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Environmental Solutions

The vibrational impact of oil and gas operations on the human experience

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From the early 2000s to present shale production or oil and gas operations in the continental United States has increased by more than 500% (U.S. Energy Information Administration 2019.) This increase in activity has helped turn such operations into a more common action that everyday Americans are experiencing. With this commonality it should be true that data is presented to be included with other common actions that humans are accustomed to so that there is a way to compare and rationalize experiences. Measuring vibrational data at both the source of impact and a set distance can establish a footprint of impact and determine the maximum distance the impact can travel to impact the human experience. Comparing this footprint of data for shale oil & gas operations with the historical data for common vibration impacts shows that tasks such as jackhammering contain 6 times as much vibrational impact than drilling or fracturing operations. Additionally, the data shows that the vibrational impact from oil and gas operations is dampened or decays by an order of magnitude over only a couple hundred feet. The study shows that although oil and gas operations are becoming more common for various metropolitan areas, the impact of such operations on the human experience is far less than that of common construction activities and not likely to negatively impact that experience.

Introduction

For decades there has been solid and consistent data and research into the vibration of common activities, their associated vibrational data and their correlating impact on the human experience. From the early 2000s to present shale production or Oil and Gas operations in the continental United States has increased by more than 500% (U.S. Energy Information Administration 2019) due to improvements in technology allowing for new wells to be put into production. This increase in activity has helped turn such operations into a more common action that Americans are experiencing. With this commonality vibrational data from oil and gas operations should be included with other actions that humans experience so that there is a way to compare and rationalize experiences. Measuring vibrational data at both the source of impact and a set distance establishes a footprint of impact and determines the maximum distance the impact can travel to impact the human experience. Comparing this footprint of data for shale oil and gas operations with the historical data for common vibration impacts establishes how oil and gas vibration is perceived and compares to more commonly studied construction activities.

Vibration Overview

Vibration

Vibration is defined as the oscillatory motion of a mass described in terms of displacement, velocity or acceleration. Displacement is the distance a particle or mass has moved; velocity is the instantaneous speed and direction the particle has moved; and the acceleration is the rate of change of the velocity or speed. Vibration amplitudes are expressed in peak particle velocity (PPV) or the root mean square (RMS) velocity. Peak Particle Velocity, or PPV, is a commonly used measurement for vibration and is defined as the displacement and direction of particles per second due to vibrations. The PPV is typically measured in millimeters or inches per second.

This study documented the following vibration levels:

- Transverse PPV – The peak particle velocity measured in the transverse, or x-direction
- Vertical PPV – The peak particle velocity measured in the vertical, or z-direction
- Longitudinal PPV – The peak particle velocity measured in the longitudinal, or y-direction
- Vector Sum PPV – the peak particle velocity measured in the vector sum, or summation of x, y, and z directions

It would be beneficial to measure vibration level of oil and gas operations and compare it against the vibration levels from other major construction activities established by prior studies. **Table 1** shows some typical vibration source amplitudes from various types of construction equipment, as compiled by the Federal Transit Administration (1995) and Caltrans (2000) for crack-and-seat operations:

Table 1: Vibration Source Amplitudes for Construction Equipment

Equipment	Reference PPV at 25 ft. (in/s)
Vibratory roller	0.210
Large bulldozer	0.089
Caisson drilling	0.089
Loaded trucks	0.076
Jackhammer	0.035
Small bulldozer	0.003
Crack-and-seat operations	2.400

Vibration Impact

The Colorado Oil and Gas Conservation Commission (COGCC) regulates oil and gas operations in the state of Colorado. However, the rules and regulations do not contain any provisions for vibration from oil and gas operations (COGCC 2018.) Many municipal zoning ordinances only have a nuisance clause for vibration, if it is mentioned at all. In lieu of limits set by governing bodies, several studies on the human response to vibration as well as studies on structural damage are cited for comparison and analysis. The human response to vibration has been extensively studied and long established. Two studies have determined a criteria to categorize the human response to steady state vibration and transient vibration. **Table 2** summarizes the human response to steady state or continuous vibration, from an early study (Reiher, H and F.J. Meister, 1931.)

Table 2: Human Response to Steady State Vibration

PPV (in/s)	Human Response
3.6 (at 2 Hz) – 0.4 (at 20 Hz)	Very disturbing
0.7 (at 2 Hz) – 0.17 (at 20 Hz)	Disturbing
0.10	Strongly perceptible
0.035	Distinctly perceptible
0.012	Slightly perceptible

Table 3 summarizes the human response to transient, or impulsive vibration (Wiss 1974.)

Table 3: Human Response to Transient Vibration

PPV (in/s)	Human Response
2.0	Severe
0.9	Strongly perceptible
0.24	Distinctly perceptible
0.035	Barely perceptible

Based on the PPV levels and associated human responses, the studies suggest the humans may perceive steady state vibrations more easily than transient vibrations.

Vibration from oil and gas operations is considered transient by nature but for the purposes of this study has been idealized to steady state. The primary source of vibration from the operations is the act of drilling or fracturing on site, which does not occur during every day and is transient or impulsive in nature. Additionally, operations on site are realistically an orchestrated event with numerous activities ongoing that are producing vibration. For example, during drilling operations there may be mud pumps running; generators powering the equipment; and the top drive drilling pipe into the earth. Similarly, there may be multiple activities during fracturing operations. For the simplicity of the results this study idealizes all of the separate activities to simply 'drilling' or 'fracturing' operations. The limits in **Tables 2** and **3** suggest that thresholds for perception and annoyance are higher for transient vibration than for continuous or steady state vibration.

