Long-Distance Measurement of Pile Driving Vibrations

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ABSTRACT
Concerns about vibrations from pile driving for a wind turbine facility prompted monitoring at turbine construction sites and at distant domestic water wells within a 120 square kilometer project area. Ground conditions consisted of 10 to 20 m of soft clay overlying thin glacial till and black shale bedrock. Vibrations were measured at the ground surface at turbine construction sites, at the top of bedrock near the turbines and at domestic water well casings at distances of 570 m to more than 4.3 km from pile driving. Monitoring was completed during test pile and subsequent production pile driving. Vibrations were measured with conventional construction monitoring geophones and high-sensitivity accelerometers. This paper summarizes pre-construction vibration magnitude estimates, monitoring data and comparisons of data to pile driving conditions, well pump operations, nearby traffic and farming and published vibration attenuation relationships.

RÉSUMÉ
Les préoccupations soulevées par les vibrations causées par les travaux de battage de pieux dans le cadre d'un projet d'éoliennes ont incité à effectuer une surveillance des conditions au site de construction des turbines et des puits d'eau domestique sur une zone de 120 kilomètres carrés. Les sols de cette zone étaient principalement composés d'un horizon d'argile molle de 10 à 20 m recouvrant de minces horizons de till glaciaire et des substrats rocheux schisteux noirs. Les vibrations ont été mesurées à trois différents endroits, soit : à la surface du sol sur le site de construction des turbines, au sommet du substrat rocheux à proximité des turbines et aux cuvelages des puits d'eau domestiques localisés à des distances entre 570 m allant à plus de 4,3 km des travaux de battage. La surveillance a été effectuée pendant la mise à l'essai et lors de la production des travaux de battage. Les vibrations ont été mesurées à l'aide d'instruments classiques de surveillance de vibration tels que des géophones et accéléromètres à haute sensibilité. Cet article résume les estimations d'amplitude des vibrations avant les travaux de construction, les données de surveillance et les comparaisons des données aux conditions de battage d'éolienne, les opérations de pompage des puits, la circulation, les opérations d'agriculture avoisinantes et les relations d'atténuation des vibrations publiées.

1 INTRODUCTION

Concerns related to vibrations associated with pile driving for a wind turbine facility prompted a program of monitoring at turbine construction sites and domestic water wells in an approximately 120 square kilometer project area. Ground conditions in the area typically consist of a 10 to 20 m thick deposit of soft clay overlying relatively thin glacial till and black shale bedrock.

For more than 50 years, groundwater wells in the region have been drilled using cable tool systems with steel casings driven into the glacial till or to the top of weathered rock. The majority of wells have no screens and draw water through the casing bottom opening or through an open hole drilled into the rock. A group of residents within the region were concerned that vibrations from pile driving might cause rock particles to become suspended in well water.

Vibration magnitudes were measured at the ground surface at 34 turbine foundation construction sites at distances ranging from 3 to nearly 30 m and in the bedrock surface at a depth of about 19 m at distances ranging from about 10 to 70 m. Domestic water well casing vibrations were also measured at distances ranging from about 570 m to more than 4.3 km from 625 individual piles. Monitoring included pre-construction test pile and subsequent production pile driving phases. Vibrations were measured with conventional construction monitoring geophones as well as high-sensitivity accelerometers. This paper summarizes pre-construction vibration magnitude estimates, monitoring data and comparisons of the data to pile driving conditions, well pump operations, nearby traffic and farming. A site-specific vibration attenuation curve is compared to published relationships to evaluate the surface and subsurface magnitudes, propagation and attenuation characteristics of ground vibrations. Vibrations of various magnitudes emanating from multiple sources detected by the monitoring are summarized in this paper.

2 BACKGROUND

Literature reviews and analyses were completed before construction to evaluate vibration risks to water wells from pile driving and, later, turbine operation (e.g., Wiss 1981; Dowding, 1996; CALTRANS 2004 and others). Foundation piles were to be driven using diesel hammers striking at about 30 to 60 blows per minute. Commonly, ground vibrations from construction activities are measured by the frequency of vibrations in cycles per second (Hz) and particle velocity. Based on CALTRANS methodology and expected hammer energy, particle velocity values in soil

