

Measurements of ground-borne vibrations at two operational wind turbine facilities



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ABSTRACT

Measurements of ground-borne vibrations at two operating commercial wind turbine facilities are described in this paper. Vibration monitoring was prompted by on-going research related to dynamic responses of turbine foundations and concerns related to the effects of ground-borne vibrations on domestic water supply wells. Ground conditions varied from competent glacial till at the first site to thick, soft clay overlying shale at the second. During turbine operation on these sites, vibration magnitudes were measured at the ground surface at distances ranging from 30 to 520 m from the turbines. In addition, for the second facility, vibration measurements were completed on one turbine tower structure, the turbine foundations and in the bedrock surface at a depth of about 19 m at distances ranging from about 17 to 520 m. Water well casing vibrations were also measured at distances ranging from about 140 m to 550 m. This paper summarizes vibration monitoring data and compares measurements made on the turbine tower, turbine foundations, ground surface, and bedrock at multiple distances from the source. Monitoring also captured a low-magnitude regional earthquake, nearby traffic and farming. This paper presents data and rationale toward developing site-specific vibration attenuation curves and turbine off-set distance criteria.

RÉSUMÉ

Le présent document décrit les mesures des vibrations transmises au sol dans deux éoliennes commerciales en exploitation. La surveillance des vibrations a été motivée par les recherches en cours sur les réactions dynamiques des fondations des turbines et par les préoccupations liées aux effets des vibrations transmises au sol sur les puits d'alimentation en eau domestiques. Les conditions du sol variaient d'un till glaciaire compétent sur le premier site à une couche d'argile molle et épaisse recouvrant du schiste argileux au second. Lors du fonctionnement des turbines sur ces sites, les amplitudes de vibration ont été mesurées à la surface du sol, à des distances comprises entre 30 et 520 m des turbines. En outre, pour la deuxième installation, des mesures de vibrations ont été effectuées sur une structure de tour à turbine, les fondations des turbines et la surface du substrat rocheux à une profondeur d'environ 19 m et à des distances comprises entre 17 et 520 m environ. Les vibrations du tubage de puits ont également été mesurées à des distances comprises entre 140 et 550 m environ. Ce document résume les données de surveillance des vibrations et compare les mesures effectuées sur la tour, les fondations, la surface du sol et le substrat rocheux à de multiples distances de la source. La surveillance a également capturé un séisme régional de faible magnitude, la circulation à proximité et l'agriculture. Ce document présente les données et les raisons qui sous-tendent l'élaboration de courbes d'atténuation des vibrations spécifiques au site et de critères de distance décalée de la turbine.

1 INTRODUCTION

Wind power generation in Ontario has expanded since 2012 and thousands of turbines have been constructed and are in operation (CANWEA 2019). As demand for renewable energy continues, wind turbines will be installed in both rural and populated areas. Low frequency acoustic signals and interaction of the wind, blade, turbine, tower, foundation and ground systems produce vibrations that propagate directly and indirectly through the surrounding ground, comparable in magnitude to seismic "background noise" (e.g., Saccorotti et al., 2011). Public concern about ground-borne vibrations can influence permitting, construction and implementation of wind energy facilities.

Propagation and attenuation of ground-borne vibrations have been studied for decades as related to seismicity, blasting, construction equipment, machine foundations and traffic, often focused on architectural or structural damage

or occupant disturbance that these ground motions may cause (e.g., Kramer, 1995; Wiss, 1981; CALTRANS, 2004). The source energy, frequency content and consequential effects of these ground motion source categories can differ by many orders of magnitude. While wind turbine systems are designed to withstand long-term structural dynamics imposed by wind forces based on well-established principles, field measurements of dynamic soil-structure interaction of foundations and the responses of the surrounding ground for near-field (i.e., < 100 m) and far-field distances specific to wind turbines have not been widely published.

In 2012, field research commenced to characterize ground conditions and dynamic turbine tower and foundation responses to wind and equipment loads at a generation facility in southwestern Ontario (Site A). This research was primarily focused on examining soil and structure fatigue when subject to near continuous, though

variable, small magnitude vibrations. In 2016, concerns expressed by the public related to a hypothesized effect of ground-borne vibrations on nearby water wells prompted vibration monitoring programs during construction and long-term operation of another wind power generation project (Site B). Data from these two sites are combined with available published research to illustrate the ranges of ground-borne vibration frequencies, magnitudes and their attenuation over long distances with the expectation that this work will assist with understanding attenuation of ground motions within the magnitude and frequency spectrum of wind turbines and to develop appropriate offset distances to areas of specific habitation or land use constraints.