Two studies are referenced for the limits on structural damage. The maximum allowable PPV before permanent damage is sustained is recommended by (Dowding 1996) in **Table 4**:

Table 4: Dowding Building Structure Vibration Criteria

Structure and Condition	Limiting or Max PPV (in/s)
Historic and some old buildings	0.5
Residential structures	0.5
New residential structures	1.0
Industrial buildings	2.0
Bridges	2.0

The American Association of State Highway and Transportation Officials (AASHTO 1990) recommends maximum vibration levels for preventing damage to structures from transient construction and maintenance activities in **Table 5**:

Table 5: AASHTO Maximum Vibration Levels for Preventing Damage

Type of Structure	Limiting or Max PPV (in/s)
Historic sites or other critical locations	0.1
Residential buildings, plastered walls	0.2 – 0.3
Residential buildings in good repair with gypsum board walls	0.4 – 0.5
Engineered structures, without plaster	1.0 – 1.5

The limits established by AASHTO suggest that older structures have a low tolerance for vibration, while newer structures constructed with modern building materials respond better. Furthermore, structures that are engineered such as commercial or industrial buildings may withstand ten times the amount of vibrations than that of a historic or critical structure.

Vibration Criteria

Vibration data for this study is compared to the most conservative limits for both human response and structural damage. Though many structures are not historic and the composition of building materials are largely unknown in a given area, the most conservative limit allows for a broader application of the drilling and fracturing data. The following limits are utilized for comparison against drilling and fracturing vibration levels:

- Reiher, H and F.J. Meister, 1931 “Slightly perceptible” limit of 0.012 in/s for steady-state vibration response in humans (**Table 2**)
- Wiss 1974 “Barely perceptible” limit of 0.035 in/s for transient vibration response in humans (**Table 3**)
- Dowding 1996 “Historic and some old buildings” limit of 0.5 in/s for preventing damage to structures (**Table 4**)
- AASHTO 1990 “Historic or other critical locations” limit of 0.1 in/s for preventing damage to structures (**Table 5**)

Vibration data for the oil and gas operations is also compared against the construction equipment vibration levels established by the Federal Transit Administration (1995) and Caltrans (2000) presented in **Table 1**.

Method & Results

A Brüel & Kjær Type 4450 vibration analyzer was used to measure vibration levels at the monitoring location. **Appendix A** lists the manufacturer’s specifications for this meter. The software modules in the Type 4450 allows for real-time vibration analysis, analysis of time histories for broadband parameters, and documentation of measurements through recording of measured vibration. The 4450 vibration meter continuously sampled sound levels logging the specified data every minute; therefore, each one hour period provided 60 readings.

Prior to beginning the monitoring, the 4450 meters were calibrated using the Brüel & Kjær reference calibration file. Full manufacturer calibration documentation is available upon request.

After monitoring, the data collected by the 4450 vibration level meter was downloaded to a computer using Brüel & Kjær Sentinel Software for Hand-held Analyzers. The manufacturer's software coupled with Excel spreadsheets was used to summarize the data.

On Site Measurements

As referenced in **Table 1**, the data from the Federal Transit Authority for various construction operations and their matching vibrational data is measured at 25 feet from the source. The optimal or desired deployment location would be at a 25 foot distance from the central source of operations for both drilling and fracturing operations in order to match the reference data. For both drilling and fracturing operations, the spread of equipment is vast and can nearly cover every inch of a standard pad site which are approximately 300 feet by 300 feet. In both cases deployment was not feasible at 25 feet from the well heads but a deployment location inside the operational footprint was chosen. By comparison to the data in **Table 1** the measurement of data for both drilling and fracturing operations likely was far more intense due to the scale of operations covering such a greater area and deployment being within that operational footprint.

The on site monitoring for drilling operations was placed approximately 250 feet southeast of the well heads that were being drilled on site. The on site monitoring for fracturing operations was placed approximately 190 feet northeast of the wellheads on site. In addition to drilling and fracturing operations vibration levels were impacted by people walking or vehicles driving near the monitors.

The baseline vibration level surveys were conducted from approximately 12:00 a.m. on Tuesday, March 19, 2019 to 12:00 a.m. on Monday, April 1, 2019. **Table 6** and **7** summarize the averages of the study at the on site monitoring points for drilling operations and fracturing operations, respectively.