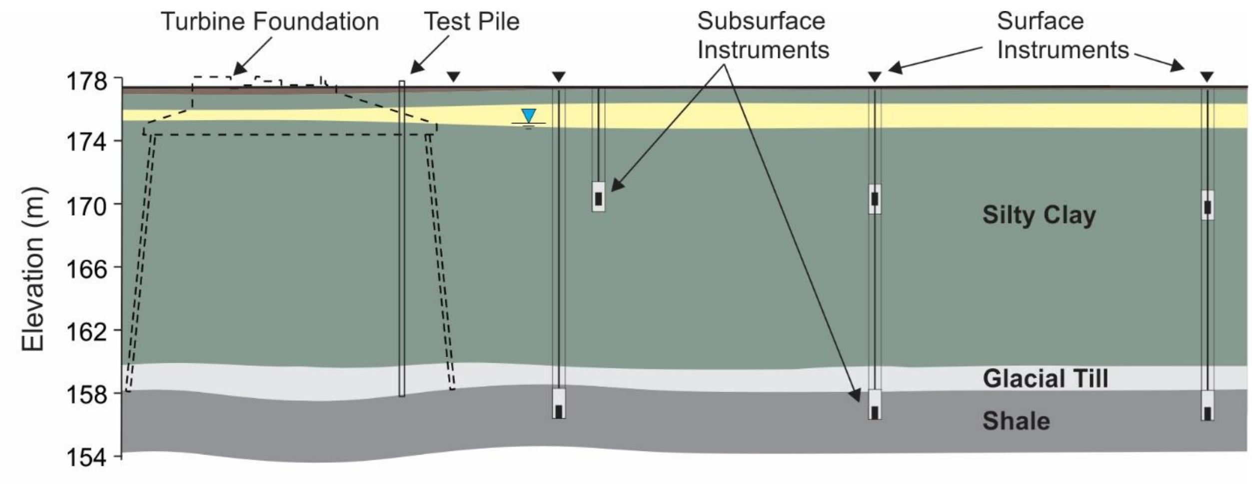

Figure 1. Profile of test pile site illustrating surface and subsurface instrumentation, test pile, turbine foundation and subsurface conditions.

and rock were estimated for multiple distances (Table 1) as a conservative basis for pre-construction evaluation and compared to published information (Table 2).

Table 1. Pre-Construction Vibration Magnitude Estimates

Distance (m)	Particle Velocity (mm/s)	
	Rock	Soil
10	19	17
100	≈1	≈2
500	<0.1	0.4
1000	<0.1	0.2

Table 2. Examples of Vibration Magnitudes and Effects

Examples	Particle Velocity (mm/s)
Equipment requiring extraordinary stability	$3x10^{-3}$
ISO threshold for hospital operating rooms	0.1
Steady state vibrations slightly perceptible	0.3
Transient vibrations barely perceptible	0.9
Transient threshold for historic structures	6 to 13
Limit for residential buildings	13
Conservative threshold for wells and utilities	50
Major building damage expected	152

Summarized from Siskind 2000 and CALTRANS 2004

Relevant literature related to ground vibrations induced by operating wind turbines was also reviewed (e.g., Snow 1997, Styles et al. 2005, Fiori et al. 2009, Botha 2013, Edwards 2015). Snow (1997) observed that the maximum ground vibration intensity (at any frequency) at sensors 100 m from a wind turbine supported on a spread foundation did not exceed 0.015 mm/s (RMS). Styles et al. (2005) measured maximum velocities (RMS) on a wind turbine foundation of about 0.07 mm/s. Fiori et al. (2009) studied vibrations associated with wind turbine foundations supported by sandy soils and indicated that the maximum vibration intensity was on the order of 0.15 mm/s or less as measured directly on the foundation. Botha (2013) reported typical ground vibrations, measured 92 m away from a turbine foundation supported by weathered rock, of less than 0.01 mm/s (RMS) under high turbine power output with occasional peaks near 0.015 mm/s. Using a seismometer located 125 m from a turbine, Edwards (2015) reported unfiltered ground surface vibrations, including those generated by the turbine and other sources, of less than about 0.002 mm/s (RMS) and concluded that *"…it is unlikely that seismic noise generated by the turbines would be perceived by area residents."* Published research indicated that, while vibration measurements could be made and specifically identified as being related to wind turbines, the vibration magnitudes were in the realm of seismic "noise" that might be relevant only to specialized scientific measurement equipment.

3 PROJECT SUMMARY

The project site, located in southwestern Ontario, is relatively flat and dominated by farm fields. 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, ranging from about 10 to 20 m thick, with undrained shear strengths typically between 15 and 35 kPa;
- sand and gravel with varying proportions of silt and clay, representing ice-contact outwash or glacial till, with an average thickness of about 2 m; and
- fine-grained black shale bedrock of the Devonian Kettle Point Formation.

Since the ground conditions were soft, a circular mass concrete foundation, built at the bottom of a 2.7 m deep excavation, and 18 steel pipe piles driven to the top of bedrock were used to support each turbine. A single test pile was driven at turbine sites T42 and T5, to refine the foundations design and measure ground vibration responses to pile driving. The T42 test pile site included driving and partially extracting a single pile with surface, subsurface and domestic water well vibration monitoring.

Vibration monitoring for the T5 test pile was completed only at the ground surface and at two distant water wells. Test piles were 410 mm outside diameter pipe piles driven with a closed-end and later filled with concrete. The closed-end on the test piles was formed with a 430 mm diameter, 50 to 60 mm thick steel plate. Production piles were plugged with cement grout to allow subsequent drilling and rock anchor installation. Pile driving was completed using a 110 kJ diesel hammer at 35 to 56 blows per minute.

