Measurement and Assessment of Road Traffic-induced Vibration –

A Case History

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Introduction

This paper describes first the two-week long survey of the road traffic-induced groundborne vibration.

It then presents the results of the survey in tabular and graphical formats starting with a sample of the vibration events listed in chronological order, the vibration time history, the daily results for a 16 h day and 8 h night, and the vibrograms of selected simultaneous events at two locations.

Finally, it discusses the results and compares with the relevant criteria, as required.

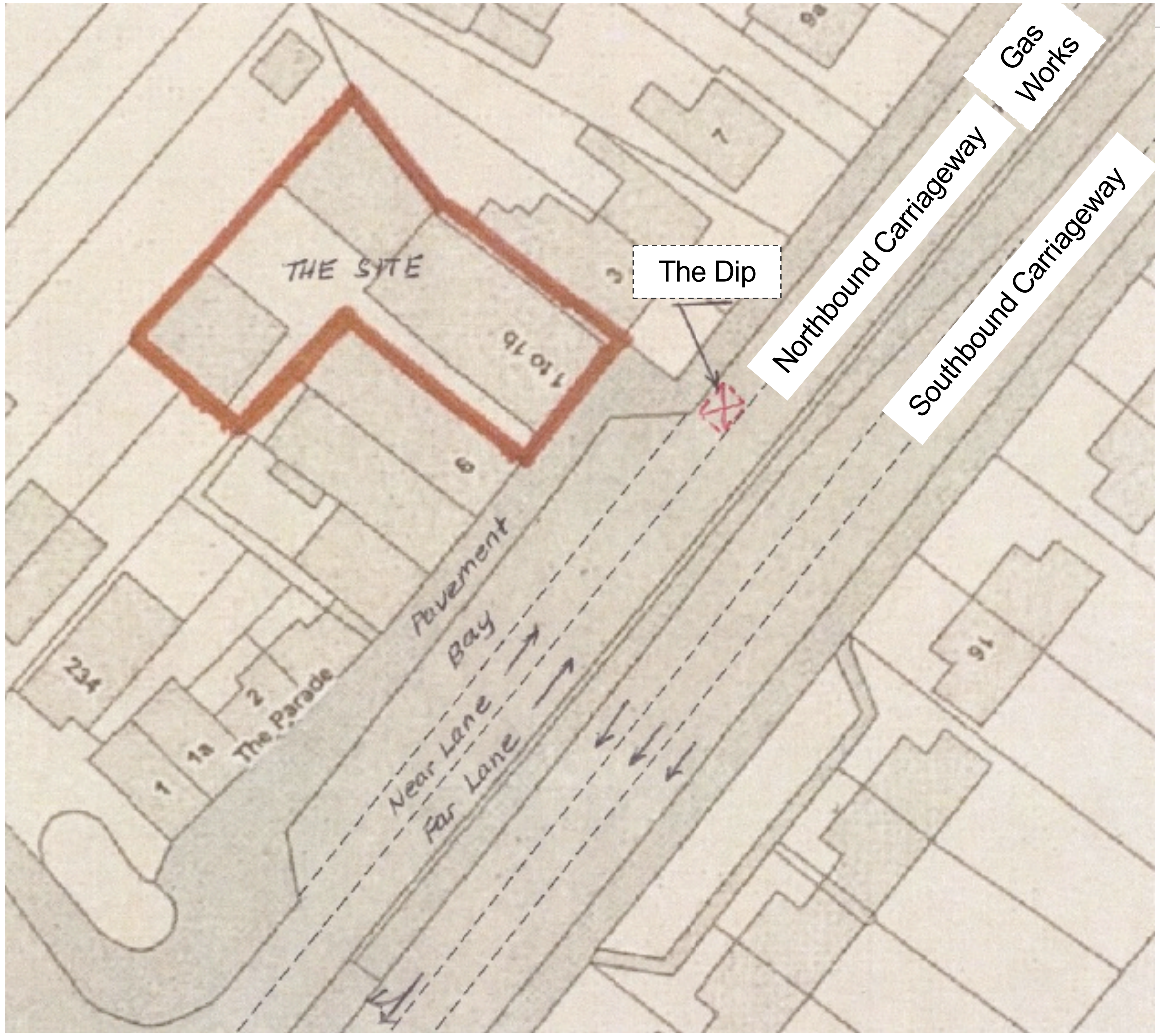


Figure 1. The Site

Figure 2. The Dip in the Road Surface and the Building under Investigation

Figure 3. The Cracks in the Front Elevation

Figure 4. The Dip and Gas Works

Background

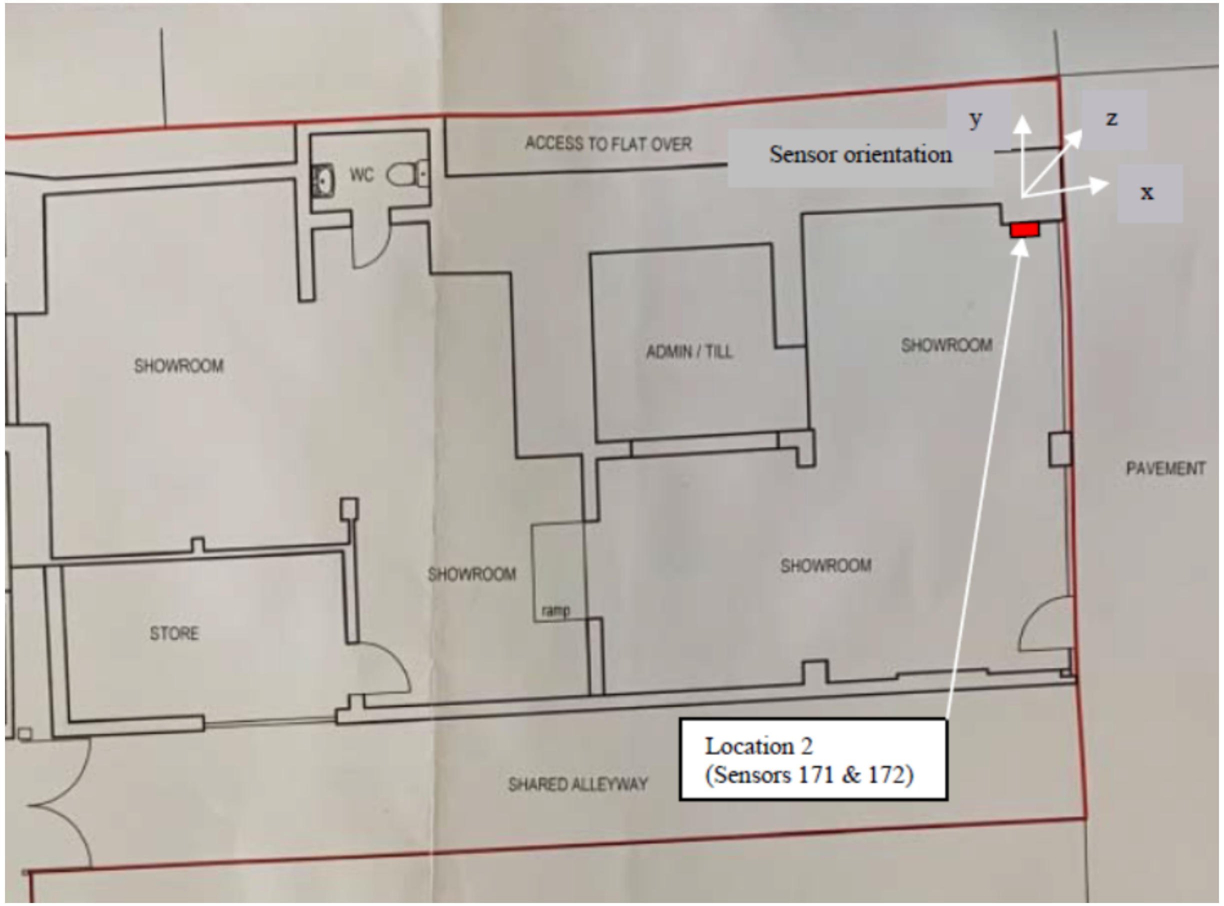
The premises under investigation is the 60s detached 2-storey brick building comprising a shop to the ground floor and a three bedroom flat above. The premises is located on a busy dual-carriageway trunk road, see Figure 1. The client is the property owner and occupier.

The client and his family have been bothered and disturbed by the excessive floor vibration in the flat during the day and night ever since a square-shaped dip in the road surface was created from the previous trench in the near lane approx. 4 years ago. This dip runs across the full width of the lane and is located approx. 9 m away from the front elevation of the building, see Figure 2.