Table 6: Drilling Operations on Site Daily and Overall Study Vibration Level Averages (in/s)

Description	Transverse PPV (in/s)	Longitudinal PPV (in/s)	Vertical PPV (in/s)	Vector Sum PPV (in/s)
Monday, March 25, 2019	0.0026	0.0024	0.0036	0.0051
Tuesday, March 26, 2019	0.0023	0.0020	0.0032	0.0045
Wednesday, March 27, 2019	0.0028	0.0026	0.0043	0.0058
Thursday, March 28, 2019	0.0022	0.0021	0.0036	0.0048
Friday, March 29, 2019	0.0023	0.0023	0.0040	0.0052
Saturday, March 30, 2019	0.0036	0.0029	0.0047	0.0066
Sunday, March 31, 2019	0.0030	0.0030	0.0043	0.0060
Average	**0.0027**	**0.0025**	**0.0039**	**0.0054**

Table 7: Fracturing Operations On Site Daily and Overall Study Vibration Level Averages (in/s)

Description	Transverse PPV (in/s)	Longitudinal PPV (in/s)	Vertical PPV (in/s)	Vector Sum PPV (in/s)
Tuesday, March 19, 2019	0.0011	0.0011	0.0013	0.0021
Wednesday, March 20, 2019	0.0013	0.0012	0.0013	0.0023
Thursday, March 21, 2019	0.0048	0.0040	0.0036	0.0073
Friday, March 22, 2019	0.0044	0.0037	0.0031	0.0066
Saturday, March 23, 2019	0.0049	0.0042	0.0034	0.0075
Sunday, March 24, 2019	0.0053	0.0041	0.0035	0.0078
Monday, March 25, 2019	0.0046	0.0036	0.0032	0.0068
Average	**0.0036**	**0.0030**	**0.0027**	**0.0056**

Tables 6 and **7** establish Vector Sum PPVs for both drilling and fracturing operations based on one week of monitoring and data collection at each operation. Next, the study data is compared against the construction equipment vibration data from the Federal Transit Authority so that a reference PPV level from drilling and fracturing operations can be established and compared against other construction equipment operations.

Table 8 shows the reference Vector Sum PPVs from the Federal Transit Authority but modified with the inclusion of data for drilling and fracturing operations so as to draw some conclusions from the study averages.

Table 8: Modified version of Table 3: Vibration Source Amplitudes for Construction Equipment

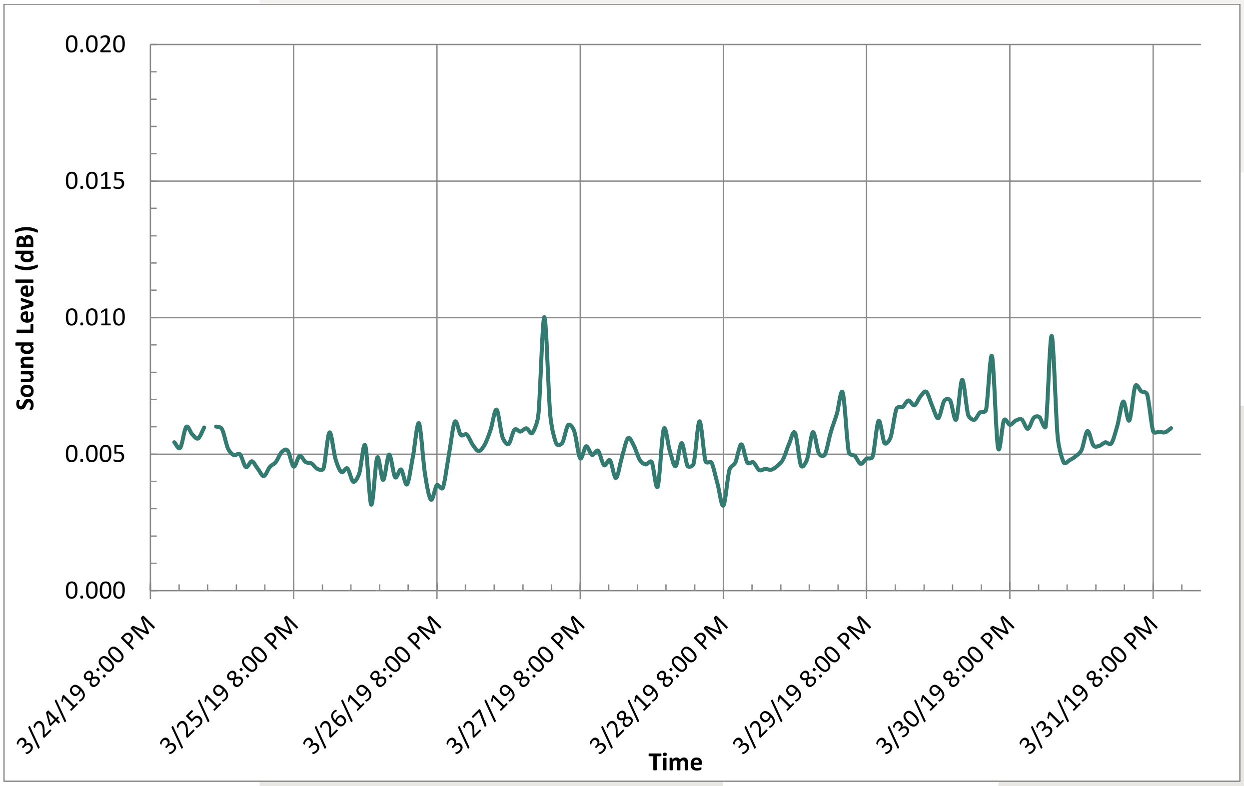
Equipment	Reference PPV at 25 ft. (in/s)
Vibratory roller	0.210
Large bulldozer	0.089
Caisson drilling	0.089
Loaded trucks	0.076
Jackhammer	0.035
*Fracturing Operations	*0.0056
*Drilling Operations	*0.0054
Small bulldozer	0.003
Crack-and-seat operations	2.400

*Added data from field studies for comparative imagery, not part of Federal Transit Authority data reference.