2 BACKGROUND

An early study by Snow (1997) observed maximum ground vibration intensity (at any frequency) at sensors 100 m from a wind turbine did not exceed 0.015 mm/s (RMS)¹. Schofield (2001) measured ground motions near a wind power facility that consisted of 399 turbines, each about 50 m tall. Measurements were made at distances ranging from 24 m to 18 km to the nearest of the turbines. The strongest motions were detected at a frequency of about 4.3 Hz with ground particle velocities of about 5.6×10^{-3} mm/s at 24 m from the nearest turbine, 1.7×10^{-3} mm/s about 710 m away, and about 3.9×10^{-5} mm/s at 18 km away. Styles et al. (2005) measured maximum RMS particle velocities on a turbine base of about 0.07 mm/s, below the threshold for human perception of about 0.1 mm/s (ISO 1997). Fiori et al. (2009) studied vibrations associated with wind turbine foundations supported by sandy soils and their potential effects on a gravitational wave observatory. They measured maximum vibration intensity on the order of 0.15 mm/s or less as measured on the foundation. Botha (2013) reported ground vibrations intensity levels of less than 0.01 mm/s (RMS) under high turbine power output with occasional peaks near 0.015 mm/s measured 92 m away from a turbine foundation supported by weathered rock. In 2015, the Geological Survey of Canada (Edwards, 2015) conducted observations of background seismic “noise” (vibrations) at the Summerside, Prince Edward Island wind turbine facility. In this case, the turbine was supported on a large reinforced concrete spread foundation bearing on clayey sand glacial till or weathered sandstone bedrock. At 125 m away, a seismometer measured unfiltered ground motions, including those generated by the wind turbine, less than about 2,000 nm/s (RMS). In all these cases, while the measurements may have been relevant for seismic background noise and its effects on or measurement by highly sensitive scientific research equipment, the measurements were far below thresholds of human perception. Yet, clear relationships illustrating the attenuation of the ground vibrations were not well established.

¹ RMS defines the root mean squared value, or the positive square root of the arithmetic mean of the square of each value in the time series, useful where the average value of a signal would tend

3 TURBINE SITES AND MONITORING SYSTEMS

3.1 Site A

Site A is characterized by relatively flat topography and rural farmlands typical along the northern shore of Lake Erie in southwestern Ontario (see Tyldesley et al., 2013; Kiss et al., 2014; Kiss, 2016; González-Hurtado et al., 2016 and 2017; Postman et al., 2017). Turbines at Site A have a blade diameter of 93 m and a steel tower with a hub height of 80 m supported on a concrete mass foundation with an approximately 19 m diameter bearing about 3 m below the ground surface. Ground conditions consist of (in order of depth):

- heavily weather upper crust of clayey silt glacial till extending to a depth of about 1.5 m, with an undrained shear strength typically around 115 kPa;
- partially weathered lower crust of clayey silt till approximately between the depths of 1.5 to 4.5 m, with an undrained shear strength of about 240 kPa; and
- unweathered clayey silt till; with a typical undrained shear strength of about 85 kPa.

A survey of ground-borne vibrations was conducted over two days for durations of 1 to 8 hours. Three portable high frequency triaxial seismometers, sampling at a rate of 128 Hz, were placed at locations up to 1,000 m away from the turbine base. Four uniaxial tiltmeters and one triaxial accelerometer were mounted within the turbine and data from these instruments was continuously collected while the seismometer survey was underway.

3.2 Site B

Site B is also characterized by relatively flat farmlands and is situated between Lakes St. Clair and Erie in southwestern Ontario (see Kiss et al., 2018). Turbines at Site B have a hub height of 99.5 m with blade lengths of 55 m. The subsurface conditions typically consist of (in order of depth):

- nil to 8 m of sand and silt below the farmland surface;
- regionally extensive glaciolacustrine silty clay, 10 to 20 m thick, with undrained shear strengths typically between 15 and 35 kPa;
- sand and gravel ice-contact outwash or glacial till, with an average thickness of about 2 m; and
- fine-grained black shale bedrock.

Because of the soft ground, circular mass concrete foundations, built at the bottom of a 2.7 m deep excavation, and 18 steel pipe piles driven and anchored to the top of bedrock were used to support each turbine.

At Site B, four turbines were monitored to varying degrees. Instrumentation at one turbine location included:

towards zero and gives an idea of the range of velocities in the signal.