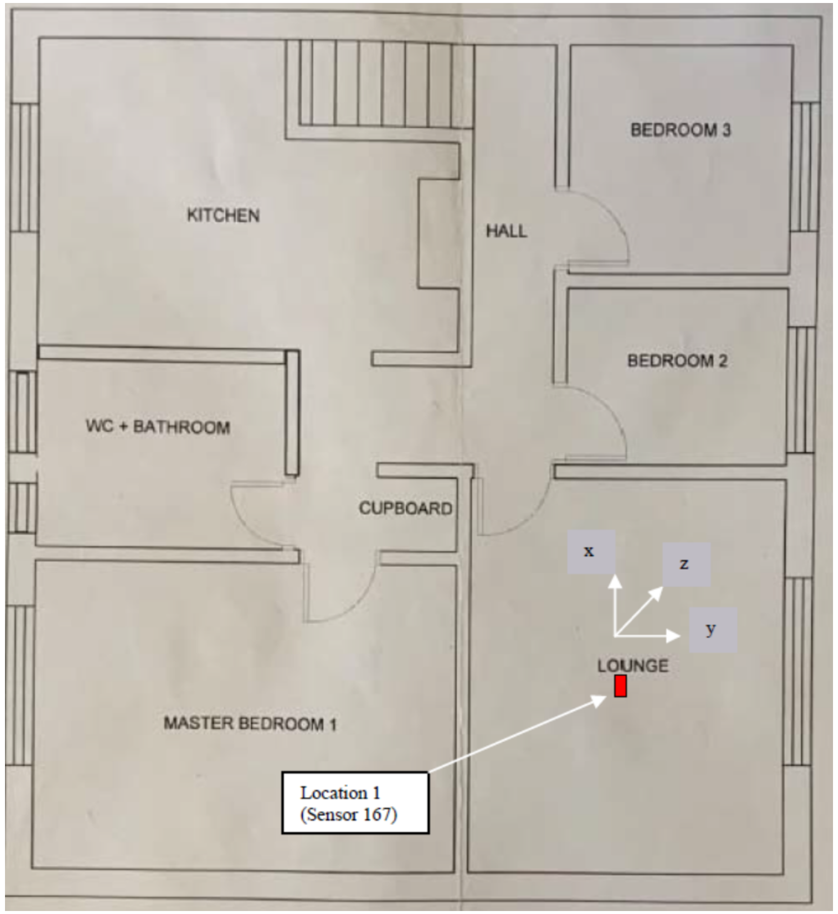
The client noticed cracks appearing in the render above the window in the front elevation about 2 years ago, see Figure 3.

The client requested a vibration survey to assess the impact of the traffic-induced groundborne vibration on the building and its occupiers, taking advantage of the fact that the near lane of the carriageway was temporarily closed for gas works being carried out about 40 m up the road from the building, see Figure 4. The client wanted scientific evidence that the dip in the road surface was the main cause of the excessive vibration in the building.

Figure 1a. Plans of the Premises showing the Vibration Measurement Locations



Ground Floor



First Floor

The Vibration Survey

The vibration survey was carried out in accordance with BS 6472-1 *Guide to evaluation of human exposure to vibration in buildings* and BS 7385-2 *Guide to damage levels from groundborne vibration.*

In this presentation reference is also made to DIN 4150-3 *Effects on structures* and BS 5228-2 *Code of practice for noise and vibration control on construction and open sites*.

The survey consisted of measuring a level of vibration over a period of two weeks at two locations, as follows:

Location 1 (Floor) – Near the middle of the suspended timber-joist floor of the 4x5 metres lounge;

Location 2 (Foundation) – On the concrete slab of the shop floor next to the external wall facing the road, see Figure 1a.

Tri-axial geophones were set up to capture vibration samples of a 5-second duration (including a 1-second pre-trigger) at both locations simultaneously when a vibration level in the foundation exceeded 0.15 mm/s PPV. Measurements could not, however, be triggered by the geophone on the upper floor.

The above arrangement minimized the possibility of capturing vibration samples contaminated by vibration from internal activities such as footsteps, services etc.

A vibration time history was also recorded, however, on the foundation only.

Figure 4. The Dip and Gas Works

There were four different traffic conditions throughout the survey owing to the closure of two lanes, (i.e. one lane at the time), of the northbound carriageway for gas works, as follows:

1. Near lane closed, the far lane open
2. Far lane closed, the near lane open
3. Near lane closed, the far lane open again
4. Both lanes open

Figure 5. Sample of Road Traffic Vibration Events Captured Simultaneously at Locations 1 & 2 (in Chronological Order)

Filename Event No.	Sensor No.	Measurement Location	Date	Trigger Time	Peak Particle Velocity (mm/s)				Dominant Frequency (Hz)			Freq-Weighted Peak Acceleration (mm/s^2)			Vibration Dose Value ($mm/s^{1.75}$)		
					True Vector Sum of PPV	max PPV_X	max PPV_Y	max PPV_Z	F_X	F_Y	F_Z	$a_{d,x}$	$a_{d,Y}$	$a_{b,Z}$	$VDV_{d,x}$	$VDV_{d,y}$	$VDV_{b,z}$
VIB04054	172	Location 2	04.11.19	8:38:33	0.32	0.06	0.03	0.32	11	0	11	0.856	0.503	22.005	0.408	0.292	12.541
VIB04055	167	Location 1	04.11.19	8:38:33	1.06	0.14	0.38	1	11	10	10	1.878	4.844	69.423	1.192	2.626	37.083
VIB04056	172	Location 2	04.11.19	8:43:14	0.35	0.06	0.04	0.35	11	11	10	0.890	0.613	22.995	0.430	0.304	11.803
VIB04057	167	Location 1	04.11.19	8:43:14	1.27	0.19	0.42	1.21	10	10	10	2.475	5.272	82.656	1.219	2.785	40.680
VIB04058	172	Location 2	04.11.19	8:46:15	0.48	0.07	0.06	0.48	2	8	11	1.012	0.855	35.744	0.530	0.471	18.117
VIB04059	167	Location 1	04.11.19	8:46:15	1.3	0.21	0.5	1.24	11	13	11	2.728	6.343	86.437	1.797	3.592	47.610
VIB04060	172	Location 2	04.11.19	8:47:58	0.29	0.05	0.03	0.29	5	0	11	0.731	0.493	19.106	0.386	0.286	11.563
VIB04061	167	Location 1	04.11.19	8:47:58	1.45	0.14	0.34	1.45	11	11	15	1.817	4.340	108.920	1.091	2.367	49.492
VIB04062	172	Location 2	04.11.19	8:50:04	0.35	0.05	0.04	0.35	11	11	11	0.761	0.636	24.699	0.431	0.311	13.595
VIB04063	167	Location 1	04.11.19	8:50:04	1.11	0.14	0.4	1.04	11	11	11	1.874	5.026	73.634	1.098	2.983	40.875
VIB04064	172	Location 2	04.11.19	8:51:43	0.22	0.03	0.02	0.21	0	0	13	0.488	0.371	15.625	0.209	0.218	6.951
VIB04065	167	Location 1	04.11.19	8:51:43	0.6	0.1	0.22	0.58	13	15	13	1.354	2.842	43.100	0.734	1.315	20.719
VIB04066	172	Location 2	04.11.19	8:53:44	0.16	0.02	0.02	0.15	0	0	15	0.369	0.389	11.685	0.176	0.177	5.317
VIB04067	167	Location 1	04.11.19	8:53:44	0.49	0.06	0.16	0.47	15	15	15	0.850	2.118	34.832	0.453	1.082	16.309
VIB04069	172	Location 2	04.11.19	8:56:38	0.29	0.04	0.05	0.29	11	11	11	0.667	0.686	19.902	0.363	0.369	11.249
VIB04070	167	Location 1	04.11.19	8:56:38	1.05	0.16	0.44	0.99	13	10	15	2.113	5.600	70.248	1.246	2.806	36.027
VIB04071	172	Location 2	04.11.19	8:58:07	0.38	0.06	0.06	0.37	11	11	11	0.879	0.872	27.032	0.504	0.431	15.562
VIB04072	167	Location 1	04.11.19	8:58:07	1.16	0.19	0.38	1.1	11	11	15	2.467	4.858	79.454	1.306	2.900	49.797
VIB04073	172	Location 2	04.11.19	9:02:55	0.17	0.03	0.02	0.16	0	0	15	0.521	0.402	11.192	0.233	0.208	6.029
VIB04074	167	Location 1	04.11.19	9:02:55	0.48	0.11	0.18	0.47	10	15	13	1.490	2.329	34.014	0.850	1.366	20.006
VIB04075	172	Location 2	04.11.19	9:04:49	0.23	0.03	0.02	0.22	0	0	13	0.523	0.403	16.470	0.233	0.249	7.839
VIB04076	167	Location 1	04.11.19	9:04:49	0.75	0.07	0.25	0.72	13	10	13	0.991	3.241	51.914	0.623	1.600	23.702
VIB04077	172	Location 2	04.11.19	9:12:35	0.22	0.03	0.03	0.21	0	0	15	0.494	0.480	15.117	0.277	0.255	7.837
VIB04078	167	Location 1	04.11.19	9:12:35	0.69	0.08	0.25	0.64	11	15	10	1.100	3.211	46.967	0.534	1.588	25.940
VIB04079	172	Location 2	04.11.19	9:14:02	0.32	0.06	0.04	0.32	11	11	11	0.863	0.656	22.189	0.476	0.381	12.724
VIB04080	167	Location 1	04.11.19	9:14:02	1	0.16	0.35	0.95	10	11	11	2.135	4.459	64.830	1.238	2.700	37.780
VIB04081	172	Location 2	04.11.19	9:17:48	0.2	0.03	0.01	0.19	0	0	10	0.495	0.262	12.744	0.235	0.153	6.247
VIB04082	167	Location 1	04.11.19	9:17:48	0.56	0.09	0.21	0.52	11	10	11	1.250	2.671	34.402	0.572	1.312	18.063

