TruHorizon
Environmental Solutions

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

Brent M. Cummings and Katherine E. Grisham
TruHorizon Environmental Solutions

ADDENDUM

Reference document to provide a calculation for vibration over distance.

Calculation Overview

Reference

The Federal Transit Authority put together a table of typical vibration source amplitudes from various types of construction equipment, as is shown in Table 1 of the full White Paper and below:

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

All the data in Table 1 is referenced to a 25 ft. setback but it would be helpful to see what this data looks like at greater distances that are more realistic for where the human experience of say a homeowner might be. With that said there are numerous variables that make it difficult to accurately calculate the vibration over distance. But the U.S. Federal Transit Administration's Noise and Vibration Manual did arrive at a rough equation that could be utilized for approximating these vibration velocities at distance.

$$PPV_{equip} = PPV_{ref} \times (25/D)^{1.5}$$

Where: PPVequip is the calculated peak particle velocity in units of in/sec of the construction equipment type at the distance of interest, PPVref is the reference vibration level for that type of construction heavy equipment in in/sec at the reference distance of 25 feet, from Table 1, and D is the distance from the equipment to the structure or seismograph, in feet. This equation combines all the physical details of vibration movement through the ground in the 1.5 exponent and all the characteristics of the source vibration in the reference velocity, PPVref, which is related to the source energy. In this equation, the distance from the vibration source, D, is in the denominator of the factional rightmost factor. So, the calculated vibration PPV decreased as the distance increases, just as one would expect.

Modified for Use Case

The equation as it currently exists works for use in calculating the vibration velocity at distances further than 25 feet for reference construction equipment. If we are to utilize the equation for calculating the 25 foot reference vibration velocity levels of drilling and fracturing then we will need to rearrange the equation a bit as follows:

Original Equation: $PPV_{equip} = PPV_{ref} \times (25/D)^{1.5}$

➔ $PPV_{equip}(\frac{in.}{s}) = PPV_{ref}(\frac{in.}{s}) \times (25\,(ft.)/D\,(ft.))^{1.5}$

➔ $\frac{PPV_{equip}(\frac{in.}{s})}{(25\,(ft.)/D\,(ft.))^{1.5}} = \frac{PPV_{ref}(\frac{in.}{s}) \times (25\,(ft.)/D\,(ft.))^{1.5}}{(25\,(ft.)/D\,(ft.))^{1.5}}$

➔ $\frac{PPV_{equip}(\frac{in.}{s})}{(25\,(ft.)/D\,(ft.))^{1.5}} = PPV_{ref}(\frac{in.}{s})$

➔ $PPV_{ref}(\frac{in.}{s}) = \frac{PPV_{equip}(\frac{in.}{s})}{(25\,(ft.)/D\,(ft.))^{1.5}}$

Rearranged Equation: $PPV_{ref} = \frac{PPV_{equip}}{(25/D)^{1.5}}$

This rearranged equation would allow us to calculate the reference 25 foot distance vibration velocities of drilling and fracturing operations by using data collected from the field studies.

Method & Results of Field 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 2** and **3** summarize the averages of the study at the on-site monitoring points for drilling operations and fracturing operations, respectively.

Table 2: 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 3: 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 2 and **3** 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 4 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 4: 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 1** '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 3**), 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.

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.)

Table 5: 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**

TruHorizon
Environmental Solutions

Table 6: 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 5 and 6 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 7** 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 7: 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 7 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 7** 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 7** 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 7** 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 7** 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.

Method & Results of Calculated Data

The following results and data were approximated utilizing the FTA equation that we rearranged above in this report:

Rearranged Equation: $$PPV_{ref} = \frac{PPV_{equip}}{(25/D)^{1.5}}$$

From our field data we have the following established known variables that we can plug into this equation so that we can approximate the 25 foot reference distance vibration velocity levels for drilling and fracturing operations.