- pairs of triaxial and uniaxial accelerometers were installed within the bedrock near the bedrock-till interface and at the mid-depth of the soft clay;
- borehole pairs, with one hole for deep accelerometers and another for mid-depth accelerometers, were located at approximately 10, 30 and 50 m from the turbine;
- pairs of triaxial and uniaxial accelerometers were installed within two steel pipe piles, just above the rock, at positions around the foundation perimeter separated by 90 degrees;
- pairs of triaxial and uniaxial accelerometers installed within the circular mass concrete foundation, above the instrumented piles; and
- two triaxial accelerometers installed within the turbine tower, at the approximate half-height (about 49 metres above the foundation) and about 28 m below the top of the tower (about 67 metres above the foundation)

The remaining three turbines were instrumented as follows:

- pairs of triaxial and uniaxial accelerometers mounted within the concrete turbine foundations;
- pairs of triaxial and uniaxial accelerometers within the bedrock near the bedrock-till interface, installed through the overlying soft soil using a steel well casing, with these wells located at distances ranging between 140 and 520 metres from the turbines; and
- three orthogonally-oriented accelerometers mounted on the top of the steel well casings.

High-sensitivity accelerometers (1,000 to 10,000 mV/g) were selected for instrumentation since readily available geophone/seismometer systems with appropriate sensitivity could not be effectively installed at the base of deep boreholes and reliably coupled to the rock for long durations. Accelerometers were rigidly mounted to protective housing and coupled to rock or soil at specified depths with cement grout to approximately 1 m above the accelerometer housing. The remaining borehole volumes were filled with bentonite similar in strength to the surrounding clay. The instruments were installed using steel well casings to mimic the construction of residential water wells in the area. Instrumentation, data loggers and the top of the well casing at each mock well were enclosed

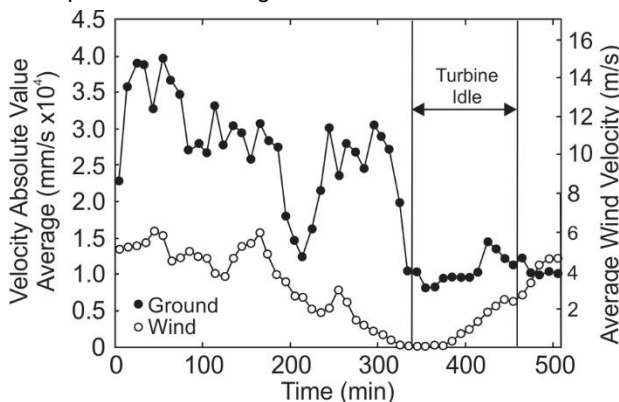


Figure 1. Absolute value of ground velocity measurements averaged over 10-minute periods compared to 10-minute average wind velocity (after Postman, et al., 2017).

in protective steel housings, with solar panel and battery power systems and remote connectivity. Site B is relatively unique in that data are being and will be collected on a near-continuous basis at high sampling frequencies (250 Hz) for 3 years. Data was stored in 10-minute files to assist with limiting lost data in the event of system malfunction or power losses and to be consistent with meteorological data collection protocols. Data presented in this paper represents the first 6 months of monitoring.

4 MONITORING DATA ANALYSES

4.1 Site A

Time histories of seismic velocity data were examined visually and large disturbances at the beginning and end of each recording, representative of personnel and instrument movements during instrument set-up were manually removed. A bandpass filter of 0.1-64 Hz was applied. Time-domain vibration amplitudes were then transformed to frequency domain by computing Fourier and power spectral density (PSD) spectra to determine which frequencies exhibited the most power and how the peak frequencies changed with distance. Signals were also compared to evaluate responses when the nearest turbine was and was not operating.

Figure 1 illustrates ground vibrations and wind velocity where the ground horizontal (in wind direction) particle velocities are represented by the absolute values of the positive and negative direction averaged for 10-minute intervals of seismograph measurements taken at 50 m from the turbine foundation. Averaging ground vibration data over 10-minute periods was consistent with typical wind power facility meteorological data that is also recorded as 10-minute average values. Power spectral densities for measurements taken at different distances from the turbine are illustrated in Figure 2.