Measurements of the vibration were made in terms of the peak particle velocity (PPV) in three orthogonal directions (i.e. x, y-horizontal & z-vertical) in respect with the major axes of the building.

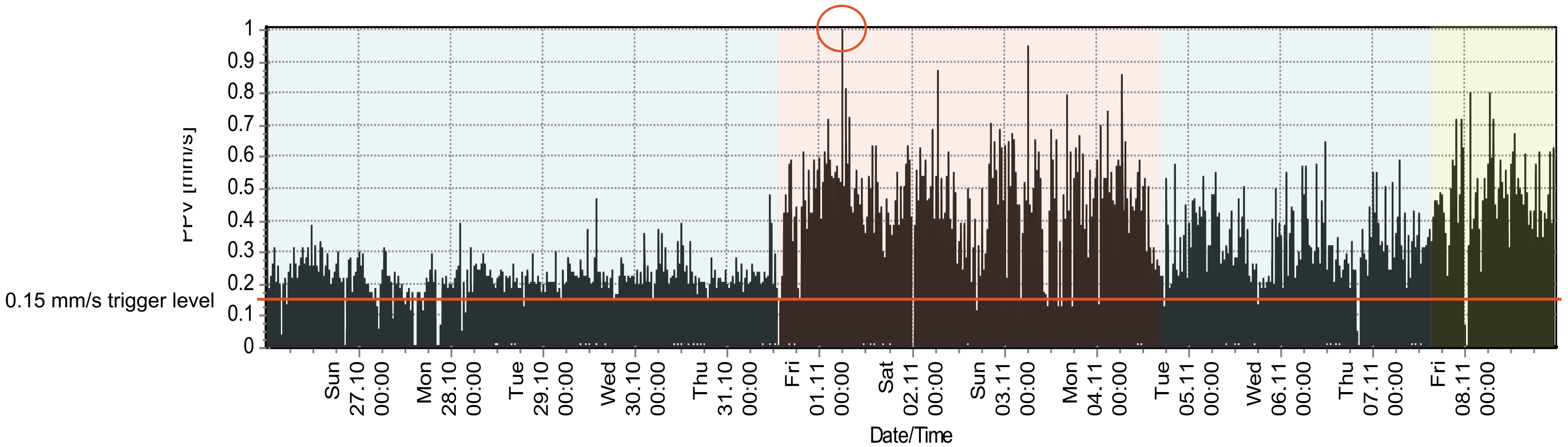
From the measurements a vibration dose value (VDV) for each of the 5-second samples was derived using the propriety VibChart software. Frequency analyses of the components were performed in the time frame before and after the maximum peak to determine the dominant frequency according to the principles of Fourier analysis.

A sample of vibration measurements of some events captured simultaneously at both locations is presented in chronological order in Figure 5. The measurements of the vibration components of all events are presented in terms of PPV in mm/s and VDV in mm/s$^{1.75}$. A dominant frequency for each component is also presented except when there was insufficient dynamics for the frequency analysis to be performed.

Since the weighted acceleration is clearly dominant in the vertical direction, the assessment was made for the vertical vibration only. All events were first sorted by the day-time and night-time measurements. Then, the events were sorted by decreasing order of magnitude from highest to smallest. All extraneous events were subsequently identified and removed from the assessment.

Finally, an overall VDV_b for each of the 16-hour day and 8-hour night was calculated and is presented in m/s$^{1.75}$ as required by BS 6472.

Figure 7. Time History of Road Traffic-induced Vibration at Location 2 (Foundation)
Max. True Vector Sum of PPV (mm/s) within Consecutive 3 s Intervals



Near lane closed | Far lane closed | Near lane closed | Both lanes open

The history of vibration on the foundation throughout the survey is presented in Figure 7.

It consists of the vibration measurements in terms of the maximum true vector sum of the peak particle velocity during consecutive 3-second intervals.

At the start of the survey when the far lane was open and the near lane was closed for gas works the maximum PPV was just below 0.5 mm/s.

When subsequently the near lane was re-open and the far lane was closed for gas works, the maximum PPV has increased to about 1 mm/s.

Then, when the far lane was re-open and the near lane was closed again there were numerous events at the maximum PPV within the range of 0.5 to 1 mm/s, i.e. higher than during the initial period under the same lane closure arrangement. It is very likely that the noticeable increase in the vibration level has been the result of a new uneven patch in the road surface of the far lane created by the latest gas works.

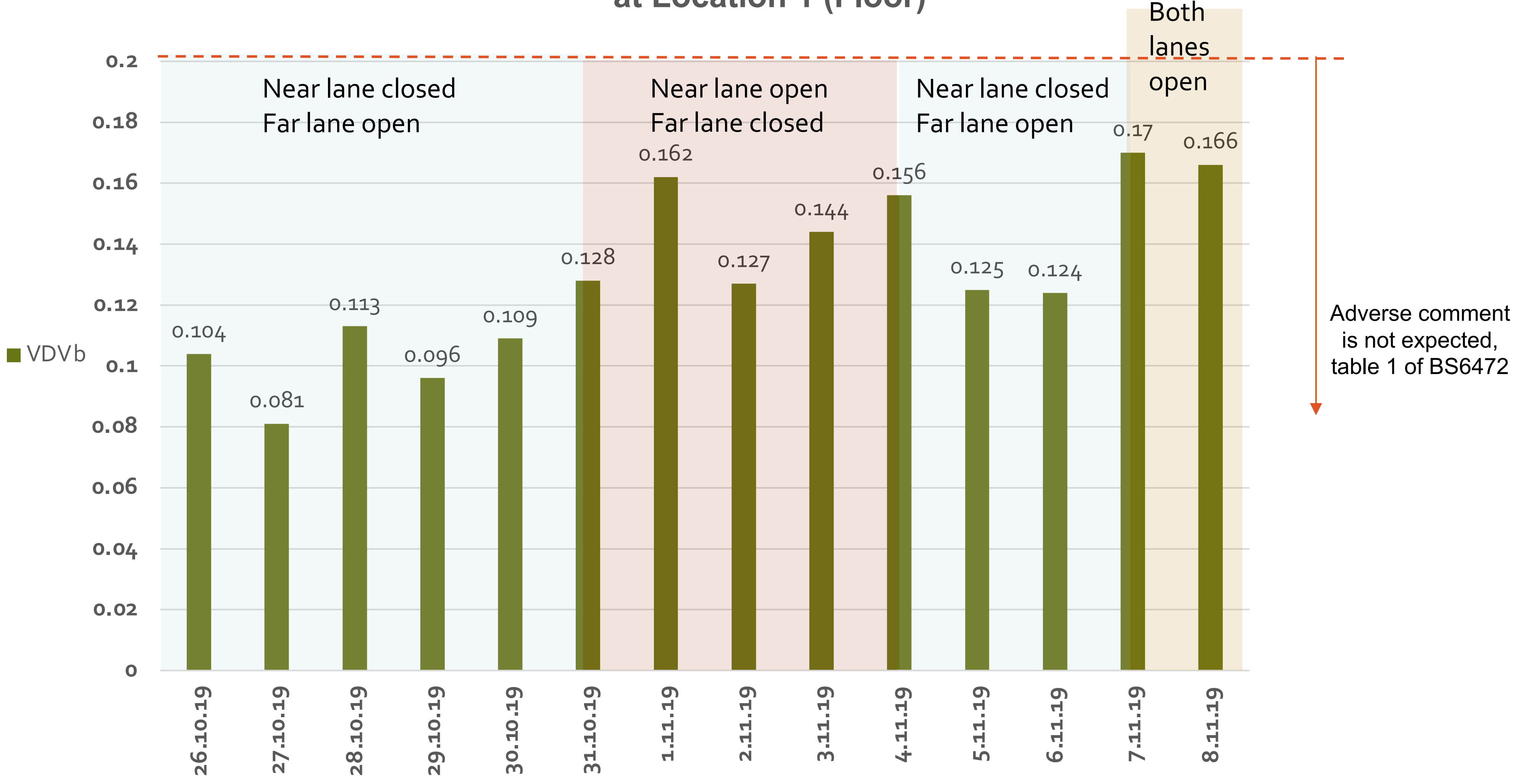
And lastly, when both lanes were subsequently open to traffic, the vibration increased again to the level during the initial period when the near lane was open and the far lane closed.