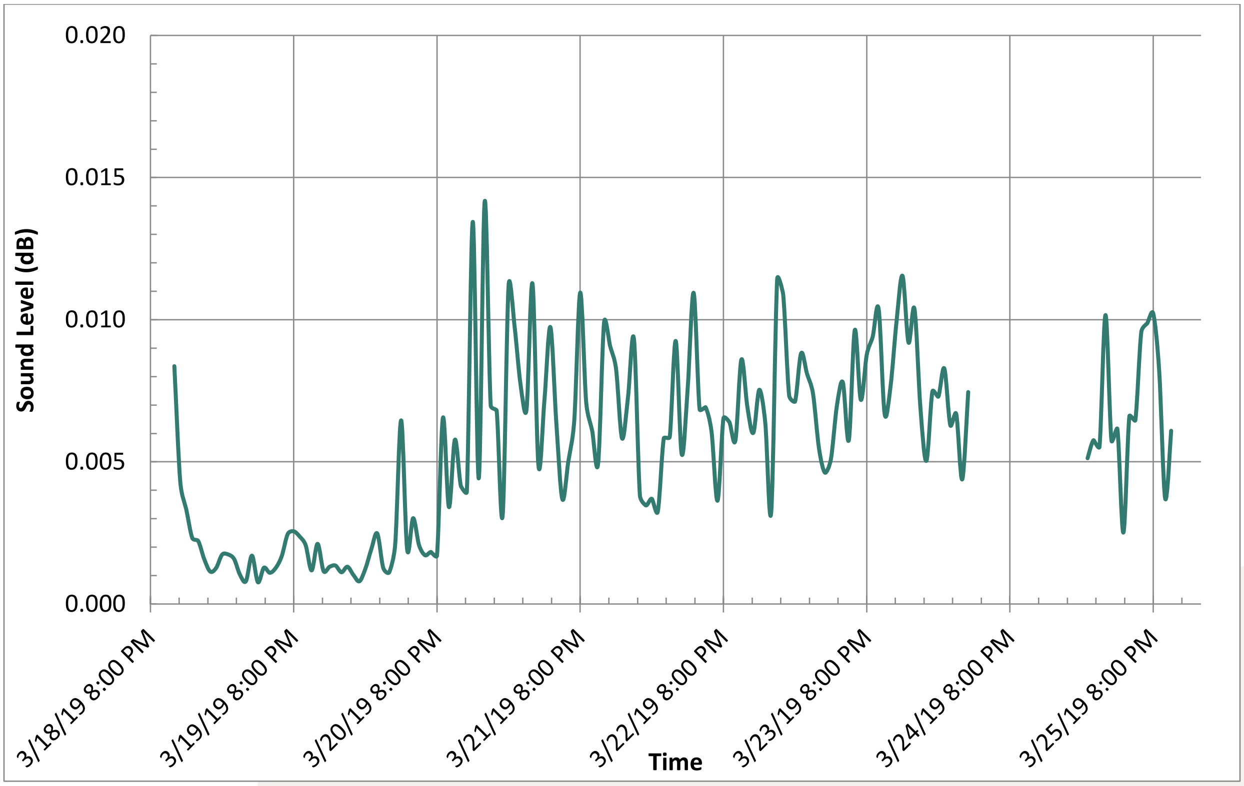
The data from drilling and fracturing operations fall well below that of some very common construction activities. The operation of jackhammers on construction sites is quintessential; so much so that when construction is demonstrated in the media there is nearly always someone operating a jackhammer. From **Table 8** 'Jackhammer' is rated at a reference PPV of 0.035 in/s and 'Loaded Trucks' is rated at a reference PPV of 0.076 in/s when measured at 25 feet. The highest occurrence of measured PPV that occurred between drilling and fracturing operations was during fracturing operations on Sunday, March 24, 2019 (from **Table 7**), at 0.0078 in/s. This average is nearly one order of magnitude lower than 'Loaded Trucks'. Drilling and fracturing operations are well below that of common construction operations when compared based on vibrational impact to the surrounding area.

For illustrative purposes, the hourly averages of both sets of data from drilling and fracturing are plotted in graphs to demonstrate how any single hourly peak data might compare against the reference PPVs for common construction activities. **Graphs 1** and **2** show the hourly Vector Sum PPVs of both drilling and fracturing operations respectively.

Graph 1: Drilling Operations Hourly Vector Sum PPV of On Site MP



Graph 2: Fracturing Operations Hourly Vector Sum PPV of On Site MP



It is evident from **Graph 1** that drilling operations have a peak hourly PPV event of no more than 0.010 in/s and from **Graph 2** fracturing operations have a peak hourly PPV event of nearly 0.015 in/s. If the peak values are compared to that of the common construction activities shown in **Table 1**, then the 'Jackhammer' operations are 2 to 3 times that of fracturing and drilling, respectively. The vibration levels from 'Loaded Trucks' is approximately 5 to 7 times that of drilling and fracturing operations respectively. Although drilling and fracturing operations take up a considerable footprint and are perceived to be sizeable their vibration impact on the pad site is less than expected when operating.