Subsequent analyses examined attenuation of vibration over various distances from the turbine as well as the influences of wind direction on ground vibration magnitudes. Two plots in Figure 3 summarize average absolute value horizontal ground particle velocity magnitudes for 5000 seconds of data obtained at 128 Hz

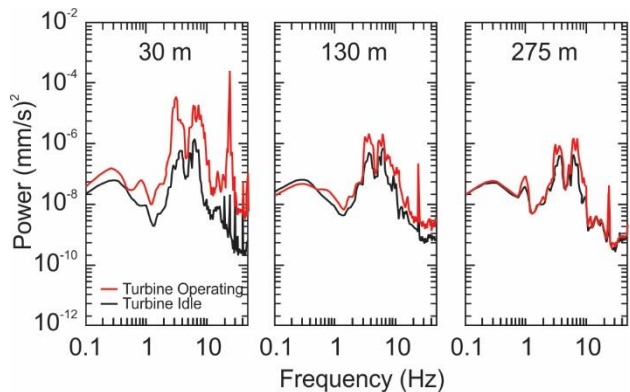


Figure 2. Power spectral density of ground velocity measurements made at 30 m, 130 m and 275 m from turbine during operation and idle periods (after Postman, et al., 2017).

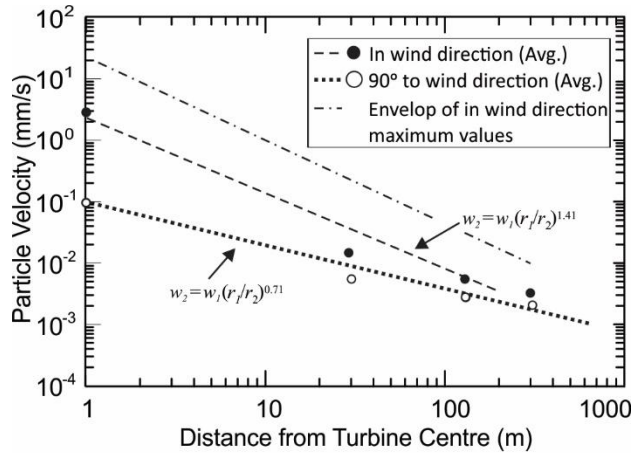


Figure 3. Velocity attenuation in wind and perpendicular to wind direction (after González-Hurtado et al. 2017).

at different distances from the turbine centre. While obtaining this data, the average wind velocity was about 10 m/s. The two plots illustrate some directionality of vibration influences and differences in attenuation behaviour. A third plot in Figure 3 (top line) illustrates similar attenuation of the maximum velocity values (in wind direction) measured during the same monitoring period. The work of González-Hurtado et al. (2017) found a reasonable approximation of the attenuation behaviour based on the work of Gutowski and Dym (1976) and Kim and Lee (2000) where:

$$w_2 = w_1 \left(\frac{r_1}{r_2}\right)^n e^{-\alpha(r_2-r_1)}$$

w_1 and w_l are the amplitudes at radial distances r_1 and r_2 from the source, and n and α are geometric and material damping coefficients, respectively. In this case, González-Hurtado et al. (2017) found that the material damping was of little influence in measured vibration amplitude attenuation, though at the far-field distances, background seismic noise may have dominated the measurement signals.

4.2 Site B

During the first 6 months of monitoring more than 2 TB of data was collected. Data analyses was therefore concentrated on typical instrument responses at wind velocities between 5 and 10 m/s, 10 and 15 m/s and 15 to 20 m/s or more to assist with evaluating whether general relationships existed between wind velocity and any instrument responses. For Site B, in contrast to Site A, averaging ground vibration data over selected periods of time was not applied because of regulatory agency concern regarding maximum values of ground motion. In addition, since accelerometers were used in this case, additional analytical steps were required to transform acceleration data to velocity for comparison to regulatory acceptance thresholds.

For analysis, 10-minute data files were selected from representative dates and times that captured the three