4 MONITORING METHODS

4.1 Test Pile Monitoring

At the T42 site the instrumentation consisted of:

- pairs of triaxial and uniaxial accelerometers installed within the bedrock near the bedrock-till interface and at the mid-depth of the soft clay (see Table 3);
- borehole pairs, with one hole for deep accelerometers and another for mid-depth accelerometers, were located at distances of 10, 30 and 50 m from the test pile (see Figure 1);
- ground surface monitoring at about 3, 10, 30 and 50 m from the test pile using conventional triaxial geophone and accelerometer systems (see Table 3); and
- single, vertically-oriented accelerometers mounted on two domestic water well casings at distances of 1,102 and 1,283 m from the test pile.

For the T5 site, vibration monitoring consisted of:

- ground surface vibration monitoring at 3, 10, 30 and 50 m from the test pile using conventional; and
- three orthogonally-oriented accelerometers mounted on two domestic water well casings at distances of 911 and 1,033 m from the test pile.

High-sensitivity accelerometers were selected for instrumentation since readily available geophone systems with appropriate sensitivity could not be effectively installed at the base of deep boreholes and reliably coupled to the rock. The accelerometers were rigidly mounted to protective housings and coupled to rock or soil at specified depths with cement grout. The remaining borehole volumes were filled with bentonite to be compatible with characteristics of the surrounding clay.

At the domestic water wells, it was impossible to measure the vibrations at the bottom of the wells without disrupting water supplies or disturbing conditions inside the well casings. Therefore, accelerometers were temporarily fixed to the steel casings using steel band clamps that exerted a force of about 2 tonnes at the contact between the accelerometers and well casings.

Multiple portable data loggers and conventional geophone construction vibration monitoring systems were used, typically sampling at rates of 256 to 1,280 Hz. Personnel visually monitored pile driving to note times of active pile hammering and pile penetration distances. Personnel were also stationed at the domestic water wells to note times and types of any activities on the sites that might influence ground vibrations (e.g., passing vehicle traffic, nearby equipment, etc.).

Table 3. Measurement Instruments

Device	Sensitivity
Triaxial accelerometer, subsurface	1000 mV/g
Uniaxial accelerometer, subsurface	10,000 mV/g
Uniaxial accelerometer, ground surface	1000 mV/g
Uniaxial accelerometer, well casings	1000 mV/g
Triaxial geophone, ground surface	0.016 to 254 mm/s

4.2 Construction Monitoring

During construction the turbine sites were grouped into seven clusters based on geographic proximity, a need to develop a variety of turbine-to-well distances, construction sequence and permission from well owners for monitoring. Full-time ground surface vibration monitoring at the turbine sites utilized conventional geophone systems located at distances ranging from about 6 to nearly 30 m from individual piles. Vibrations were also monitored at two domestic water wells within each cluster using orthogonally-oriented three accelerometer and clamping system and portable data loggers. All piles and wells were individually mapped to allow determination of pile-specific distances to monitoring devices. Pile driving and monitoring was completed over about 5 months. Personnel were stationed at pile driving and well sites to record times of all active pile driving and other nearby activities. Accelerometer data loggers were pre-programmed and tested to capture data in electronic files of 10-minute duration to minimize the potential for data loss.

5 FIELD OBSERVATIONS

5.1 Turbine Sites

Commonly, piles penetrated the first few metres of ground under their own weight or with nominal effort until the underlying glacial till and/or rock was encountered. Times during which pile driving was representative of “hard” driving on glacial till or bedrock were recorded based on penetration rates and hammer performance. Most piles were re-struck to confirm capacity, some piles were spliced and driven deeper through thicker till layers and 13 damaged piles were replaced. During pile driving, the grout plugs were commonly displaced up into the pile. The duration of active hammering the piles when in contact with glacial till or bedrock typically ranged from one to 10 minutes per pile.

5.2 Domestic Water Wells

Activities at the domestic well monitoring sites, well pump conditions and well operation included:

- crop harvesting, movement of farm vehicles and loading of haul trucks in close proximity to the wells;