The above demonstrates that the dip in the road surface of the near lane is responsible for the excessive road traffic vibration at the premises under investigation.

Figure 8. Daytime (0700-2300) Vibration in terms of Max PPV and VDV at Location 1 (Floor)

Date	Max. Peak Particle Velocity (mm/s)			Vibration Dose Value ($m/s^{1.75}$)		
	PPV - x	**PPV - y**	**PPV - z**	**$VDV_{d,day}$ - x**	**$VDV_{d,day}$ - y**	**$VDV_{b,day}$ - z**
26.10.19	0.32	0.2	1.8	0.004	0.003	0.104
27.10.19	0.23	0.27	1.33	0.003	0.003	0.081
28.10.19	0.23	0.22	0.53	0.004	0.004	0.113
29.10.19	0.54	0.34	1.41	0.004	0.004	0.096
30.10.19	0.34	0.31	**3.01**	0.005	0.004	0.109
31.10.19	0.47	0.74	1.88	0.005	0.009	0.128
1.11.19	0.37	1.01	2.62	0.004	0.011	0.162
2.11.19	0.34	0.86	1.96	0.004	0.010	0.127
3.11.19	0.35	0.9	2.23	0.005	0.010	0.144
4.11.19	0.39	0.62	2.7	0.006	0.009	0.156
5.11.19	0.31	0.58	2	0.005	0.006	0.125
6.11.19	0.32	0.32	2.86	0.005	0.004	0.124
7.11.19	0.43	1.29	2.98	0.006	0.011	**0.170**
8.11.19	0.47	0.92	2.31	0.005	0.011	0.166

Figure 9. Daytime Vertical Vibration in terms of VDV_b in $ms^{-1.75}$ at Location 1 (Floor)



A summary of the daytime floor vibration measurements in three orthogonal directions in terms of PPV and $VDV_{d/b,day}$ is presented in a tabular format in Figure 8.

From the table, it is apparent that the level of vibration in the vertical direction was significantly higher than in horizontal directions. The highest daytime floor vibration in the vertical direction was within the range of 0.5 to 3 mm/s max PPV and 0.08 to 0.17 $m/s^{1.75}$ $VDV_{b,day}$.

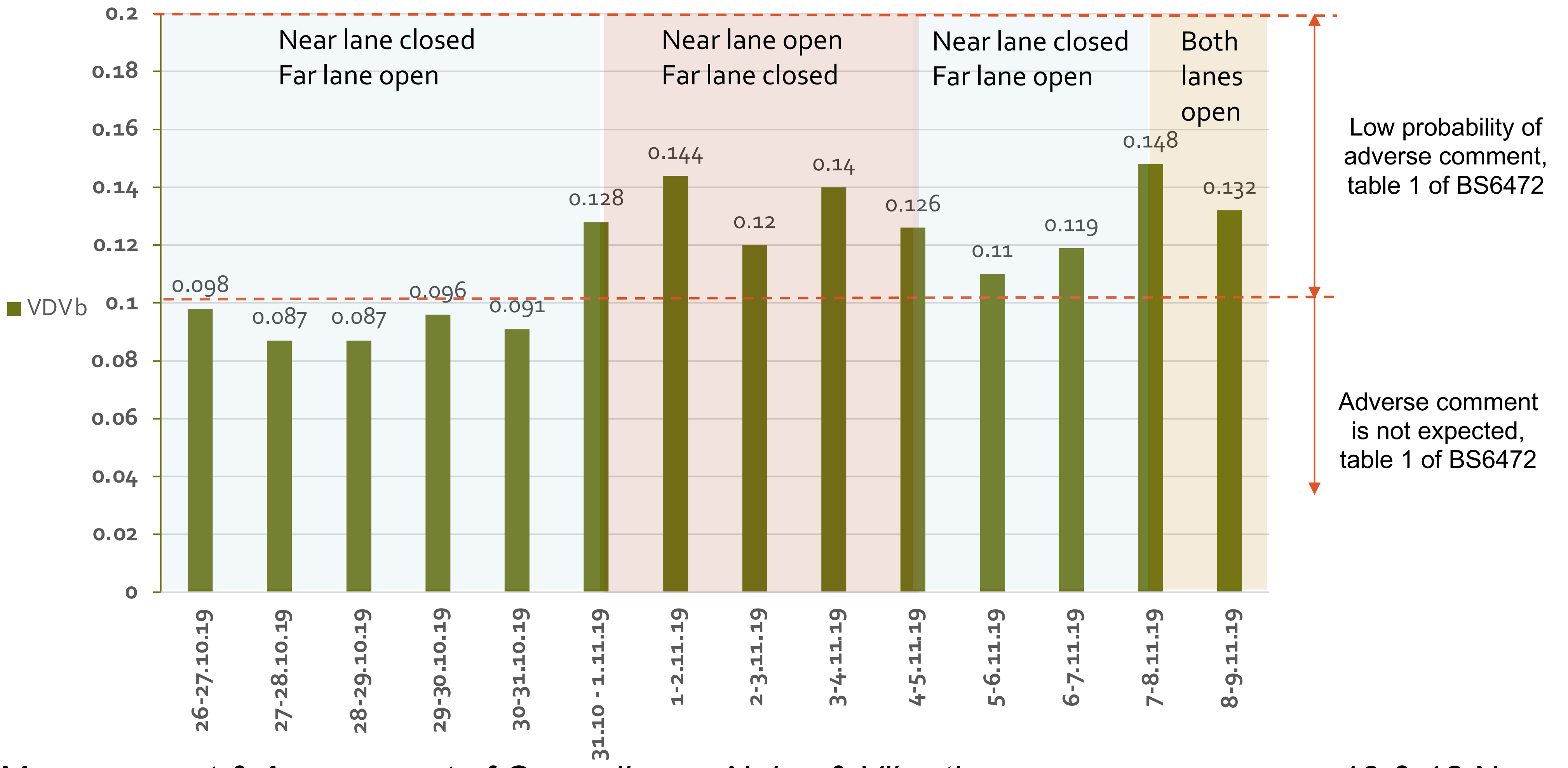
The daytime VDVs in the vertical direction are also presented in a graphical format in Figure 9. From the graph it can be seen that the $VDV_{b,day}$ was noticeably higher during the periods when the near lane was open than when it was closed. Nevertheless, all $VDVs_{b,day}$ were below 0.2 $m/s^{1.75}$ and according to table 1 of BS 6472-1 *“adverse comment is not expected”.*

The majority of vibration events during the day have, however, exceeded 1 mm/s and many of them even exceeded 2 mm/s PPV, which means that the floor vibration generated by numerous vehicles traversing the dip in the road would readily be perceptible by the occupiers of the building. According to table B.1 of BS 5228-2 vibration at this level in residential environment is likely to cause complaint.