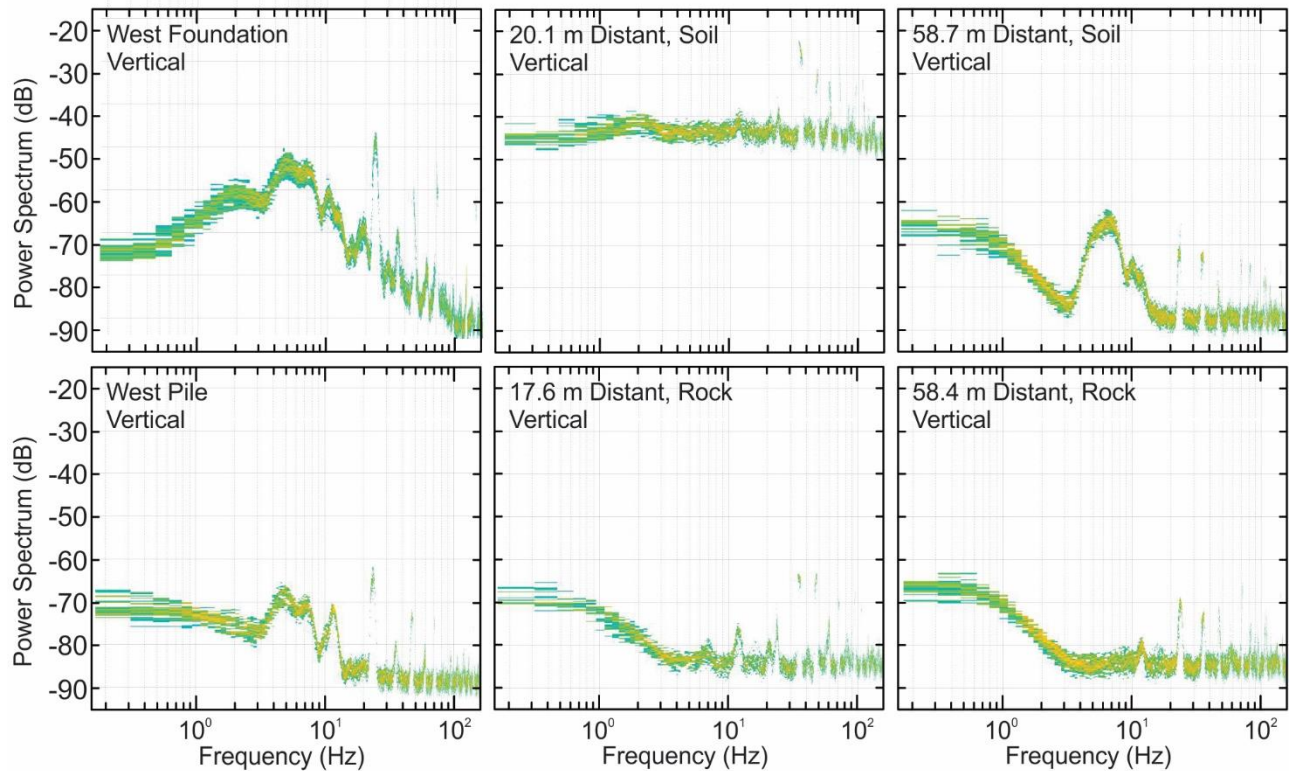


Figure 4. Examples of persistence diagrams for 10 minute data files collected at 250 Hz where the colour bands in the figures illustrate the greatest proportional signal density at any given frequency.

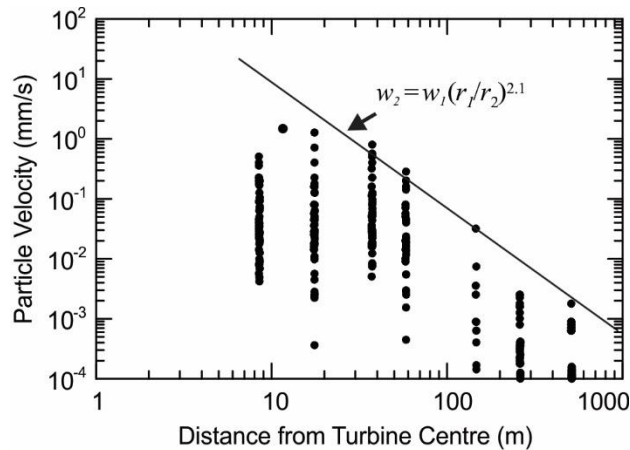


Figure 5. Envelope of maximum ground particle velocity measurements in rock.

wind velocity categories described above. Acceleration time histories were examined for obvious evidence of transient influences. Data was detrended based on the mean acceleration values to address all but the most extreme temperature drift. Data files were then subjected to fast Fourier transform (FFT) analyses to transform acceleration-time data to the frequency domain and to permit integration to velocity magnitudes for the entire 10 minutes of data, thus including both persistent, transient and background noise signals. Verification of Parseval's theorem was also completed to ensure that the recorded energy in the time domain was the same as the energy in the frequency domain. Since the monitoring systems could not be observed continuously, acceleration time histories could not be used to correlate transient signals to specific site activities except for specific instances while personnel were on-site, contrary to work completed during the construction phase of this same project (Kiss et al., 2018). Transient signals, in this case, included:

- vehicles entering the turbine sites for maintenance;
- municipal road traffic (see Kiss et al., 2018);
- farm equipment operations;
- pedestrian traffic near the instruments;
- animal movements near and in instrument containers;
- wind and rain striking the instrument containers; and
- electrical power perturbations.

