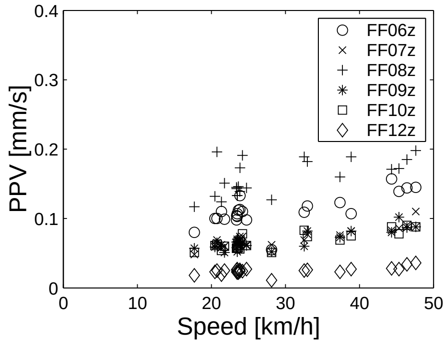



Figure 18: Free field PPV ($z$) vs train speed.

## 3.4 *Response in the building*

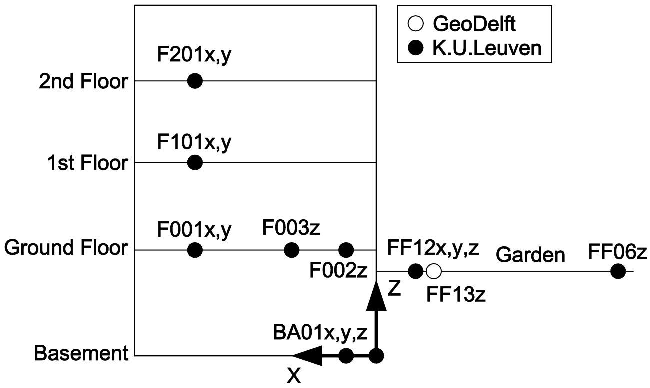
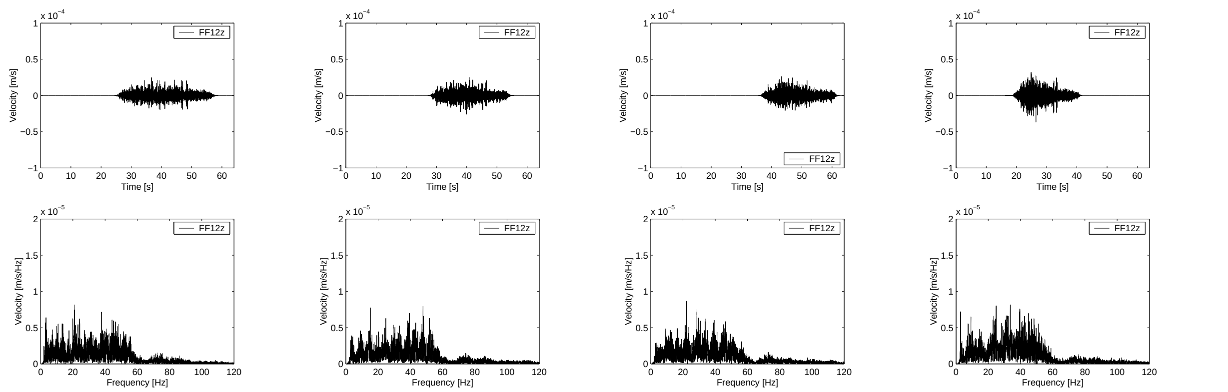


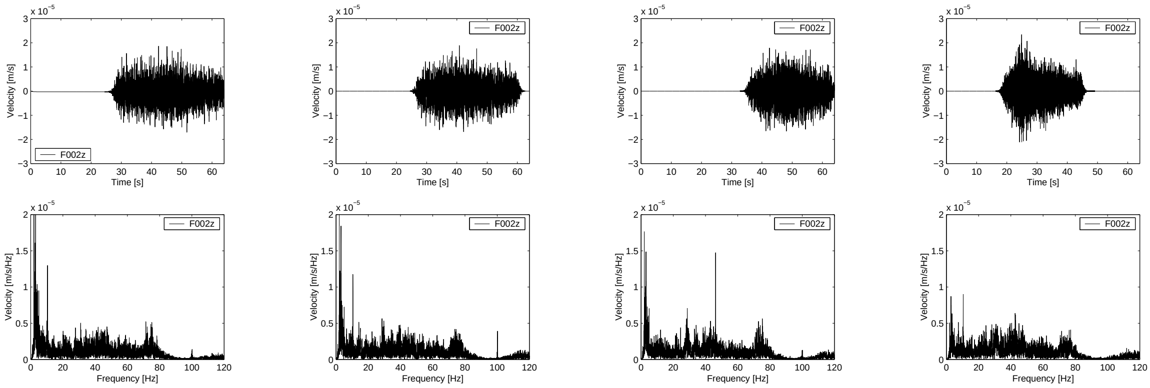

Figure 19: Position of the accelerometers in the building at 25 York Terrace West.

