Monitoring Ground Vibration arising from Piling and Civil Engineering Projects

By Andy Maslin of Accudata Limited
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1. Introduction

This guide is intended for use by anyone who wishes to gain a basic understanding of how to monitor and quantify ground borne vibration arising from piling and other activities caused by civil engineering works.

The author has many years' experience working in the field measuring vibration in order to prevent damage to structures during building projects.

Why is it necessary to measure ground vibration?

It goes without saying that in order to quantify a problem, or potential problem, it is first necessary to measure it.

There are basically three reasons why there may be a requirement to measure vibration during civil engineering works:

a. To ensure that levels of vibration do not cause damage to property.
b. To prevent annoyance to people by maintaining the lowest possible levels.
c. To demonstrate compliance with conditions.

It is also becoming a matter of 'Best Practice' to carry out ground vibration monitoring during construction projects as part of company quality controls.

This guide will explain, in an easy to follow and practical manner, the fundamentals of ground vibration and how to measure it in order to satisfy the above three points.

2. Units of Measurement

Ground vibration is measured in terms of Peak Particle Velocity (PPV) with units in mm/s.

It should be noted that the PPV refers to the movement within the ground of molecular particles and not surface movement. The displacement value in mm refers to the movement of particles at the surface (surface movement).

The mathematical formula being:

$PPV=2\pi fa$ where PPV is in mm/s
$\pi = 3.142$
f = frequency in (cycles per second) Hz
a = displacement in mm

The formula is true only for sine waves.

3. Instrumentation

Monitoring of ground vibration is carried out using a vibrograph, also known as a seismograph. It must be understood that this is a very different instrument to that used for measuring earthquakes. Ground vibration from civil engineering projects results in frequencies above 4Hz, whereas frequencies arising from earthquakes are around 1Hz or less.

Worldwide, there are several manufacturers of these instruments and there are various styles of vibrograph, typically:

a) Basic non-logging with built-in printer – this is the traditional older type. It has no memory and output is entirely dependent upon the printer.
b) Data logging unit – no printer, data is stored in memory for subsequent download to a computer.
c) Combined type – has memory and printer, data may be printed out but is also stored for download to a computer for post processing and archiving.
d) Virtual instrument – this is a computer with an interface for the sensors. A software program effectively turns the computer into a ground vibration monitor.

Each type has its merits depending upon the requirements of the project.
The combined unit, described in (c) above is the most versatile. If for any reason the printer fails, the data is stored, conversely if the memory storage is corrupted or fails the printer may still have produced an output.
A further advantage of this type of vibrograph is that it enables the user to see the output as it is generated by the on board printer. This gives a complainant added reassurance that the data is real and has not been altered after being downloaded to the computer.

Ground vibration monitors (vibrographs) usually detect vibration by means of transducers known as geophones. A geophone consists of a powerful permanent magnet around which there is a coil made up of very many turns of fine copper wire. The mechanism is contained in a tubular metal casing.

The cylindrical magnet is held centrally in place, within the coil, by delicate springs.

A geophone operates as follows:

The casing held in contact with the ground (fixing methods are discussed in the section entitled, methodology) moves with any ground disturbance (vibration), the magnet remains steady within the assembly. A voltage, proportional to the movement of the coil is produced. This alternating (analogue) voltage is fed along a cable to the vibrograph where it is digitised and sampled. Electronic circuitry then processes the signal to produce vibration data. Cables may be several hundreds of metres in length without loss or degradation of the signal.

Vibrographs use three geophones, two in the horizontal plane at ninety degrees to each other, and one in the vertical plane. This (orthogonal) arrangement enables vibration from three directions, lateral, transverse and vertical, to be detected simultaneously. Whilst all three geophones look the same, the vertical geophone is designed only for use in an upright position and the horizontal geophones are designed for horizontal use.

The vibrograph is able therefore to measure vibration in three axes and to compute the vector sum of the three axes (also known as the resultant). It is important to realise that British Standards refer to maximum plane readings, the highest level from any one of the three axes, and not the resultant. The resultant will always have a larger value (up to ten percent higher) than the maximum plane reading.

Note that the physical movement of the geophones coil, about the magnet, is in the order of a few millimetres (typically 4 to 6), which with most vibrographs allows for the detection of peak particle velocities up to around 200mm/s. Manufacturers instruments vary, some operate on a single scale between 0.1mm/s up to 200mm/s. Others however may have different ranges and require the appropriate range to be selected.

Vibrographs, almost always, have two modes of operation, waveform or bar-graph. These terms vary between manufacturers and may be known as: impulse or continuous, trigger or histogram (bargraph) respectively.

Waveform mode (may also be called trigger mode or impulse mode) is generally used for monitoring vibration from blasting in mines or quarries. In this mode, the instrument records only when vibration exceeds a pre-set (trigger) level. As soon as vibration reaches the pre-set level the instrument records data from each of the three axes for a short period of time (sometimes called the scan time) often user selectable between 1 and 10 seconds. At the end of this time, the unit goes back to its standby mode ready for another waveform event to be recorded. The data is processed and stored or printed out, if a printer is fitted.

Note: This mode of operation is not suited to long-term recording, as is required when measuring vibration from civil engineering work, for the following reasons:

Far too much data would result, typically one page per event.
The instruments memory would soon be filled to capacity.