Off site Measurements

In addition to the on site monitoring, monitoring was completed for both drilling and fracturing operations off site. Both operations were measured at a distance of 350 feet from the edge of the pad in accordance with the noise monitor deployment requirements for oil and gas operations as stated in COGCC ordinance for the state of Colorado. The additional off-site monitoring location studies were completed to establish realistic impact of drilling and fracturing operations on the human experience. As stated previously, oil and gas operations are sprawling in footprint and can take up the entirety of a pad site at nearly 300 feet by 300 feet. Consequently, it is a rare occurrence for such a pad site to exist within 25 feet of an existing structure with inhabitants. Utilizing the required noise monitoring distance of 350 feet from a pad site per the state ordinance fit this study as the current required setback distance for a pad site or wellhead from an existing structure is 500 feet (COGCC 2018.)

Off-site baseline vibration level surveys were completed from approximately 12:00 a.m. on Tuesday, March 19, 2019 to 12:00 a.m. on Monday, April 1, 2019. **Table 9** and **10** summarize the averages of the study at the off site monitoring points for drilling operations and fracturing operations, respectively.

Table 9: Drilling Operations Off Site Daily and Overall Study Vibration Level Averages (in/s)

Description	Transverse PPV (in/s)	Longitudinal PPV (in/s)	Vertical PPV (in/s)	Vector Sum PPV (in/s)
Monday, March 25, 2019	0.0003	0.0003	0.0002	0.0004
Tuesday, March 26, 2019	0.0003	0.0003	0.0002	0.0004
Wednesday, March 27, 2019	0.0003	0.0003	0.0002	0.0005
Thursday, March 28, 2019	0.0003	0.0002	0.0002	0.0004
Friday, March 29, 2019	0.0002	0.0003	0.0002	0.0004
Saturday, March 30, 2019	0.0003	0.0003	0.0002	0.0005
Sunday, March 31, 2019	0.0002	0.0002	0.0002	0.0004
Average	**0.0003**	**0.0003**	**0.0002**	**0.0004**

Table 10: Fracturing Operations Off Site Daily and Overall Study Vibration Level Averages (in/s)

Description	Transverse PPV (in/s)	Longitudinal PPV (in/s)	Vertical PPV (in/s)	Vector Sum PPV (in/s)
Tuesday, March 19, 2019	0.0004	0.0005	*	0.0006
Wednesday, March 20, 2019	0.0003	0.0003	*	0.0004
Thursday, March 21, 2019	0.0007	0.0005	0.0004	0.0009
Friday, March 22, 2019	0.0007	0.0007	*	0.0010
Saturday, March 23, 2019	0.0008	0.0007	*	0.0011
Sunday, March 24, 2019	0.0007	0.0005	*	0.0009
Monday, March 25, 2019	0.0007	0.0006	*	0.0009
Average	**0.0006**	**0.0005**	**0.0004**	**0.0008**

*Corruption in the Vertical direction individual recordings, but Vector Sum was correctly recorded.

Tables 9 and 10 establish the Vector Sum PPVs for both drilling and fracturing operations when measured at a 350 foot distance from the edge of the pad for one week of monitoring and data collection at each operation. The total averages of the off site data is then compared against the criteria established earlier in this report. **Table 11** shows the data from the previously cited studies and the off site study averages. Only the lowest, most narrow criteria from each of the previously cited studies was chosen to compare to the off-site study averages.

Table 11: Comparison of Reference Levels to Off Site Overall Study Vibration Levels (in/s)