To separate continuous or semi-continuous vibrations that might be caused by operating turbines from transient sources that otherwise may be masked by averaging, a persistence power spectrum was generated to illustrate the percentage of total signal time that any given frequency is present (MATLAB, 2017). Examples of these persistence diagrams are illustrated in Figure 4 where the magnitude of acceleration (a , in m/s) is transformed to signal power, measured in decibels (dB), using $ydB = 20\log_{10}(a)$ and plotted relative to frequency. These persistence diagrams assisted with reducing the influence of natural slow ground motions and other anthropogenic seismic noise on signal analysis since complex algorithms would likely be required to discern the turbine-generated ground motions from the background conditions (Sery and Napoly, 1996; Amirikas et al., 2005; Bialowons et al., 2006; Flores-Estrella et al.,

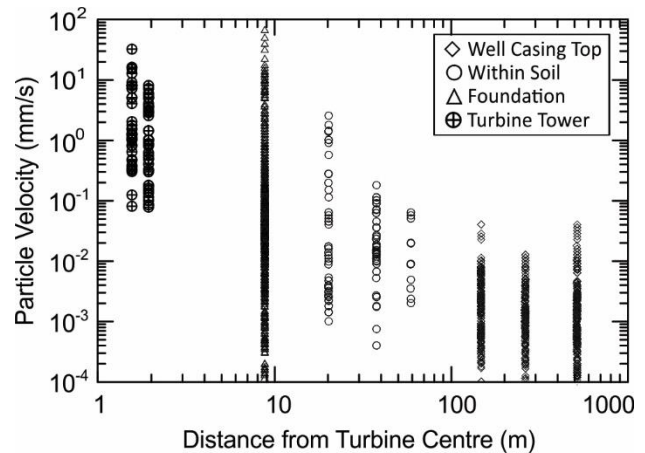


Figure 6. Maximum ground particle velocity measurements on turbine tower, on foundation, within soil (8 m depth) and on well casings at ground surface.

2017). In this case, the turbines at Site B would be expected to exhibit a blade pass frequency in the range of about 0.8 to 1 Hz. Marcillo and Carmichael (2018) noted that similar turbines produced a distinct and persistent seismic noise characterized by peaks at integer harmonics of the blade pass frequency. Therefore, ground motion amplitudes identified in the persistence spectra at 1 Hz and any higher frequency velocity peaks were used as a basis among the various instruments for evaluation of distance-amplitude attenuation characteristics. Other filtering algorithms were used to limit the real or perceived potential influence of filters and signal power suppression that might otherwise be used to address FFT spectra noise and leakage.

Given the complexity of the persistence spectra, multiple peak values were selected as points of comparison amongst instruments. The velocity amplitude at 1 Hz was chosen for all instruments along with three additional velocity values at subsequent peaks within the spectra. These peaks typically fell within frequency bands of about 1 to about 5 Hz, 5 to 10 Hz and greater than 10 Hz.

As part of the analyses, 10-minute data files were selected from 20 dates that exhibited wind velocities ranging from near calm to over 20 m/s. Figures 5 and 6 summarize maximum velocity values, integrated from the persistence diagram acceleration peaks and frequency, regardless of measurement direction and wind velocity. Figure 5 illustrates maximum ground particle velocity measurements (regardless of direction) obtained at the turbine pile foundation (where anchored to rock), and at near and far field distances within the rock. These data exhibit an envelope of attenuation behavior that is also reasonably characterized by the geometric attenuation relationship summarized above. Figure 6, however, illustrates more complex behavior, where an envelope of data cannot be used to define overall attenuation responses. Within this figure, vibration magnitudes for the turbine tower (distance < 2 m from centre), the turbine foundation concrete base at about 8 m from the centre, within the soft clay soils (at about 8 m depth) and measured at the top of steel well casings embedded through the soft clay soil and seated at the top of rock.