Figure 19 shows that accelerometers have been placed in tri-axial directions in the garden and in the basement of the building at 25 York Terrace West, in the vertical direction on two points on the slab of the ground floor and in both horizontal directions on a column on three floors.




*a. 23.86 km/h.* *b. 32.96 km/h.* *c. 38.88 km/h.* *d. 47.60 km/h.*

Figure 20: Time history (top) and frequency content (bottom) of the vertical velocity at the point FF12z in the garden for four speeds of the test train.




*a. 23.86 km/h.* *b. 32.96 km/h.* *c. 38.88 km/h.* *d. 47.60 km/h.*

Figure 21: Time history (top) and frequency content (bottom) of the vertical velocity at the point F002z on the slab on the ground floor for four speeds of the test train.

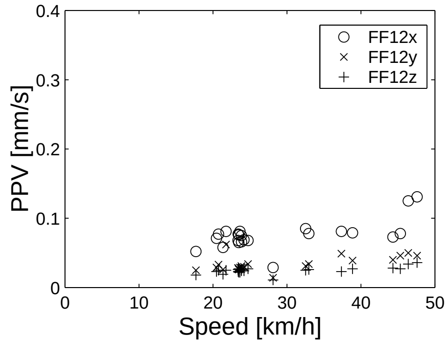



Figure 22: PPV ($x$, $y$ and $z$) in the garden vs train speed.

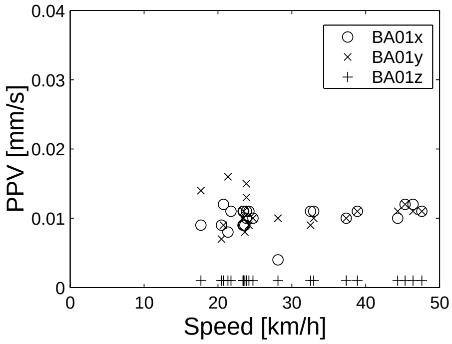



Figure 23: PPV ($x$, $y$ and $z$) in the basement vs train speed.

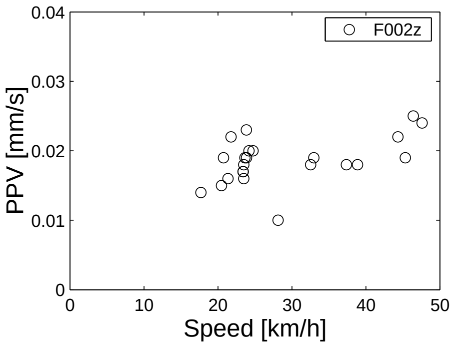



Figure 24: PPV ($z$) on the slab of the ground floor vs train speed.

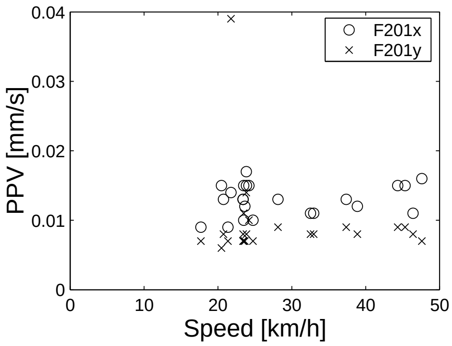
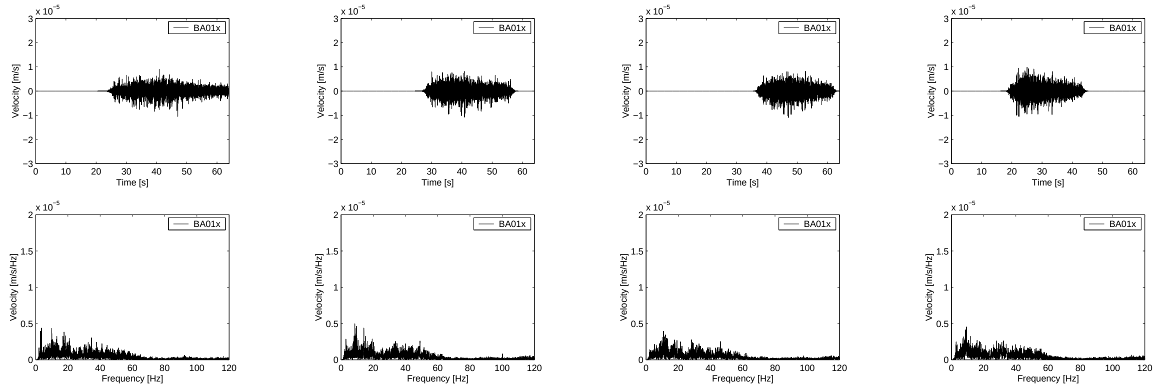



Figure 25: PPV ($x$ and $y$) on the column on the second floor vs train speed.