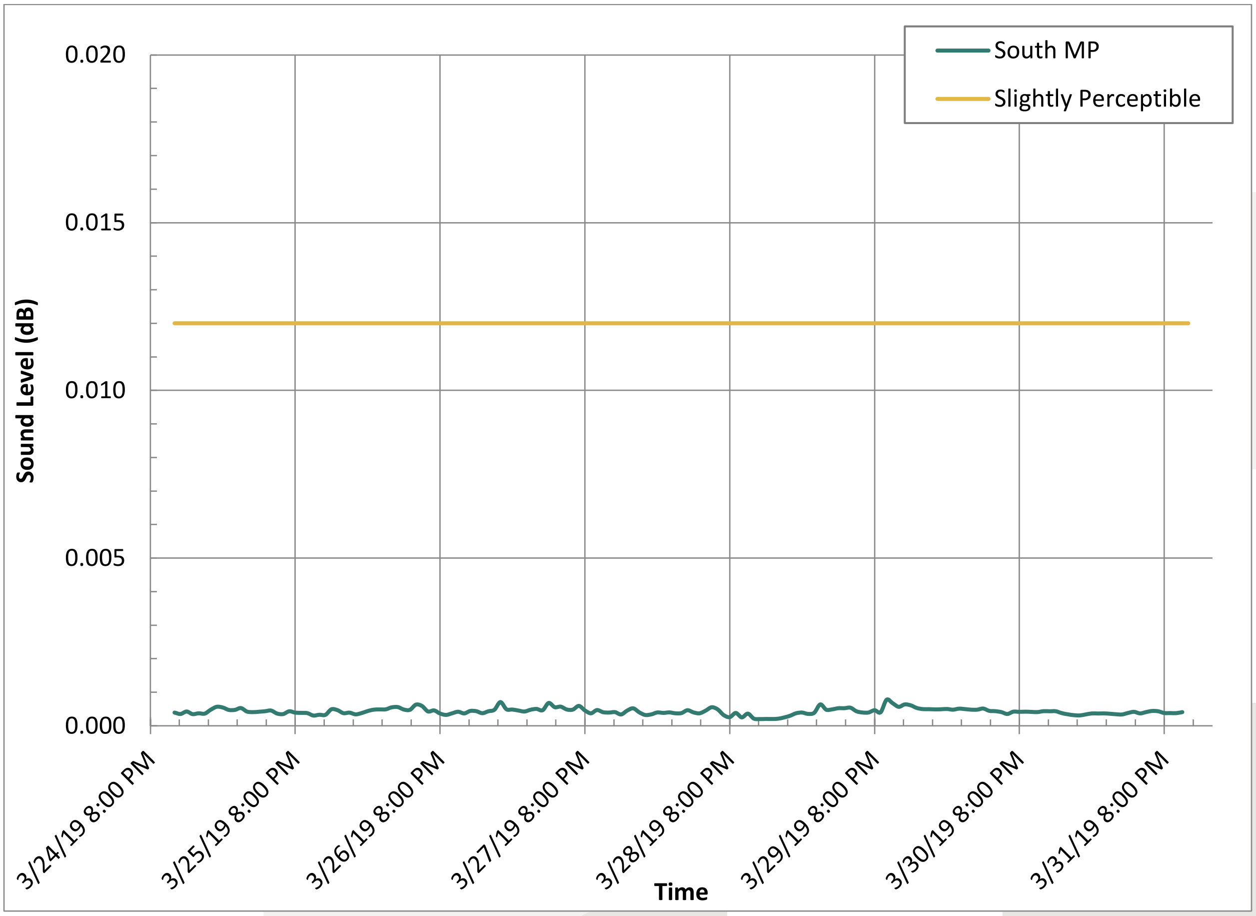
PPV (in/s)	Human Response or Type of Structure or Description	Title of Reference Table	Reference
0.5	Historic and some old buildings	Building Structure Vibration Criteria	(Dowding 1996)
0.1	Historic sites or other critical locations	Preventing Damage	(AASHTO 1990)
0.035	Barely perceptible	Transient Vibration	(Wiss 1974.)
0.012	Slightly perceptible	Steady State Vibration	(Reiher, H and F.J. Meister, 1931.)
0.0008	Fracturing Operations Off Site Vector Sum PPV	Fracturing Operations Off site data	This Report
0.0004	Drilling Operations Off Site Vector Sum PPV	Drilling Operations Off site Data	This Report

Table 11 shows that the off-site study averages are at minimum a 2nd order of magnitude lower from the reference data. For illustrative purposes in comparing the data, some calculations were performed to see how great a difference there is between the off-site study averages and the reference data. The Dowding 1996 reference data point from **Table 11** of 0.5 in/s before damage occurs to historic or older buildings is 625 times greater than the study averages for fracturing operations and 1,250 times greater than the study averages for drilling operations. The AASHTO 1990 reference data point from **Table 11** of 0.1 in/s to prevent damage from occurring to historic or older buildings is 125 times greater than the study averages for fracturing operations and 250 times greater than the study averages for drilling operations. The Wiss 1974 reference data point from **Table 11** of 0.035 in/s before vibration levels are "barely perceptible" is over 43 times greater than the study averages for fracturing operations and over 87 times greater than the study averages for drilling operations. The Meister 1931 reference data point from **Table 11** of 0.012 in/s before vibration levels are "slightly perceptible" is 15 times greater than the study averages for fracturing operations and 30 times greater than the study averages for drilling operations. Again, only the lowest, most narrow criteria from each of the previously cited studies was chosen for comparison to demonstrate how great a difference there is between this reference data and the study data. Drilling and fracturing operations at a distance of 350 feet from a structure of any typical construction should not receive any