Figure 10. Night-time (2300-0700) Vibration in terms of the Max PPV and VDV at Location 1 (Floor)

Date	Max. Peak Particle Velocity (mm/s)			Vibration Dose Value ($m/s^{1.75}$)		
	PPV - x	**PPV - y**	**PPV - z**	**$VDV_{d,night}$ - x**	**$VDV_{d,night}$ - y**	**$VDV_{b,night}$ - z**
26-27.10.19	0.28	0.32	1.8	0.003	0.004	0.098
27-28.10.19	0.24	0.36	1.37	0.003	0.003	0.087
28-29.10.19	0.22	0.34	1.05	0.003	0.004	0.087
29-30.10.19	0.36	0.37	1.68	0.004	0.004	0.096
30-31.10.19	0.26	0.28	1.33	0.003	0.003	0.091
31.10 - 1.11.19	0.47	0.74	1.88	0.005	0.009	0.128
1-2.11.19	0.45	1.21	2.39	0.005	0.011	0.144
2-3.11.19	0.38	0.74	1.76	0.004	0.009	0.120
3-4.11.19	0.34	0.86	2.5	0.004	0.010	0.140
4-5.11.19	0.42	0.34	2.39	0.005	0.004	0.126
5-6.11.19	0.4	0.39	2.11	0.004	0.004	0.110
6-7.11.19	0.5	0.43	2.58	0.005	0.004	0.119
7-8.11.19	0.43	1.33	**2.86**	0.004	0.011	**0.148**
8-9.11.19	0.32	0.74	2.23	0.004	0.009	0.132

Figure 11. Night-time Vertical Vibration in terms of $VDV_{b,night}$ in $m/s^{1.75}$ at Location 2 (Floor)



A summary of the night-time floor vibration measurements in three orthogonal directions in terms of PPV and $VDV_{b/d,night}$ is presented in a tabular format in Figure 10.

From the table, it is apparent that the level of vibration in the vertical direction was significantly higher than in horizontal directions. The highest night-time floor vibration in the vertical direction was within the range of 1 to 2.9 mm/s max PPV and 0.09 to 0.15 $m/s^{1.75}$ $VDV_{b,night}$.

The night-time $VDVs_{b,night}$ in the vertical direction are also presented in a graphical format in Figure 11. From the graph it can be seen that during the initial period when the near lane was closed and the far lane was open the $VDVs_{b,night}$ were just below 0.1 $m/s^{1.75}$. When the gas works in the far lane were completed, the far lane was re-open and the near lane was closed again, the $VDVs_{b,night}$ were just above 0.1 $m/s^{1.75}$. The increase in the VDV can be attributed to a new uneven patch created in the far lane by the latest gas works.

When the near lane was open (irrespective of whether the far lane was closed or open) the $VDVs_{b,night}$ were within the range of 0.1 to 0.2 $m/s^{1.75}$ which according to table 1 of BS 6472-1 there is "*low probability of adverse comment".*

The majority of vibration events during the night have, however, exceeded 1 mm/s and many of them even exceeded 2 mm/s PPV, which means that the floor vibration generated by numerous vehicles, traversing the dip in the road, would readily be perceptible by the occupiers of the building. According to table B.1 of BS 5228-2, the vibration at this level in residential environment is likely to cause complaint.

Figure 12. Maximum Peak Z-Component Particle Velocity –v- Dominant Frequency Vibration Events at Location 1 (First Floor) and Location 2 (Foundation) Captured During 16-h Day and 8-h Night on 30-31 October 2019

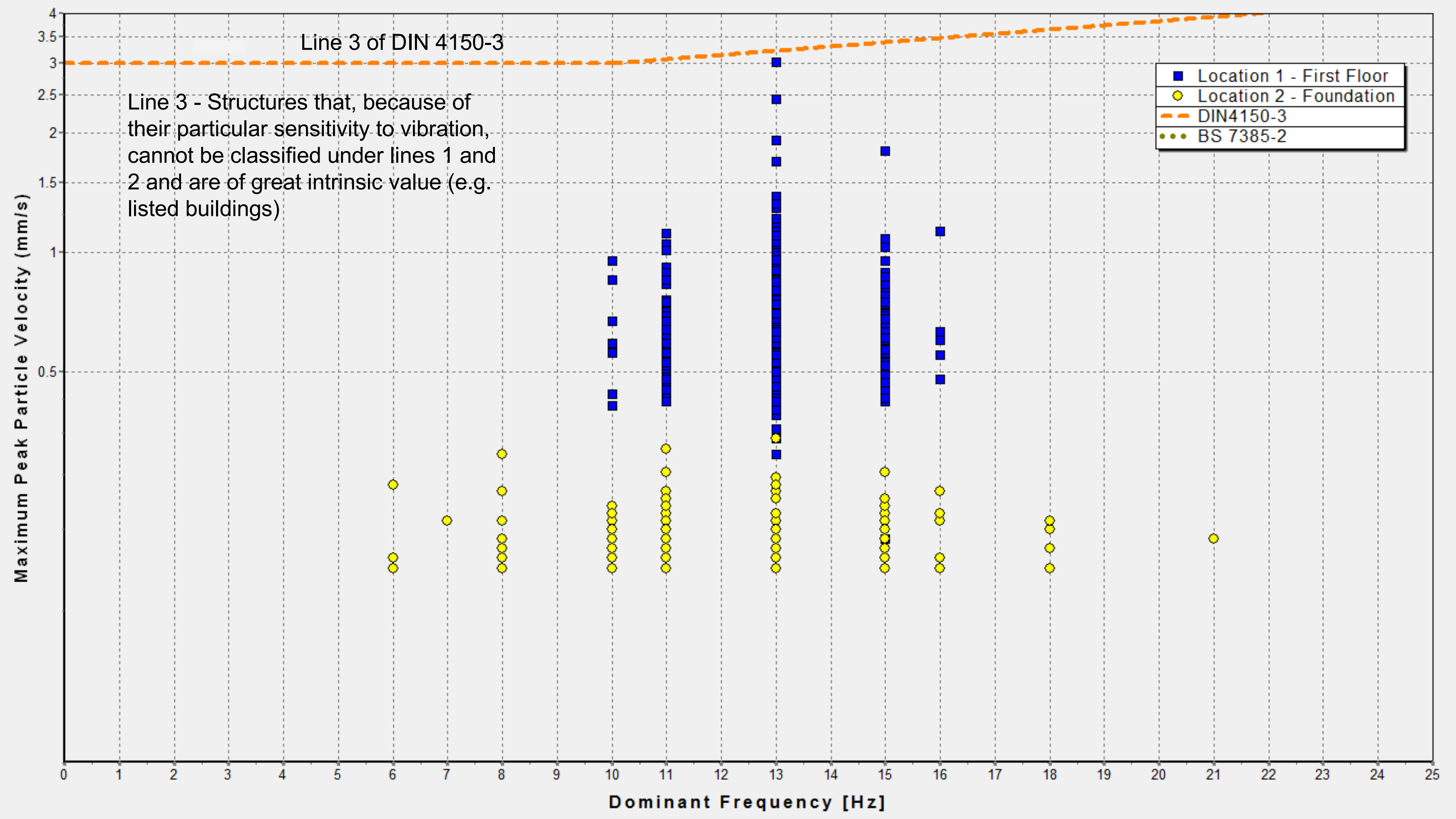
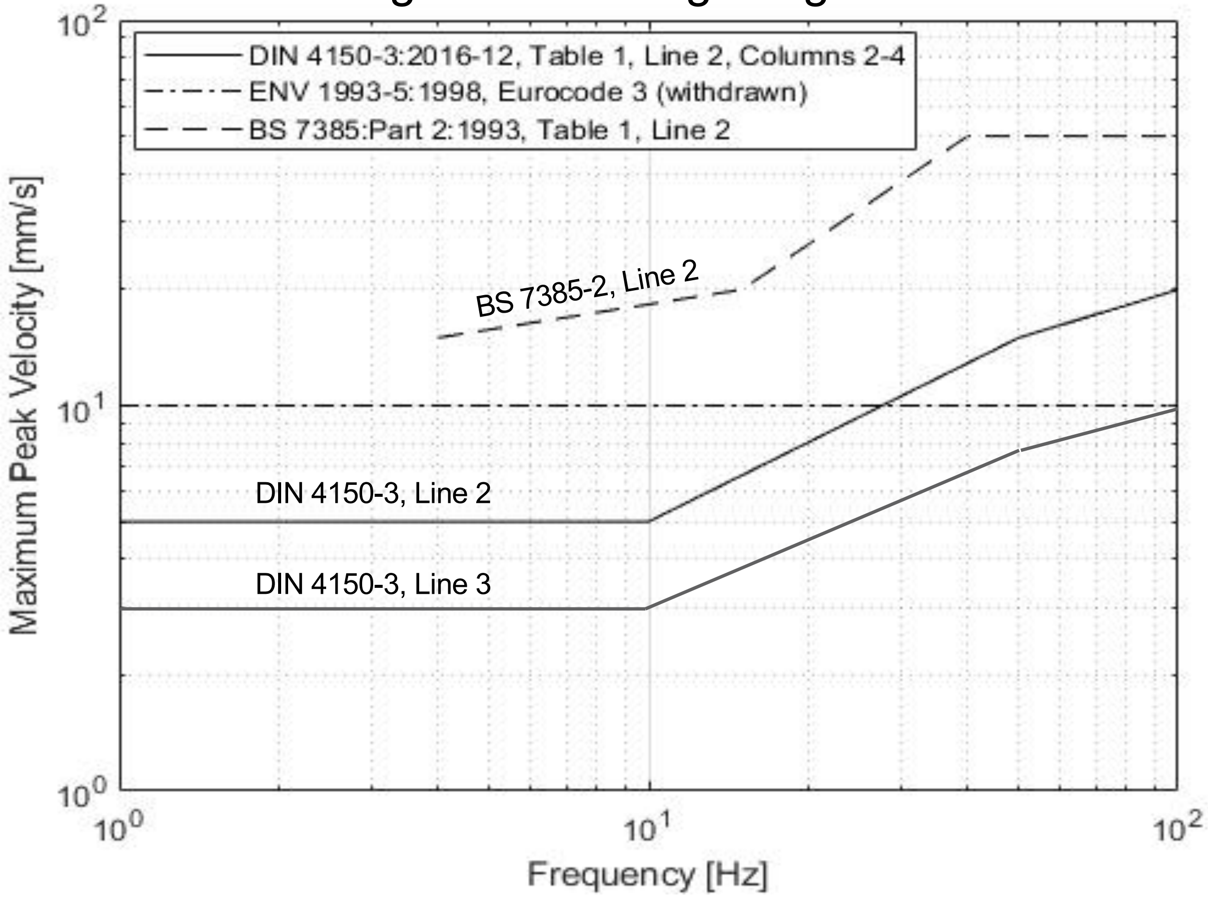