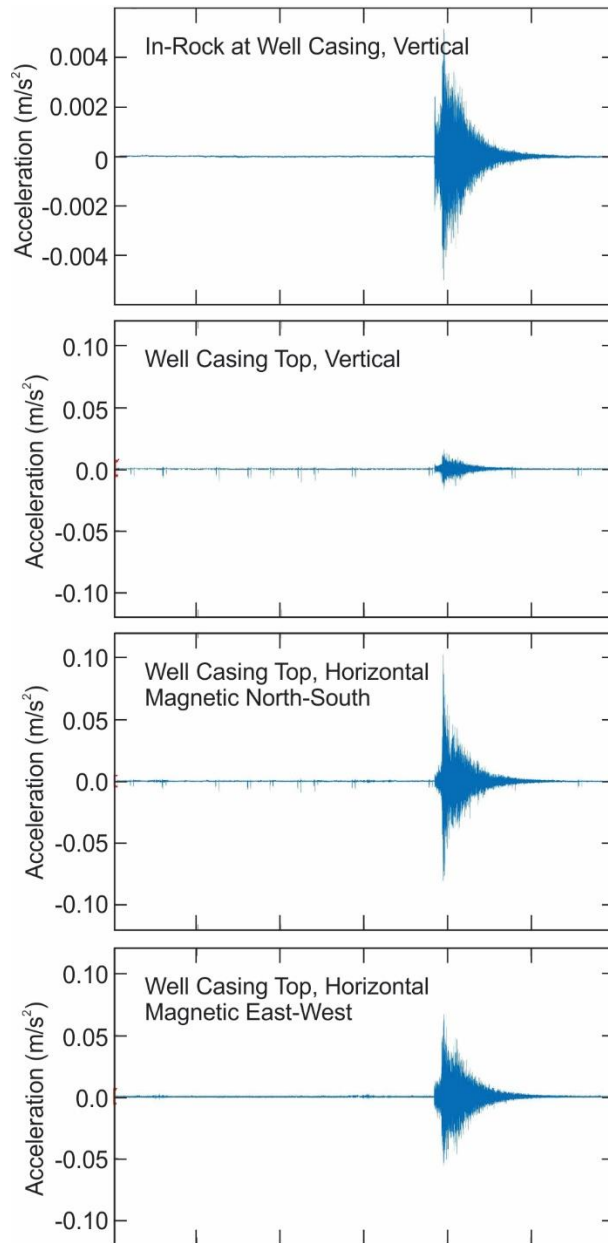


Figure 7. Instrument responses to Amherstburg earthquake of April 19, 2018 at distance of 72 km.

On April 19, 2018 a magnitude 4.1 earthquake was recorded in Southwestern Ontario long after construction (USGS 2018, NRC 2018). Based on seismic monitoring data and epicentral distances, peak ground acceleration and velocity at the project site were likely to have been in the range of 2.7×10^{-3} to 5.5×10^{-3} m/s² and 0.06 to 0.21 mm/s, respectively. A vertically oriented accelerometer grouted into the rock (15 m below ground surface) 72 km from the epicenter, installed for the vibration monitoring program, recorded a vertical acceleration of 5.5×10^{-3} m/s², consistent with USGS data and epicenter distance. Measured vertical earthquake-induced acceleration at the top of the steel well casing was about 2.9 times the value measured in rock just below the base of the steel casing.

Maximum horizontal casing acceleration was as much as 3.9 times the vertical well casing response. These results indicated that the vertical steel casing embedded in the soft clay amplified well casing accelerations at the ground surface as compared to those measured in rock during the earthquake. Horizontal vibrations also dominated the ground responses to this external event (see Figure 7).

5 CHALLENGES

Field monitoring at both sites presented challenges including:

- while both sites were within rural areas, nearby road traffic and passage of farming equipment contributed to transient peak instrument responses as well as background seismic noise (also see Kiss et al. 2018);
- periodic measurements at Site A did not capture responses during high wind velocity events;
- instruments mounted on the surface of the Site A foundations were susceptible to significant signal noise due to coupling issues;
- unstable AC power affected data loggers;
- ambient heat within the turbine bases and data logger protection boxes affected electronics;
- prior to final grading, some long-term instrument locations were flooded by severe weather, tripping electrical fuses, causing power losses and damaged data connections;
- extended periods of cloudy weather and limited daylight periodically combined to exceed solar power generation and battery storage at remote instruments;
- computer “malware” was embedded within cellular modems hardware that inhibited data logging and communications and required multiple updates and in-field interventions;
- software compatibility between modems and data loggers was affected by automatic updates, manual updates and power outages/restarts;
- datalogger and local mass-storage software programming problems;
- rodents and a weasel periodically burrowed into and nested within the remote steel instrument boxes, despite wire mesh, steel wool, insulation and stone protection and, on occasion, chewed through the electronic connection wires;
- data collection had to be interrupted when directly downloading data from each of the data loggers;
- internal or on-site external data logger storage capacity was exceeded on occasion;
- subsurface triaxial accelerometers responded intermittently and exhibited significant signal noise, likely associated with moisture entering the housing and wiring systems, the physical size of the accelerometer, cable lengths and other factors;
- in one case a data logger malfunctioned and had to be replaced; and
- theft and vandalism of remote instruments.