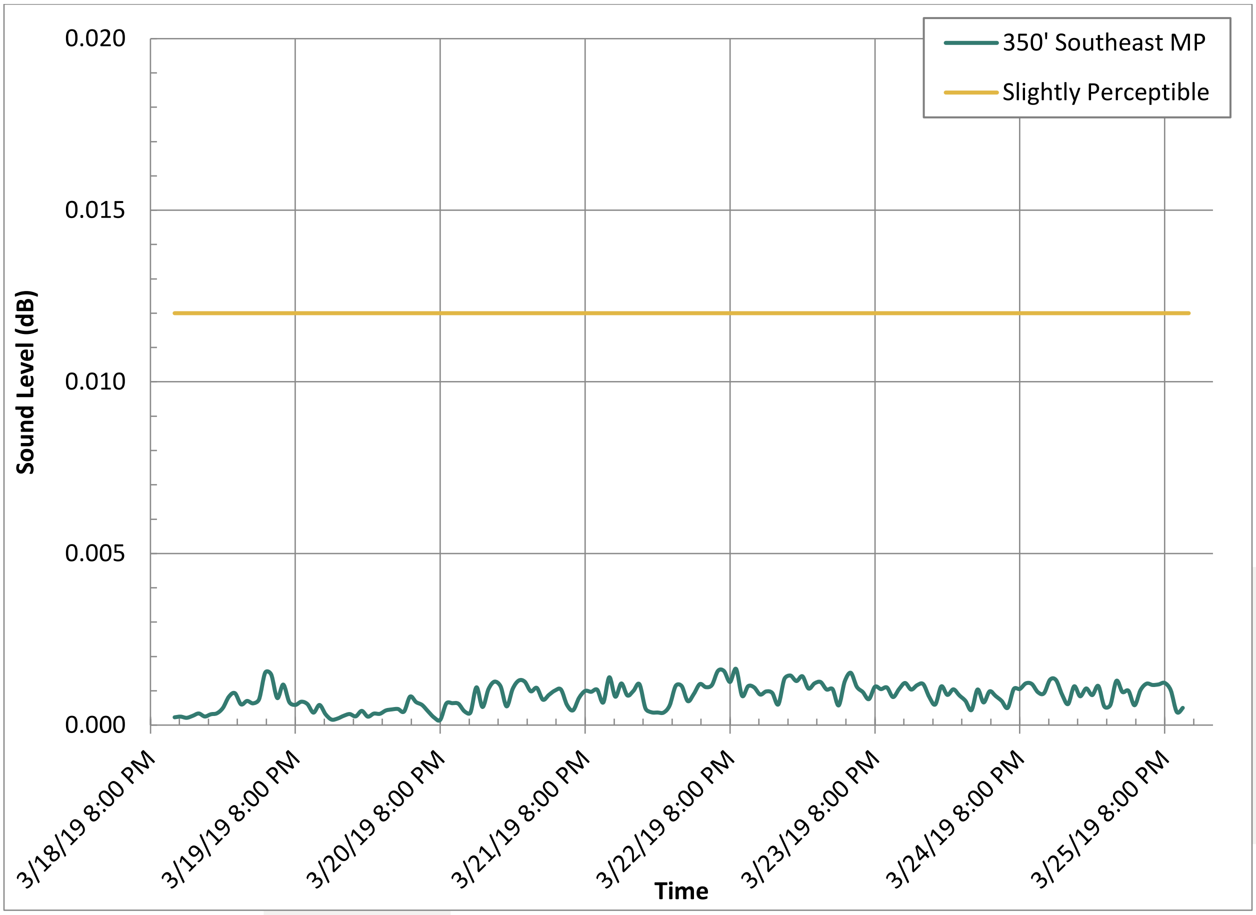
damage from operations and vibration levels will not be perceptible to the human experience based on this data.

The hourly averages of both sets of data from off site drilling and fracturing are plotted in graphs so any single hourly peak is visible and might compare against the reference PPVs. **Graphs 3** and **4** show the hourly Vector Sum PPVs of both drilling and fracturing operations as well as the lowest reference level on the chart for illustrative purposes. The reference level on the chart is from the Miester reference in Table 4 of 0.012 in/s for vibration levels that are “slightly perceptible” to the human experience.

Graph 3: Drilling Operations Hourly Vector Sum PPV of Off Site



Graph 4: Fracturing Operations Hourly Vector Sum PPV of Off Site



Graphs 3 and **4** demonstrate that neither drilling or fracturing operations have a peak hourly PPV event of 0.005 in/s. The Miester reference in Table 4 of 0.012 in/s for vibration levels that are "slightly perceptible" to the human experience was added to the above graphs to illustrate the difference. Moreover, this is only reference data point that could be included in these graphs and still keep the study data legible.

Conclusions

Drilling and Fracturing operations are comprised of many surface level operations with the highest vibrational impact on site coming from that of a generator or a diesel truck idling. Drilling and fracturing operations' most significant events are occurring below surface level and in many instances miles away from any residential area where there can be an impact on the human experience. Additionally, the medium of the earth is well suited to dampen and mitigate the vibrational impact of these operations since they are primarily occurring deep within the medium of earth or soil. The data in this study shows that just over the distance of 350 feet or more from on site to off site monitoring locations that the Vector Sum

PPV decreases by more than an order of magnitude. This decrease in data over several hundred feet shows that not only is the vibrational impact of these operations not strong enough to travel large distances but that the soil of the earth does a considerable job dampening vibrations.

Finally, the operations of drilling and fracturing for the oil and gas industry are typically regulated for handling the required setback distances of gas well sites from nearby structures. This study shows that that the minimum setback distance established by the COGCC adequately protects structures from possible damage or negative impact on the human experience from vibration.

Although oil and gas operations are becoming more common for various metropolitan areas, the vibrational impact of such operations on the human experience is far less than that of common construction activities and not likely to negatively impact that experience.

Limitations

There are several limitations of this study which are important to note. At the time of publication drilling and fracturing operator data is unavailable and thus cannot be correlated or compared against the vibration data to pinpoint exactly which activities occurred during the study. Vibration is idealized to steady-state. The study is limited to one week of data collection; optimally data would be collected during the entirety of drilling and fracturing operations on the sites, which can last from 30 to 90 days or more. Lastly, the off-site meter on the fracturing site was deployed approximately 250 feet from a two lane county road; any vibrations caused by passing road traffic that may have been picked up by the meter would be included and indistinguishable from site operations.