Figure 6.Transient (short-term) vibration damage thresholds for residential buildings and buildings of great intrinsic value



BS 7385-2, Line 2 – Unreinforced or light framed structures. Residential or light commercial building

DIN 4150-3, Line 2 – Residential buildings and buildings of similar design and/or occupancy

DIN 4150-3, Line 3 - Structures that, because of their particular sensitivity to vibration, cannot be classified under lines 1 and 2 and are of great intrinsic value (e.g. listed buildings)

The vibration events captured simultaneously on the floor and foundation during a period when all lanes were open to traffic are shown in terms of the max PPV versus dominant frequency in Figure 12.

From the chart it can be seen that the level of vibration is markedly higher on the floor than on the foundation. The dominant frequency of most events on both the floor and foundation is within the range of 11 to 15 Hz with the13 Hz frequency being the most common.

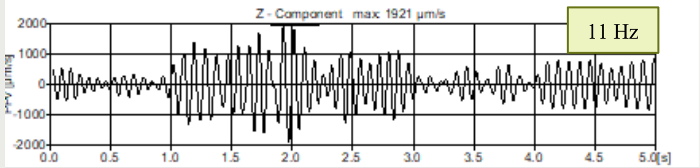
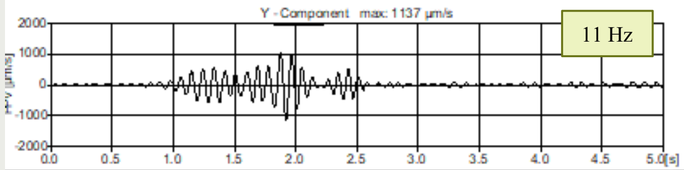
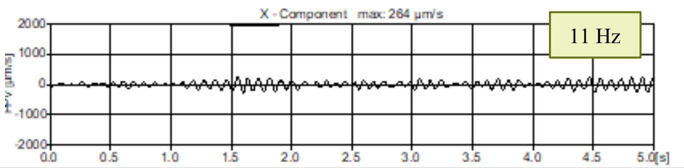
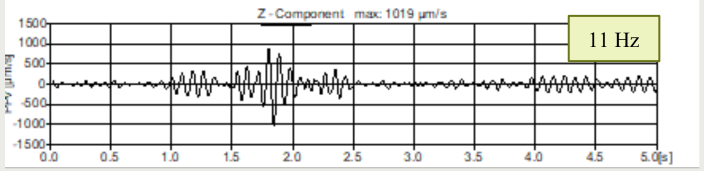
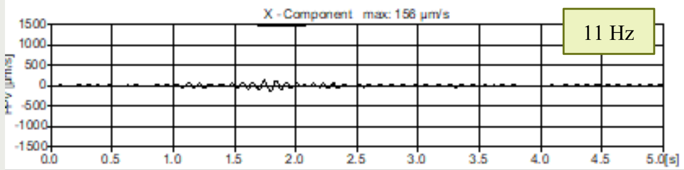
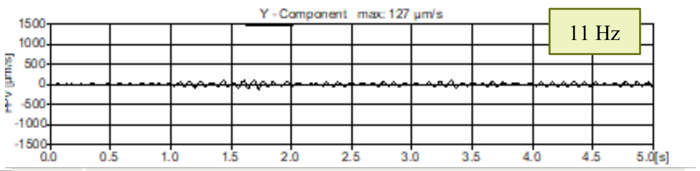
From the chart it can also be seen that the level of vibration on the foundation is not only below Line 2 of BS 7385-2[(1)](that refers to residential or light commercial buildings) but also below Line 3 of DIN 4150-3[(2)] (that refers to structures of particular sensitivity and great intrinsic value).

Both Line 2 od BS 7385-2 and Line 3 of DIN 4150-3 are shown in Figure 6.

(1) BS 7385-2: 1993, Table 1. Transient vibration values for cosmetic damage, Line 2 – Unreinforced or light framed structures. Residential or light commercial type buildings

(2) DIN 4150-3: 2016-12, Table 1. Guideline values for $v_{i,\ max}$ *in mm/s for assessing the effects of short-term vibrations on structures, Line 3 - Structures that, because of their particular sensitivity to vibration, cannot be classified under lines 1 and 2 and are of great intrinsic value (e.g. listed buildings)*

Figure 13. Details of the highest event at Location 2 (Foundation) and the simultaneous event at Location 1 (Floor)
Max PPV Vibrograms

Loaction/ Event	Vertical	Radial	Transvers
Location 1 Floor VIB01340			
Location 2 Foundation VIB0339			
Amplification Foundation to Floor	1.9 = 1921/1019	7.2 = 1137/156	2.1 = 264/127

Notes:
1) Measurements in the transverse direction at Locations 1 and 2 are given by x- and y- axis components respectively;
2) Measurements in the radial direction at Locations 1 and 2 are given by y- and x- axis components respectively;
3) Dominant frequency (Hz) for the maximum velocity is shown on each vibrogram, see inset.

Details of the highest vibration event captured on the foundation together with the simultaneous event on the upper floor during the two-week long survey are presented in Figure 13. This consists of the PPV vibrograms of the three orthogonal components and the respective dominant frequencies.

The vibrogram of the vertical motion on the foundation consists of three bursts of vibration within a 1.5 s time interval with the second burst being the highest, which indicates that this event was most likely generated by a HGV traversing the dip in the road.

The highest vibration level in the vertical direction on the foundation was at approx. 1 mm/s PPV, which resulted in approx. 2–fold amplification in the upper floor.

At both locations the motion velocity in horizontal directions was markedly lower than in the vertical direction. There was approx. 2- and 7-fold amplification in the transverse and radial directions respectively on the upper floor.

At both locations all components had the same dominant frequency at 11 Hz.