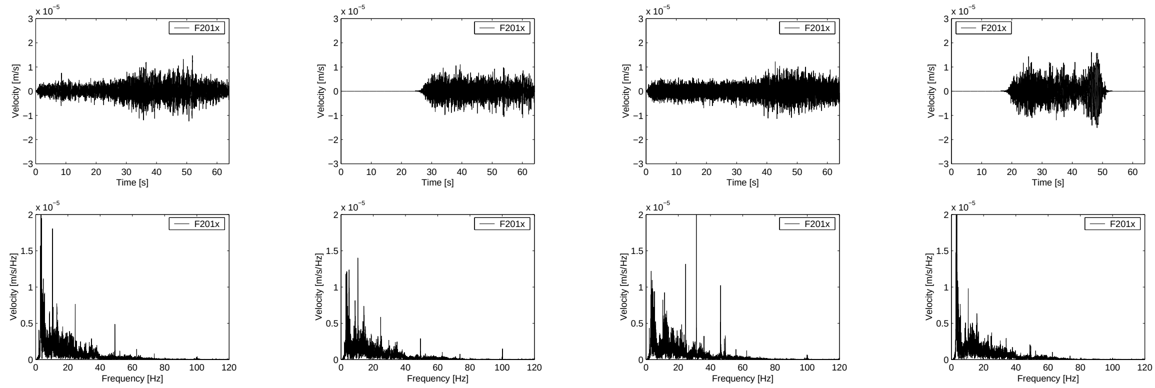
Figures 20 and 21 compare the time history and frequency content of the vertical velocity in the garden in front of the building (FF12z, at a horizontal distance of 65 m from the tunnel) and at mid-span of the slab on the ground floor (F002z). Figures 22, 23 and 24 show the PPV in tri-axial directions in front of the building and in the basement, as well as the vertical PPV on the slab of the ground floor. Horizontal components in the free field are larger than the vertical component (figure 22). Again, a very weak dependency of the PPV on the train speed is found. The vibrations are attenuated in the basement of the building (figure 23). The vertical accelerometer was not well calibrated, however, explaining the erroneous small values of the vertical component in the basement. PPV values on the slab of the ground floor are larger than in the basement due to amplification at the slab's resonance frequencies.

Figures 26 and 27 compare the time history and frequency content of the lateral velocity (perpendicular to the tunnel) in the basement (BA01x) and on the column on the second floor (F201x), while figures 23 and 25 summarize the PPV in the corresponding points.




*a. 23.86 km/h.* *b. 32.96 km/h.* *c. 38.88 km/h.* *d. 47.60 km/h.*

Figure 26: Time history (top) and frequency content (bottom) of the horizontal velocity at the point BA01x in the basement for four speeds of the test train.




*a. 23.86 km/h.* *b. 32.96 km/h.* *c. 38.88 km/h.* *d. 47.60 km/h.*

Figure 27: Time history (top) and frequency content (bottom) of the horizontal velocity at the point F201x on the column of the second floor for four speeds of the test train.

## 4 Conclusion

Elaborate vibration measurements have been made during the passage of a test train at speeds varying between 20 and 50 km/h in the north-bound Bakerloo line tunnel in Regent's Park, London. Data have been collected on the axle boxes of the test train, on the track, on the tunnel invert and wall, in the free field and in two buildings at 70 m from the tunnel. These results allow to study the variation of vibration amplitudes and frequency content as a function of the distance to the track and the train speed.

Whereas the peak particle velocities on the axle boxes of the train, on the track and on the tunnel increase with increasing train speed, this tendency if far less pronounced or even not present in the free field and in the building. This is probably due to the attenuation of the higher frequencies in the response due to material and radiation damping in the soil.

As wheel and rail roughness have been measured and the dynamic characteristics of the track and the soil have been determined independently, the present experimental data will be used for the validation of a numerical prediction model under development.

## Acknowledgements

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