6 CONCLUSIONS

Field monitoring of ground-borne vibrations at two operating wind energy sites in Ontario demonstrates that:

- vibration amplitudes and turbine operations are positively correlated within the first 100 to 150 m from the turbines, as expected (Figure 1);
- vibration magnitudes diminish exponentially with increasing distance so that at 100 m or more distant from the turbine centre, vibrations were below typical thresholds of human perception of 0.1 mm/s (Figures 5 and 6);
- ground vibration amplitudes decay exponentially and at distances on the order of 500 m background seismic noise dominates measurements and masks any influence of the turbines (Figure 4);
- near-field ground vibration amplitudes associated with turbine operations peak at frequencies in the range of 2-10 Hz (Figures 2 and 4);
- ground responses are strongest in the wind direction, and wind velocity appears to affect vibration magnitude as may be intuitively suspected, though additional work is needed to discern quantifiable trends (Figure 3);
- higher frequency vibrations attenuate more rapidly than the lower frequency vibrations, as may be expected based on research related to other ground vibration sources (Figures 2 and 4);
- in these cases, while geometric and material damping may be theoretically relevant, geometric attenuation plays a more important role, particularly at far-field distances on the order of hundreds of metres (see Figure 3 and Gonzalez-Hurtado et al. 2017);
- the maximum ground vibration velocities and geometric damping coefficients are broadly comparable with those found in the literature for other surface-based vibration sources;
- maximum ground vibration velocity at Site B was greater than Site A (Figure 8), likely as the combined result of higher wind velocities occurring during capture of some data, larger turbine systems and pile foundation support through very soft ground;
- ground responses at distances on the order of 30 m or more are dominated by horizontal components in the wind direction;
- in the soft ground conditions at Site B, vibrations propagating through rock were amplified at the ground surface and top of the instrumented well casings, as evident by measurements made during turbine operations and a local small-magnitude earthquake (Figure 7); and
- further work is necessary to better understand the form of the generated waves (surface and body) and the relative contributions of the foundation type, soil materials and heterogeneity, strain levels and meteorological conditions.

Measurements of ground-borne vibrations at two sites in Ontario has permitted understanding and demonstration of distance and vibration attenuation relationships associated with wind turbine operations. In these cases,

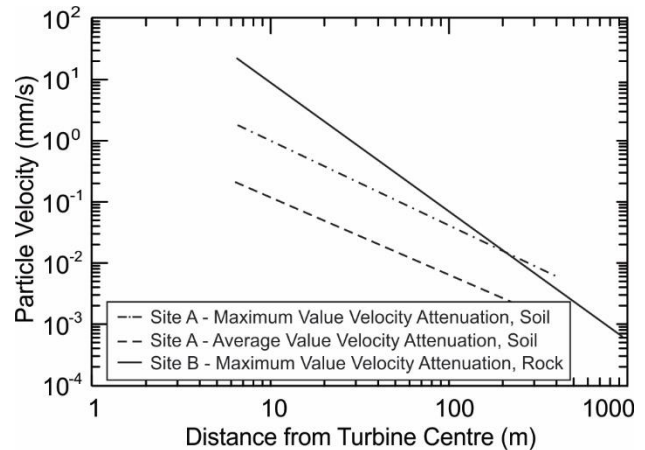


Figure 8. Attenuation of ground-borne vibration velocity in wind direction.

measurements made on the turbine structures (tower and foundations) assisted with identifying and characterizing vibration frequency spectra and tracking instrument responses at great distances. However, use of on-structure measurements is not necessarily useful for estimation of vibrations at large distances because of the complexities in the highly localized structural responses to wind excitation. While both monitoring programs experienced challenges during data collection, the volume of data has provided ample evidence for a better understanding of overall wind, structure and ground system behavior. Since the ground vibrations associated with the operating wind turbines are of extremely small amplitudes, signal capture, processing, analysis and interpretation is challenged by natural and anthropogenic background seismic noise. Data analysis for these two sites applied a variety of techniques to identify signals associated with turbine operation and relate these to wind velocity, wind direction and ground-borne propagation for both research and regulatory purposes. Averaging techniques were most helpful in relating ground vibration amplitudes to wind velocities given the challenges associated with correlating specific maximum wind velocity (gusts) to specific ground vibration amplitudes. Use of maximum ground vibration velocity was appropriate for regulatory purposes in characterizing distances at which ground vibrations might be perceived or have an influence on the surrounding environment.

7 ACKNOWLEDGEMENTS

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