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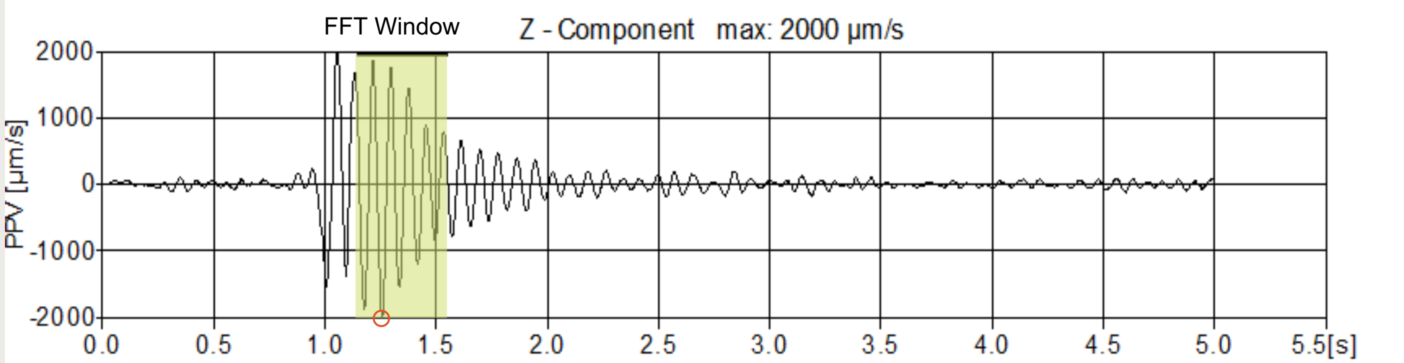
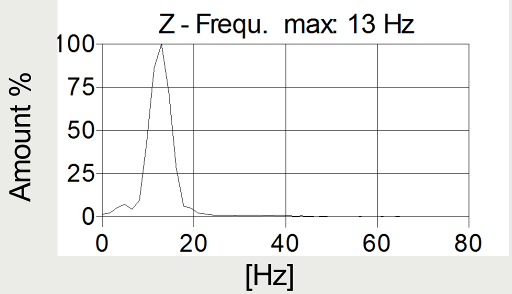
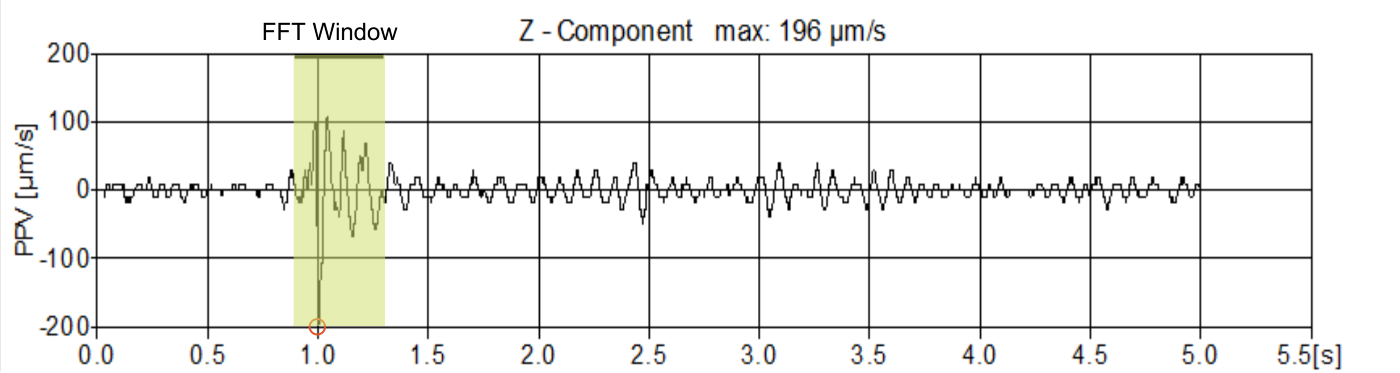
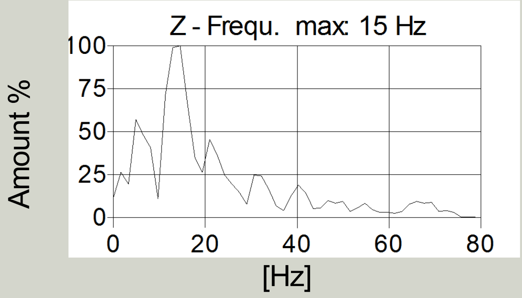
Figure 14. Details of Vibration Event that resulted in a 10-fold Amplification of the Vertical Motion Velocity PPV Vibrograms for Locations 1 (Floor) and Location 2 (Foundation)

Location/Event	Max PPV Vibrograms	FFT Frequency Analysis
Location 1 First Floor VIB05171		 The highest frequency harmonics
Location 2 Foundation VIB05170		 The highest frequency harmonics

Details of the vibration event that resulted in a 10-fold amplification of the vertical motion velocity from the foundation to floor is presented in Chart 14. This consists of the PPV vibrograms of the vertical components of vibration captured simultaneously on the floor and foundation. The frequency analysis is also presented.

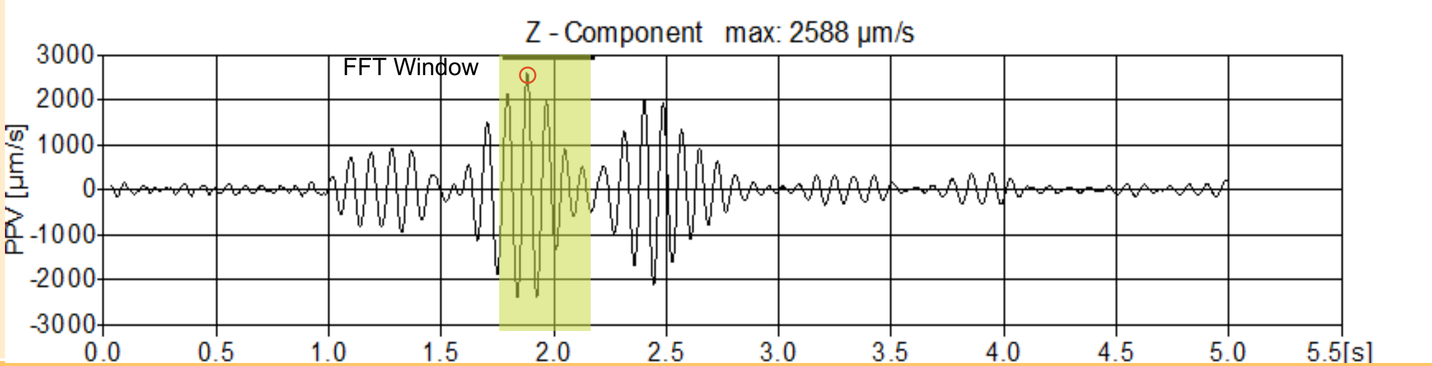
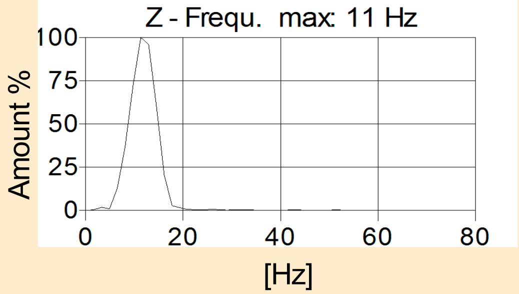
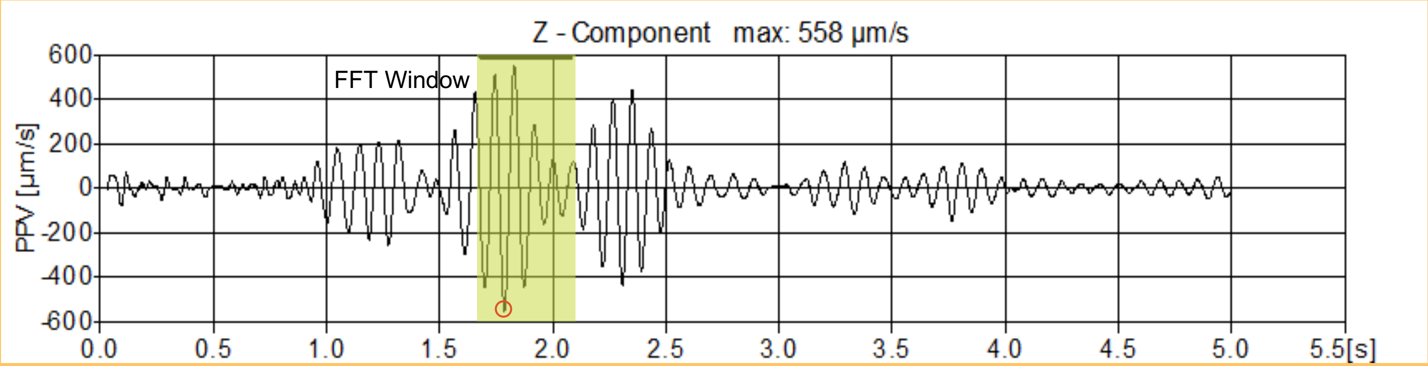
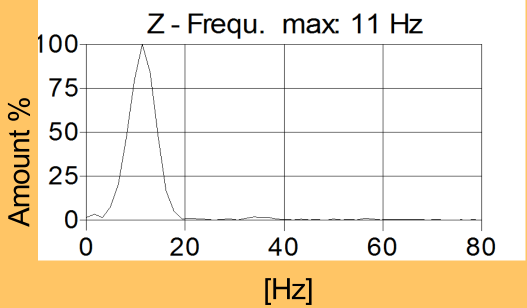
The vibrogram on the foundation shows a sudden increase immediately followed by a sudden drop in the level of vibration. The vibration was fully damped within 0.5 s. The vibrogram on the floor shows a 1.5 s duration damped sinusoidal vibration. This event was generated by a heavy impact which could have been caused by a faulty axle suspension system on a vehicle.