Acknowledgements

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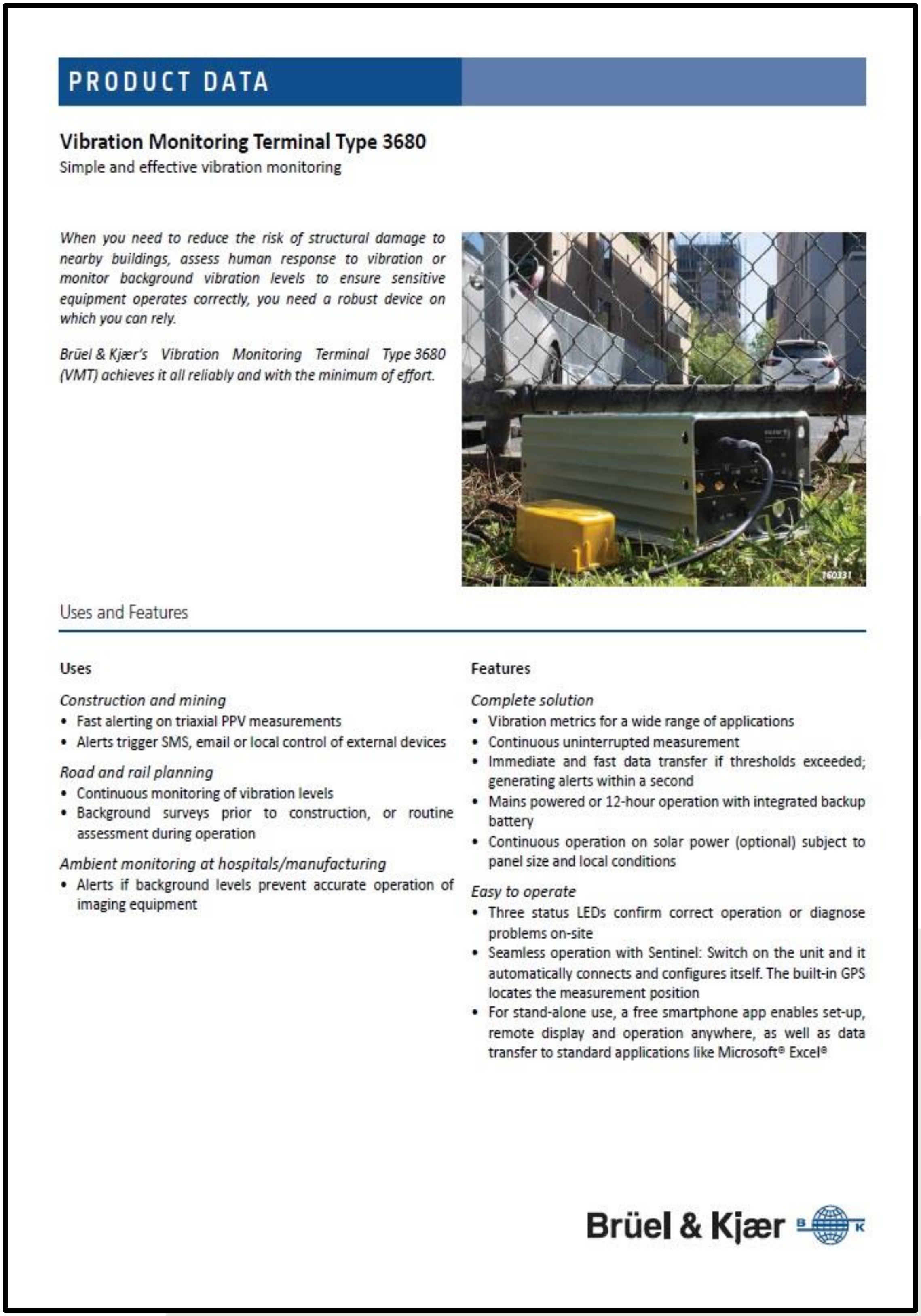
Appendix A

METER MANUFACTURER's SPECIFICATIONS



PRODUCT DATA

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When you need to reduce the risk of structural damage to nearby buildings, assess human response to vibration or monitor background vibration levels to ensure sensitive equipment operates correctly, you need a robust device on which you can rely.

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Uses and Features

Uses

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- Fast alerting on triaxial PPV measurements
- Alerts trigger SMS, email or local control of external devices

Road and rail planning

- Continuous monitoring of vibration levels
- Background surveys prior to construction, or routine assessment during operation

Ambient monitoring at hospitals/manufacturing

- Alerts if background levels prevent accurate operation of imaging equipment

Features

Complete solution

- Vibration metrics for a wide range of applications
- Continuous uninterrupted measurement
- Immediate and fast data transfer if thresholds exceeded; generating alerts within a second
- Mains powered or 12-hour operation with integrated backup battery
- Continuous operation on solar power (optional) subject to panel size and local conditions

Easy to operate

- Three status LEDs confirm correct operation or diagnose problems on-site
- Seamless operation with Sentinel: Switch on the unit and it automatically connects and configures itself. The built-in GPS locates the measurement position
- For stand-alone use, a free smartphone app enables set-up, remote display and operation anywhere, as well as data transfer to standard applications like Microsoft® Excel®

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