Table 8: Field collected variables for use in rearranged FTA equation

On Site Monitoring	D (ft)	PPVequip (in/s)
Drilling	250	0.0056
Fracturing	190	0.0054
Off Site Monitoring	**D (ft)**	**PPVequip (in/s)**
Drilling	350	0.0004
Fracturing	350	0.0008
Drilling	475	0.0004
Fracturing	475	0.0008

Table 8 shows the distances of on site and off site monitoring as well as the measured vibrational velocity (PPV) levels at each monitoring location for each operation type. Additional in this table we have added the distance of 475 feet to account for 350 feet from the edge of the pad but then also 150 feet into the center of the pad but then setback 25 feet from the center. This is based on our earlier assumption of pad site's typically being 300 feet by 300 feet in size, approximately. If we plug these variables into our rearranged equation from the FTA:

Rearranged Equation: $$PPV_{ref} = \frac{PPV_{equip}}{(25/D)^{1.5}}$$

Table 9: Results of the Reference 25 ft Vibrational Velocities (PPV) of Drilling and Fracturing Operations

On Site Monitoring	D (ft)	PPVequip (in/s)	PPVref (in/s)
Drilling	250	0.0056	0.1708
Fracturing	190	0.0054	0.1173
Off Site Monitoring	**D (ft)**	**PPVequip (in/s)**	**PPVref (in/s)**
Drilling	350	0.0004	0.0210
Fracturing	350	0.0008	0.0419
Drilling	475	0.0004	0.0331
Fracturing	475	0.0008	0.0663

The results in Table 9 show an increase in the PPV levels from the larger distances to the 25 foot distance which is to be expected but the amount of increase is substantial. The data from drilling and fracturing operations on site falls well above that of some very common construction activities. From **Table 1** '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. Before based on the field measurements and some conservative approximations we were able to show that the PPV levels would be comfortably well below that of a Jackhammer and Loaded Trucks but now using the calculated results the PPV levels of drilling and fracturing would sit somewhere in between those construction operations.

For the off-site monitoring based on field data, we originally showed that levels are extremely far below any of the criteria that we put the data up against. Once again, similarly to the on-site monitoring calculated results, the use of the rearranged equation from the FTA to approximate the 25 foot PPV levels of drilling and fracturing had a negative impact on our results. The calculated results for 25 foot PPV levels for drilling and fracturing now would easily exceed the Meister 1931 reference data point from **Table 7** of 0.012 in/s before vibration levels are "slightly perceptible" and also in some cases exceed The Wiss 1974 reference data point from **Table 7** of 0.035 in/s before vibration levels are "barely perceptible". Fortunately, the use of the equation does not elevate levels high enough to reach the structural impact criteria.

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 from the field** 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 based on **data from the field**.

However, in our attempt to calculate an idealized 25 foot measurement whilst utilizing an acceptable equation for approximating vibration over distance levels we discover data that would say otherwise. Based on the results from the field when compared to the approximated/calculated results, the limitations of the equation from the FTA becomes clear. Additionally, the inclusion of this approximated data only harms the positive narrative found in the field results. The recommendation would be to not include or utilize this data as it seems unreliable and could only be positively substantiated with a great deal more field data to compare with. In the study we only collect 4 data points in the field in a couple directions. To qualify the calculated results, we would need to collect 20+ data points in the field so that a trend could be established. From this trend we could look at the maximum, minimum, and average data to establish a rough approximation of the results.

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

American Association of State Highway and Transportation Officials. *Standard recommended practice for evaluation of transportation-related earthborne vibrations*. Washington, DC. 1990.

Beranek, L.L. *Acoustics*. Acoustical Society of America. 1996.

Beranek, L.L. et al. *Noise and Vibration Control Engineering*. Institute of Noise Control Engineering. John Wiley and Sons. 1992.

California Department of Transportation. *State Route 101 crack-and-seat vibration study*. 2000. Sacramento, California.

Colorado Oil and Gas Conservation Commission. *Rules and Regulations*. Denver, CO. 2018.

Dowding, C.H. *Blast vibration monitoring and control. Prentice-Hall*. Englewood Cliffs, NJ. 1985.

Federal Transit Administration. *Transit noise and vibration impact assessment*. DOT-T-95-16. Office of Planning. Washington, DC. 2006.

Reiher, H., and F.J. Meister. 1931. "The effects of vibration on people." Forsch Gebeite Ingenieurwes 1931; 2:381–6 (in German) English Translation: Report No. F-TS-616-RE, Headquarters Air Material Command, Wright Field, Ohio, 1946.

U.S. Energy Information Administration, Office of Energy Analysis. 2019. "Annual Energy Outlook 2019 with projections to 2050." Washington, DC. https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf

Appendix A

METER MANUFACTURER's SPECIFICATIONS

TruHorizon
Environmental Solutions

PRODUCT DATA

Vibration Monitoring Terminal Type 3680

Simple and effective vibration monitoring

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.

Brüel & Kjær's Vibration Monitoring Terminal Type 3680 (VMT) achieves it all reliably and with the minimum of effort.

Uses and Features

Uses

Construction and mining

- 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®

Brüel & Kjær