The dominant frequency of the vertical motion in the foundation and the floor was 15 Hz and 13 Hz respectively. The 13 Hz represents the natural frequency of the suspended floor.

Because the groundborne vibration was generated by a heavy impact in the vertical direction and the receptor was in the middle of a suspended timber-joist floor, the vibration on the foundation at only 0.2 mm/s has increased 10-fold to 2 mm/s PPV on the upper floor.

Vibration generated by HGVs has typically increased up to 5-fold from foundation to floor, see Fig.15.

Figure 15. Example of Vibration Event from HGV PPV Vibrograms for Locations 1 and 2

Location/Event	PPV Vibrograms	FFT Frequency Analysis
Location 1 First Floor VIB07967		 The highest frequency harmonics
Location 2 Foundation VIB07966		 The highest frequency harmonics

An example of groundborne vibration generated by a HGV is presented in Figure 15.

This consists of the PPV vibrograms of the vertical component captured simultaneously on the foundation and upper floor. The frequency analysis is also presented.

This event was most likely generated by an articulated lorry with three sets of wheels as the vibrogram consists of three major bursts of vibration.

The vibrogram on the floor is almost an exact facsimile of the vibrogram on the foundation but approx. 4.6 times larger in magnitude.

The dominant frequency of the vertical motion at both locations was 11 Hz.

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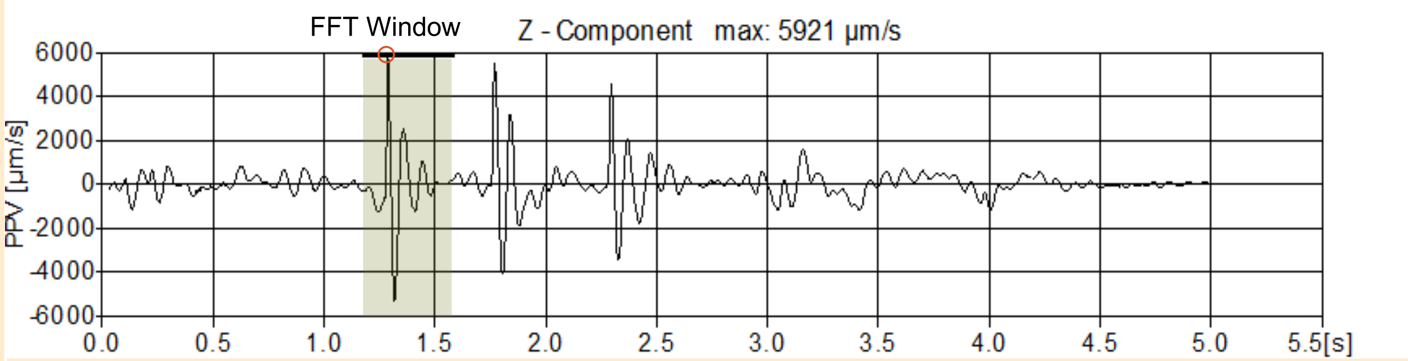
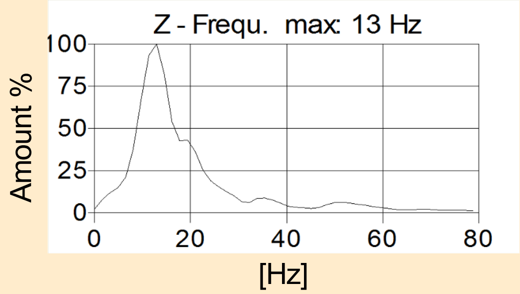
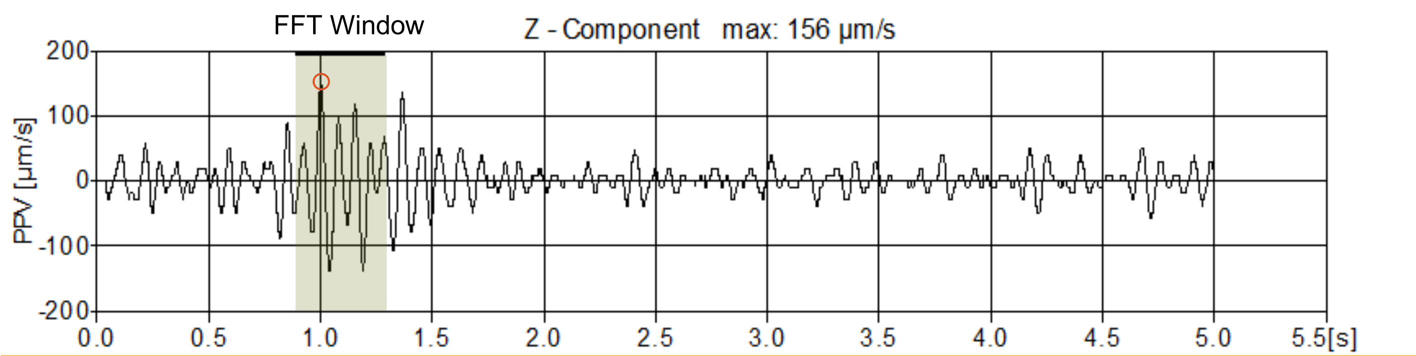
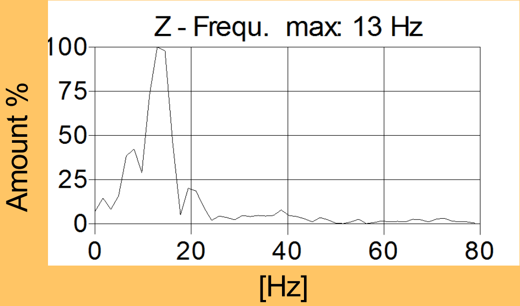
Figure 16. Example of Extraneous Event at Location 1 (Floor)
PPV Vibrograms for Locations 1 and 2

<table>
<tr><th>Location/Event</th><th>PPV Vibrograms</th><th>FFT Frequency Analysis</th></tr>
<tr><td>Location 1
First Floor

VIA31950</td><td>
</td><td>

The highest frequency harmonics</td></tr>
<tr><td>Location 2
Foundation

VIA31049</td><td>
</td><td>

The highest frequency harmonics</td></tr>
</table>

An example of the extraneous event on the floor is presented in Figure 16.

This consists of the PPV vibrograms of the vertical component captured simultaneously on the foundation and upper floor. The frequency analysis is also presented.

This event was triggered by a passing vehicle which generated groundborne vibration that has only just exceeded the trigger level of 0.15 mm/s on the foundation. In addition to the vibration from the vehicle, the geophone on the upper floor has also captured several impulsive vibration peaks with the rapid decay rate. These peaks of up to 6 mm/s PPV were spaced approx. 0.5 s apart, which suggests that they were generated by footsteps.

This and other extraneous events were excluded from the assessment.

Summary

1) The closure of the carriageway lanes for gas works allowed to determine vibration values for the day and night from the traffic in each lane and thus to confirm that the source of the excessive vibration was indeed the dip in the near lane;

2) The set-up of triggering a sensor on the floor by a sensor on the foundation, only when traffic-induced groundborne vibration exceeded a pre-set level, minimized the possibility of extraneous vibration being captured by the sensor on the floor and thus made the survey manageable;

3) In order to identify extraneous vibration captured during the unattended survey it was necessary to examine vibrograms and frequency analysis of the events;

4) 10-fold amplification of road traffic-induced vibration from foundation to floor is possible.

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