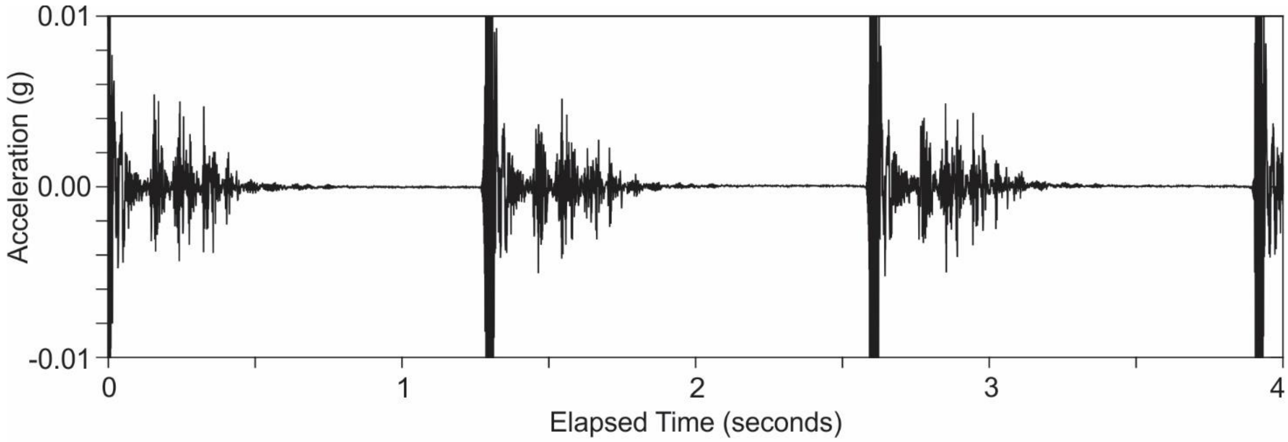

Figure 2. Responses of accelerometer (vertical direction) installed in bedrock, 11 m from pile during pile driving, illustrating four individual pile strikes and dynamic pile responses of pile steel and hammer.

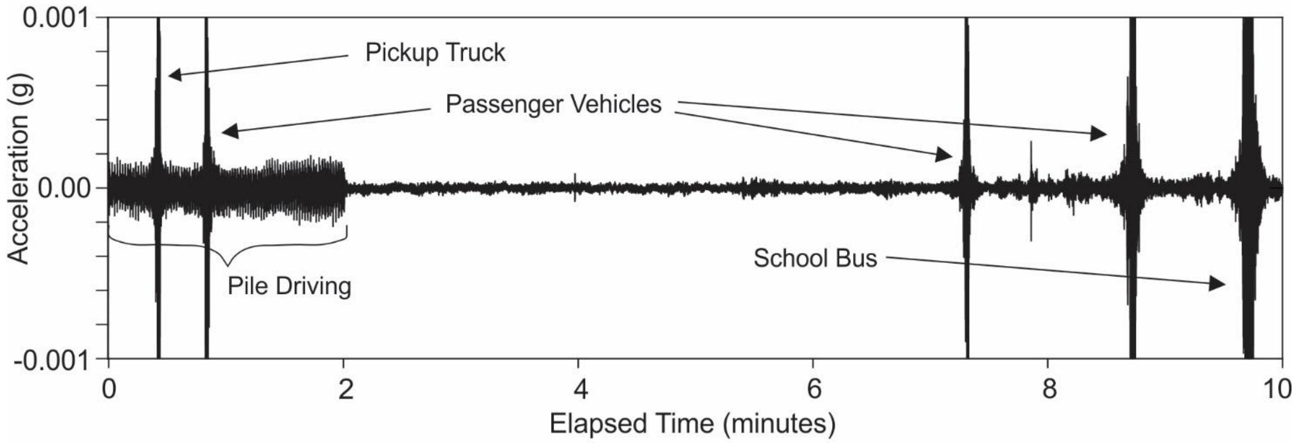

Figure 3. Responses of accelerometer (longitudinal direction) installed on well casing, 580 m from pile during pile driving, illustrating influences of pile driving and vehicles passing on road 13 m from well casing.

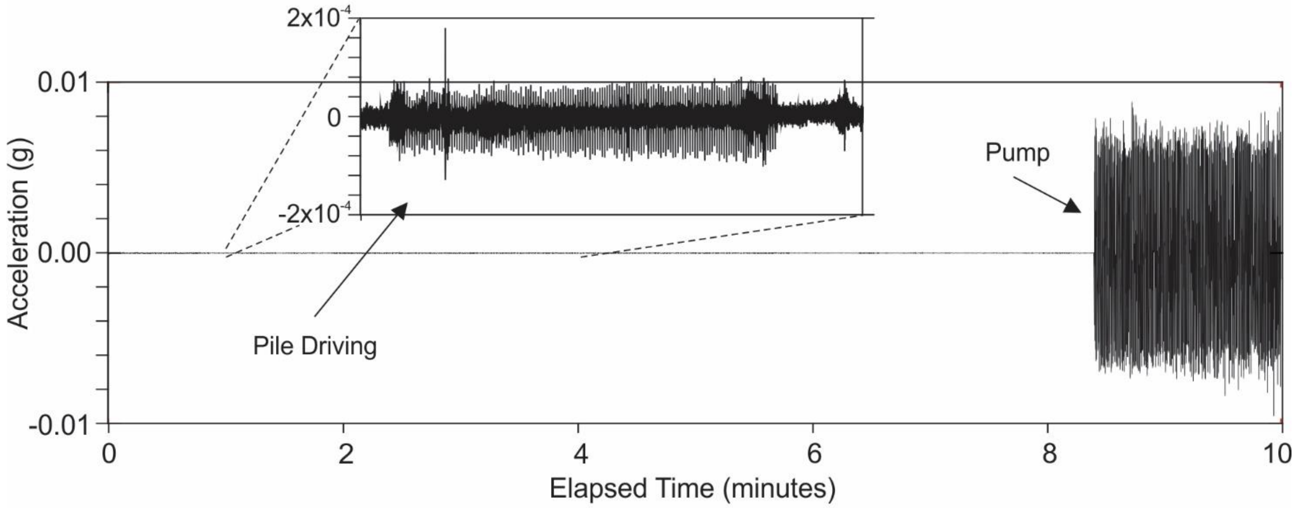

Figure 4. Responses of accelerometer (vertical direction) installed on well casing, 631 m from pile during pile driving, illustrating influences of pile driving (inset) and operating jet pump mounted approximately 1 m from casing.