Almost every vibrograph used in this mode, also allows for the measurement of air pressure using a pressure transducer (often an optional extra), usually a microphone. However, it must be borne in mind that this pressure measurement, which might very well use a decibel scale, is not acoustic noise, but a low frequency (typically 2Hz to 150Hz) peak pressure level having a linear response (i.e. no weighting filters are applied – not dB(A)).
This feature, usually only inherent in the waveform mode, is to allow for the measurement of a blast wave during explosive events such as those used in quarrying activities and must never be used to try to measure acoustic noise.

Note: Acoustic noise measurements are made between 31Hz and 20kHz with a filter ('A' weighting) to replicate the response of the human ear and use a dB(A) scale.

Bar-graph mode (may also be called continuous mode, bargraph mode or piling mode) is used for long term monitoring and is particularly useful for measuring ground vibration during civil engineering work.

In this mode, the vibrograph is constantly storing data that is presented on the printout as a histogram (bar-graph). The histogram shows peak particle velocity against time. The output shows the highest level from any axis. This way there is a continual record of the event which may be of many days duration, subject to memory constraints, paper roll (on those units that do not store information) and battery life.

Possible accessories are: Alarms, solar panels, mains adapters, car battery leads and modems.

4. British Standards

The British Standards that provide guidance for measuring ground-borne vibration are:

BS:7385 Evaluation & Measurement for Vibration in Buildings
Part 1 – Guide for Measurement of Vibrations & Their Effects on Buildings
Part 2 – Guide to Damage Levels from Ground-borne Vibration

BS:5228-2:2009+A1:2014 Code of Practice for Noise & Vibration Control on Construction and Open Sites – Part 2: Vibration

BS:6472 Evaluation of Human Exposure to Vibration in Buildings

Note: BS:7385 and BS:5228 are concerned with levels of vibration that may cause damage, whereas BS:6472 is a guide for nuisance levels. The latest revision of BS:5228, BS:5228-2:2009+A1:2014 now contains an addendum, Table 9.4: Guidance on Effects of Vibration Levels.

Vibration levels that cause damage depend upon the peak particle velocity and the frequency at which it occurs. Damage to property is likely where peak particle velocity is high when its frequency is low.

For example, due to technical difficulties there are few, if any, vibrographs that measure frequency as well as ppv in bar-graph (continuous) mode and so a worst-case situation is adopted when monitoring.

Piling using a drop hammer is considered to be of an intermittent nature. The ground vibration has settled between hammer drops. To prevent any damage levels of ppv must be kept below 15mm/s.

Piling with vibratory rigs leads to continuous ground vibration. To prevent any damage levels of ppv must be kept below 7.5mm/s.

It should be noted that the above values are used for buildings of normal construction and in a stable condition. **For historic buildings, gas pipes, oil pipelines and cast iron water mains, different criteria may apply and the above levels must not be relied upon.** Maximum levels of vibration may be specified within the plans for the particular works.

The British Standards provide full information, whereas this guide is written to help 'the man on the ground' with little prior knowledge to be able to carry out a sensible regime of monitoring and acquire accurate results whilst monitoring at the most commonly found structures.

Much of the data used to formulate monitoring standards derives from years' worth of data collected by the former United States Bureau of Mines (USBM).

The analysis of data compiled provides very accurate indicators as to levels where even the most slight on-set of cosmetic damage may result from ground-borne vibration.

5. Methodology

Ground vibration measured on a building or structure should, unless specifically stated otherwise, be measured outside the structure and at ground level.

Almost all buildings will have some cracks in plasterwork due to shrinkage, temperature changes or some other cause. In some cases it may be a sensible precaution to carry out a crack survey before the commencement of any work. This would normally be a visual check backed up by photographs showing any cracks or other deformations.

A vibrographs sensor is provided by the tri-axial geophone pack. It is crucial that this is fixed (or coupled) properly to the structure being monitored.

Methods of fixing include; bolting, gluing (using epoxy resin), spiking into the ground, sandbagging or burying.

Try to site the geophone pack on or at the structure nearest to the vibration source (the piling rig, for example).

The geophone pack must be level (within 10 degrees). There is normally an arrow on the geophone pack indicating the linear axis. It is a convention to orientate the arrow so that it points to the vibration source.

The geophone pack must never be used by placing it on its side, nor upside down due to the construction of the vertical sensor.

If a sandbag is used it must be loosely filled and placed so that its sides touch the ground around the geophone pack, whilst ensuring that the geophone pack remains level.

Never site the geophone pack on a paving slab, as this may independently move giving rise to higher readings than the adjacent structure is being subjected to.

Do not place a brick, or other heavy object, on top of the geophone pack. There is a very strong chance that it will lead to higher readings. Its centre of gravity will be raised and the object may well move independently of the geophone pack giving spurious readings.

Prevent the geophone pack from being knocked or disturbed by objects, people or animals and thus giving false readings.

6. Daily Checks

If possible, remove the paper record or download the instrument after each days monitoring session and ensure that it is safely stored or given to the relevant person. Ensure that levels have not been exceeded.

Clear the memory and check that there is sufficient paper for the next monitoring session. Ensure that the instrument is clean and dry before storing. Check the battery and charge if necessary.

7. Calibration

It is important that vibrographs are in calibration.

Vibrographs are supplied with a calibration certificate traceable to national standards. Manufacturers recommended that vibrographs are serviced and re-calibrated annually, even if they have not been used. The geophone sensors contain permanent magnets, whose magnet field strength reduces slightly year on year due to natural decay. Variations in magnetic field strength are compensated by calibration adjustments.

Annual service and calibration may also highlight other problems, some of which may be transparent to the user.

In the event of litigation, accuracy is determined by the possession of a current calibration certificate.