- connecting and manually adjusting a well pump on a monitored casing with frequent visits into the well shed;
- passenger vehicles entering and leaving well properties;
- heavy public traffic on nearby roads;
- construction of the electric power collection system trenches and conduits; and
- construction of a new gas pipeline near several wells.

Water was commonly drawn from the wells using jet pumps, mechanical lift and piston pumps. In several cases, pumps were connected to the well casings by less than 1 m of pipe and one mechanical lift pump was mounted directly on the casing. Monitored wells were located on properties that abutted local roads. Most of the paved roads were constructed in the 1960s and 1970s using unreinforced concrete, with wooden expansion joints at approximately 18 m intervals, placed on approximately 150 mm of cement-treated base. Since then, the roads have been periodically resurfaced. Typically, the concrete pavement exhibits transverse cracks that contribute to pavement and base degradation during repeated freeze-thaw and wet-dry cycles. Reflection cracking through asphalt surfaces and ridges of crack sealing compounds produce noticeable and repeated bumps that promote traffic-induced vibrations. Gravel roads near the wells typically exhibited potholes and washboard-like surfaces.

6 DATA ANALYSIS

For regulatory review and comparison to published vibration thresholds for structure damage and human perception, data was evaluated in terms of particle velocity and frequency. Geophone vibration velocity data was processed using proprietary software (Instantell 2017) to derive full waveform and long-duration monitoring time-velocity histograms. The combination of time, velocity and pile driving location permitted evaluation of distance-dependent vibration magnitude attenuation for each turbine site. Data generated by accelerometers, however, required separate processing, especially for the instruments mounted to the domestic water wells.

Time histories for each accelerometer were compared to specific site observations such as:

- vehicles passing on nearby roads, particularly for one well within 13 m of the road centreline;
- pump operation;
- passing of farm equipment;
- personnel accessing, installing, operating and adjusting well pumps; and
- pile driving.

Accelerometer data was analyzed using MATLAB (Mathworks, 2017) with the Signal Processing Toolbox. A fast-Fourier transform (FFT) algorithm was used to convert consecutive one second acceleration data intervals from the time to frequency domain with subsequent integration to the velocity. Values for each peak within the velocity spectrum for each consecutive one second interval were chosen using the “findpeaks” function. This approach limited the potential influence of filtering algorithms and signal power suppression that might otherwise be used to address FFT spectra noise and leakage while at the same time limiting FFT artefacts that appear in the low frequency range below 5 to 10 Hz when analyzing transient vibrations. Parseval’s theorem was also used to ensure that energy in the time and frequency domains were equal. A semi-automated process was implemented whereby the 10-minute multi-channel data files were evaluated for key periods of time during which piles were being driven on glacial till and/or rock and the driving energy was at its greatest. Additional 10-minute files were also evaluated for specific events such as when well pumps operated in the absence of pile driving. Analysis of each 10-minute file produced 600 individual FFT results from which peak vibration velocities were obtained. When pile driving induced vibrations could be specifically identified within the acceleration time history, isolated durations were also examined to separate pile driving influences from other transient vibration sources.

Figures 2 to 5 illustrate example acceleration time histories from accelerometers installed in rock, close to pile driving, and others attached to domestic water well casings. These Figures illustrate vibrations generated by pile driving, pumps and vehicles passing by the wells. Ground surface vibration data summarized in Figure 6 represents peak values of vertical, longitudinal and transverse geophone measurements made at any time

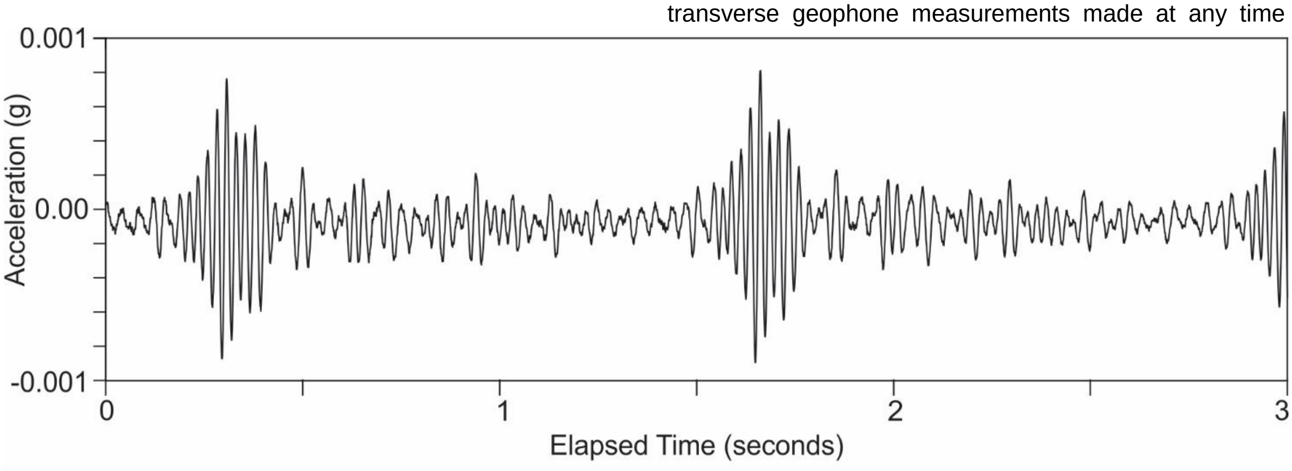

Figure 5. Responses of accelerometer (longitudinal direction) installed on well casing, 687 m from pile during pile driving, illustrating pile driving influences with time scale expanded to show 3 pile strike events.

when driving the pile on glacial till or rock. Well casing vibration monitoring summarized in Figure 6 represents the peak values of all vibration velocities measured in vertical, longitudinal and transverse directions for each analyzed data file, regardless of the vibration source.

7 DATA INTERPRETATION

Figure 6 clearly indicates patterns of vibration attenuation with increased distance from pile driving and, while the ground responses at the individual turbine sites were of different magnitudes, the patterns of attenuation were similar to those anticipated based on test pile data and the CALTRANS (2004) model. Smaller ground surface vibration responses during construction, as compared to the test pile monitoring program, were interpreted to be the combined result of piles being driven from the base of 2.7 m deep excavations that removed the surficial sand and stiff clay from the sites and allowed penetration with little resistance until the glacial till and/or rock was encountered.

Figure 7 summarizes the influence of water well pumps on well casing vibrations, where the number of measurements indicates the number of continuous periods of pump operation identified within the analyzed accelerometer data. Except for vibrations caused by individuals installing, adjusting or otherwise working on the pumps and well casings, the pumps were the largest sources of measured well casing vibrations and one or more orders of magnitude larger than those from other sources. Variability in the measurements likely reflects different pump types (e.g., mechanical lift versus jet pumps), water supply demands, pump ages, and mechanical and plumbing connections.

As illustrated by Figures 2 to 4, vibrations associated with transient traffic sources were readily identifiable, based on timed visual observations. Excluding pump influences, transient well casing vibrations from passing vehicles and farm operations were the largest source of well casing vibrations (see Figure 8). While local road conditions, vehicle sizes, axle numbers, weights and speeds likely influenced the vibration magnitudes, a trend of decreased influence of traffic as compared to distance from the road was observed and is reasonably consistent with expected ground vibration attenuation patterns.

As for the surface measurements, magnitudes of rock vibrations measured at the T42 site were less than measured during the test pile program. During the test pile program, the pile driving hammer energy was selected to be as large as possible for the equipment and there was little concern for damaging the top of the pile. The test pile was hammered for a relatively long duration at the high energy. The test pile also included a thick welded steel end cap on the pile whereas the production piles used a grout plug to reduce the ingress of soil into the pipe pile when driving. While the grout plug successfully limited the ingress of soft clay soils into the pipe, the plug frequently became dislodged and displaced upward into the pile when driving through denser soils near the top of bedrock. The net result of the plug materials and behaviour was that the energy delivered to the rock during production pile driving was less than during the test pile program.

Measured well casing vibrations induced by pile-driving were significantly smaller than those identified at the turbine site where measurements in the bedrock were made, consistent with published vibration distance attenuation characteristics, but less than those anticipated based on the test pile program and the CALTRANS (2004) model. For evaluating the energy dissipation (vibration attenuation) characteristics for this project, the approach of Gutowski and Dym (1976) and Kim and Lee (2000) was utilized where:

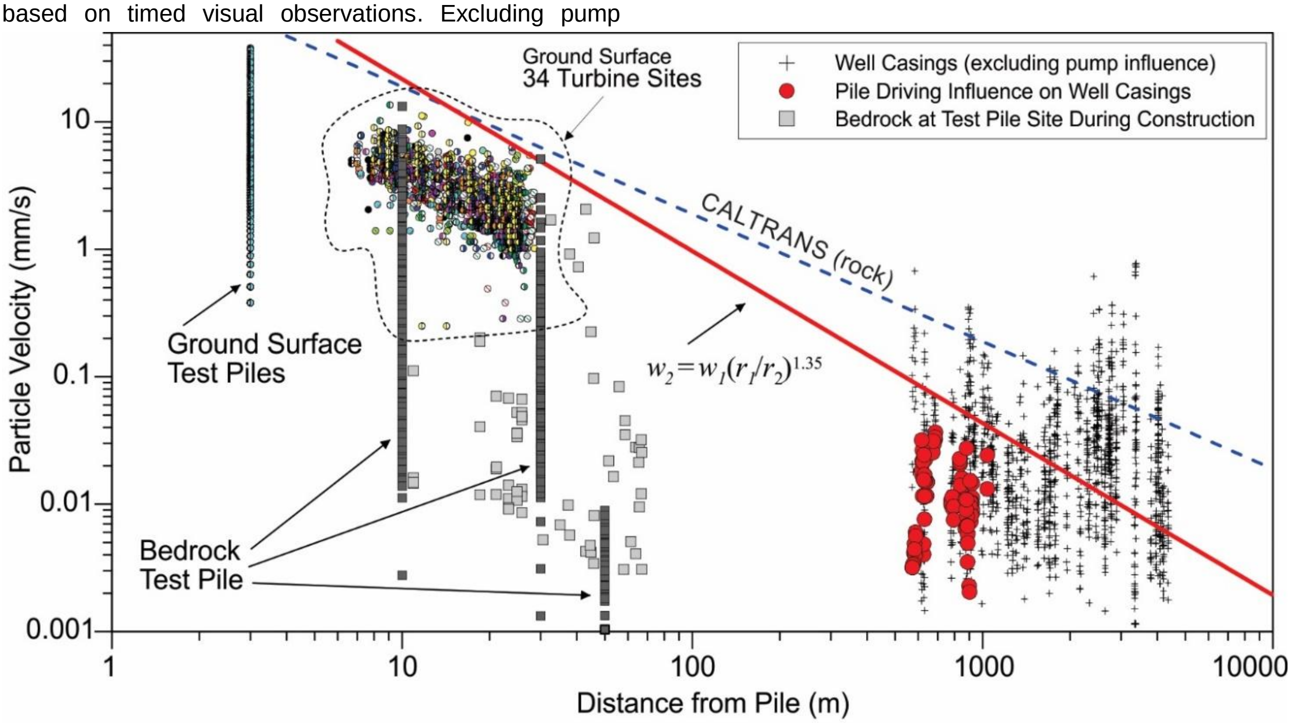

Figure 6. Measured peak particle velocities at ground surface, in bedrock and at distant well casings.

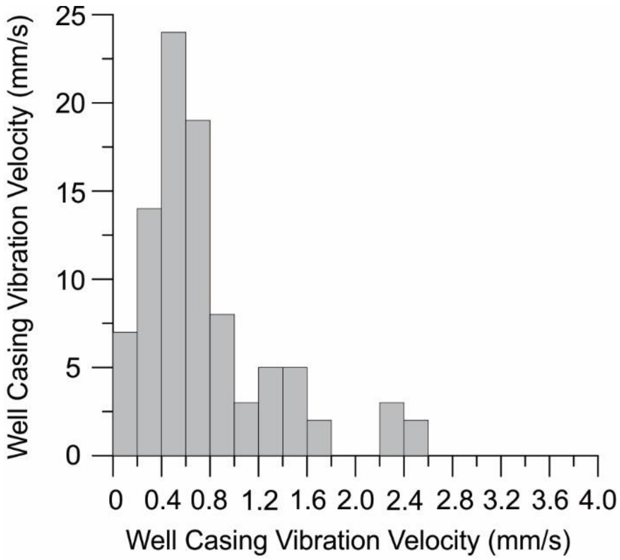

Figure 7. Maximum well casing vibrations measured while pumps were operating.

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

w_1 and w_2 are the amplitudes at distance r_1 and r_2 from the vibration source, and n and α are geometric and material damping coefficients, respectively. The value of n is related to the decrease of energy density with distance from the source, source type and form of wave propagation. In the case of a point source producing Rayleigh waves in a homogeneous isotropic elastic half-space n=1.5. Gutowski and Dym (1976) reported n values ranging from 0 to 2 associated with different vibration field cases including traffic, rail lines, pile driving, compaction and blasting. González-Hurtado et al. (2017) reported n between about 0.7 and 1.4 for ground surface vibration propagation over distances of about 300 m at an operating wind turbine facility located approximately 25 to 30 km from this project. Based on the work of González-Hurtado et al. (2017) and the monitoring data, the material damping coefficient was ignored to arrive at a reasonable and conservative method for evaluation during construction. In this case, α was considered equal to zero (no material damping) with n equal to 1.35 (see Figure 6).

Variability in the measured vibration magnitudes reflect levels of energy delivered to the rock at the pile driving site, attenuation of low-energy vibrations at the pile sites to below detectable magnitudes at wells (given the separation distances), some natural variability in ground conditions, and vibration wave form patterns as compared to the relative spatial positioning of the measuring instruments and pile tip locations. The outcome of this work demonstrated that vibration magnitudes induced by pile driving at the well locations were:

- two or more orders of magnitude less than published water well cases (e.g., Robertson et al. 1990, Rose et al. 1991, Straw and Shinko 1994, Siskind 2000);
- one or more orders of magnitude less water pump vibrations where the pumps were connected close to the well casings;
- less than vibrations induced by local road traffic;
- less than published steady-state vibrations threshold of perception;
- less than published thresholds of typical human perception of steady state vibrations; and
- comparable to or less than published values for "quiet background" conditions.

Based on the monitoring data, historical well data for the area, published research, and analytical evaluations of the effects of vibrations on water columns, suspended sediments, pore water pressures and flow rates in the wells, the vibrations were judged inconsequential for wells.

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/s^2 and 0.06 to 0.21 mm/s, respectively. A vertically-oriented accelerometer grouted into the rock about 15 m below the ground surface at one of the turbine sites (72 km from the epicenter), installed for a long-term vibration monitoring study, recorded a vertical acceleration of 5.5×10^{-3} m/s^2, consistent with expectations based on USGS data. Measured vertical earthquake-induced acceleration at the top of a steel casing, constructed to mimic the water wells, was about 2.9 times the value measured in rock just below the base of the steel casing. The maximum horizontal casing acceleration was as much as 3.9 times the vertical well casing response. These results indicated that the combination of the vertical steel casing embedded within the soft clay amplified well casing accelerations as compared to those measured in rock during the earthquake, validating the

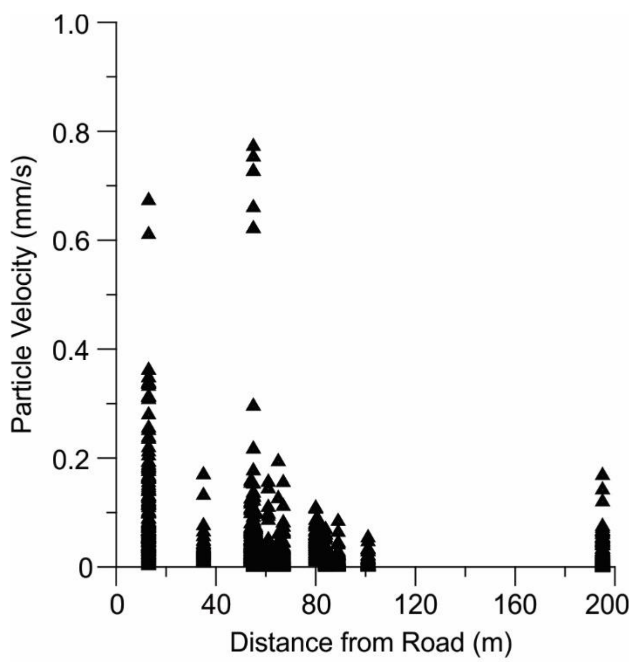

Figure 8. Maximum well casing vibrations from all sources except pumps as related to distance of well from road.

conservative methodology and results of the well casing vibrations measured during construction.

8 CHALLENGES

Given the competing requirements for installing high-sensitivity vibration monitoring equipment in small-diameter deep boreholes, the monitoring programs required adaptation of equipment not normally suited for this purpose. The long hours of outdoor monitoring conditions placed significant demands and stresses on battery-operated data logging systems. Uncertainties regarding the magnitudes and directions of propagating vibrations further prompted use of multiple instrument types in these boreholes. Upon detailed inspection and comparison of the data from these two instrument types, the peak acceleration magnitudes captured by the triaxial and uniaxial accelerometers was comparable; however, the signal-to-noise ratio for the small vibration magnitudes rendered the triaxial accelerometer data below 10 Hz to exhibit excessive artefacts when processing using FFT methods. Further, even when undertaking measurements in a largely rural area, the background seismic noise and transient vibration sources required significant labour during inspection of acceleration time history data to identify vibration sources and isolate the influences of pile-driving induced water well casing vibrations.

9 CONCLUSIONS

Vibration monitoring was completed during driving and re-striking 625 pipe piles driven for 34 wind turbine foundations. Ground surface, subsurface and well casing data were collected at distances ranging from 3 m to more than 4 km from driven piles. Pile-induced vibrations were detected for 83 piles as far away as 1,037 m. The resulting data permitted an evaluation of distance-vibration attenuation behaviour for the project. As compared to vibrations associated with well pumps, nearby road traffic, farm and passenger vehicle travel on the well sites and published acceptable vibration thresholds, vibrations at the residential well locations associated with pile driving were below reported damaging conditions in published well case histories, regulatory values for human perception of transient vibrations, below published thresholds related to residential uses and below magnitudes for other common activities at the domestic water well sites. While the data gained from the monitoring is of scientific and engineering interest related to transmission and attenuation of ground-borne vibration, the measurements supported conclusions based on earlier analytical studies that the magnitude of vibrations induced by pile driving would not adversely affect distant water wells.

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