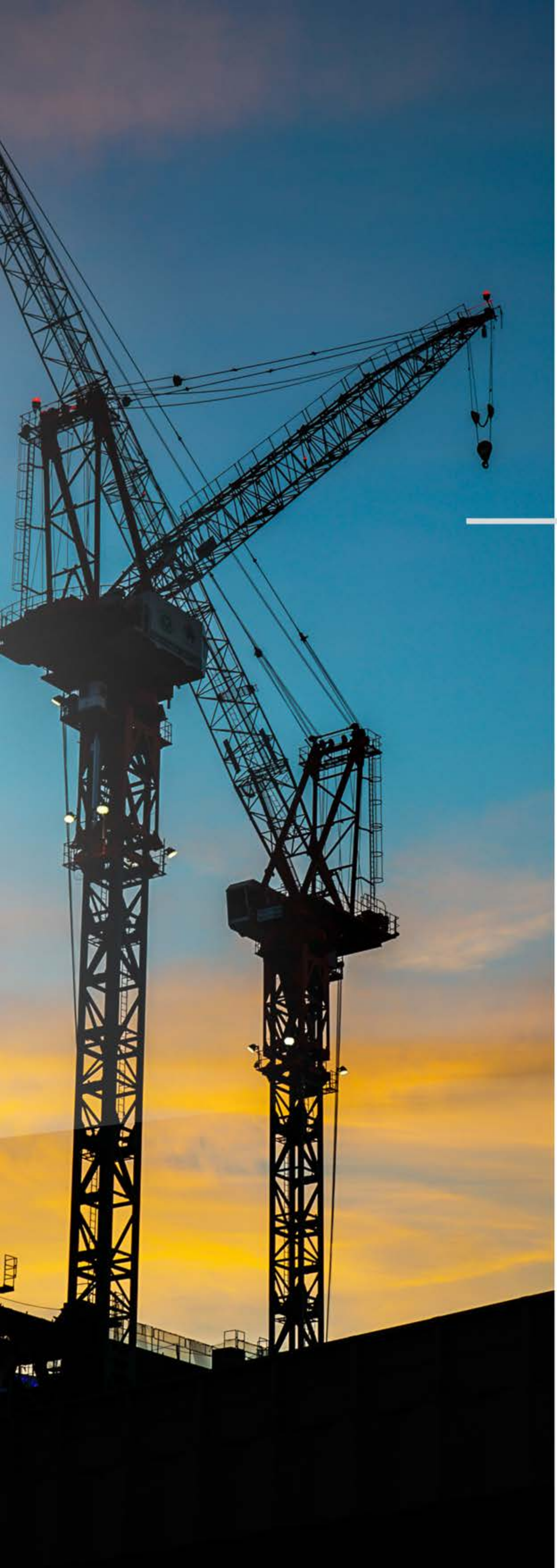

MEMS TECHNOLOGY

The Use of MEMS Accelerometers in Vibration Monitoring

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30-SECOND SUMMARY

To evaluate the suitability of a sensor, the functional requirements have to be established first. When it comes to vibration monitoring of traffic and construction activities, these requirements could be formulated as follows:

> *"The sensors must be able to measure velocities between 0.2 mm/s and 50 mm/s (or in case of accelerometers between 1 mm/s2 and 30 m/s2) over the entire frequency range of 1 to 100 Hz with an accuracy of 10 % (or 1 dB)".*

Even though both geophones and accelerometers could be used for this purpose, MEMS- ("micro-electromechanical systems") type accelerometers have definite advantages given their small size, low cost, the ability to measure static accelerations, the flat response over a large frequency range and the ability to be connected directly to the internet.

It should be noted that, while the technological advances for this type of sensors continue unabated, at this time MEMS accelerometers cannot be used to monitor more challenging IEC vibration levels (such as for extremely quiet research spaces). However this may well change at some point in the future.

INTRODUCTION

In recent years the use of sensors has progressed in leaps and bounds: whether it is the type of sensors (allowing the tracking of parameters that until recently could not be monitored, e.g., with biometric sensors), the size of the sensors (allowing them to be incorporated in more and more wearable applications) or the design of the sensors (becoming more and more sophisticated and integrated), the advances have been fast and furious.

At the same time not all these sensor developments are adopted universally. In some cases older, widely used technologies seem to remain the preferred option over more recently developed sensor types. This is certainly the case when it comes to monitoring vibrations due to traffic and construction activities, where the use of the geophone is still widespread, and the use of the so-called MEMS type sensors is often frowned upon or even completely rejected.

This paper will focus on these MEMS sensors to provide a better understanding, and hopefully a better acceptance of these sensors to monitor vibrations.

MEMS SENSORS

The acronym MEMS stands for "micro electromechanical systems" and MEMS technology allows both electronic circuits and mechanical devices to be manufactured on a silicon chip, similar to the process used for integrated circuits. The products fabricated using these techniques are composed of small moving mechanical elements that generally range from 1 to 100 micrometres (0.001 to 0.1 mm) in size. They were first developed in 1965 by Harvey Nathanson for use in microelectronic radios, but today these devices can be found in all kinds of products, ranging from video game controller, to smartphones and automobiles.

When using this technology for sensors, the sensor is composed of a suspended mass between a pair of capacitive plates, and provides the same features that you can get with any other type of sensor, such as analog voltage, current and digital output options. **The technology has revolutionized the development and market for sensors in recent years by providing fast-responding and highly reliable sensing devices that are a fraction of the size that was previously possible.**

Even the MEMS sensors themselves have become smaller as the technology developed. Initially each sensor consisted of two chips: one to house the sensing element, and another to house the signal conditioning unit. Modern MEMS sensors combine everything on a single chip. Apart from the size, the cost of this type of sensors is low, resulting in a steadily growing demand for MEMS sensors and further development to enhance their capabilities.

MEMS ACCELEROMETERS

When using MEMS sensors as accelerometers, it is important to select the right type of sensor as different sensing technologies can be applied. Two commonly used technologies are piezoresistive (PR) and variable capacitive (VC). In case of the former the sensing element consists of flexible elements (so-called flexures) on the seismic mass, which is sandwiched between the base and the lid of the sensor. The bending of the flexures results in a change in the resistance, which is directly proportional to the applied acceleration. Through gas damping the bending of the flexures is controlled to lower resonant amplification and to reduce the response in case of high frequencies. This type of sensor is well suited for monitoring high G event (e.g., blasting), but it has a lower sensitivity, and therefore is not the ideal choice for monitoring vibrations due to traffic and construction activities.

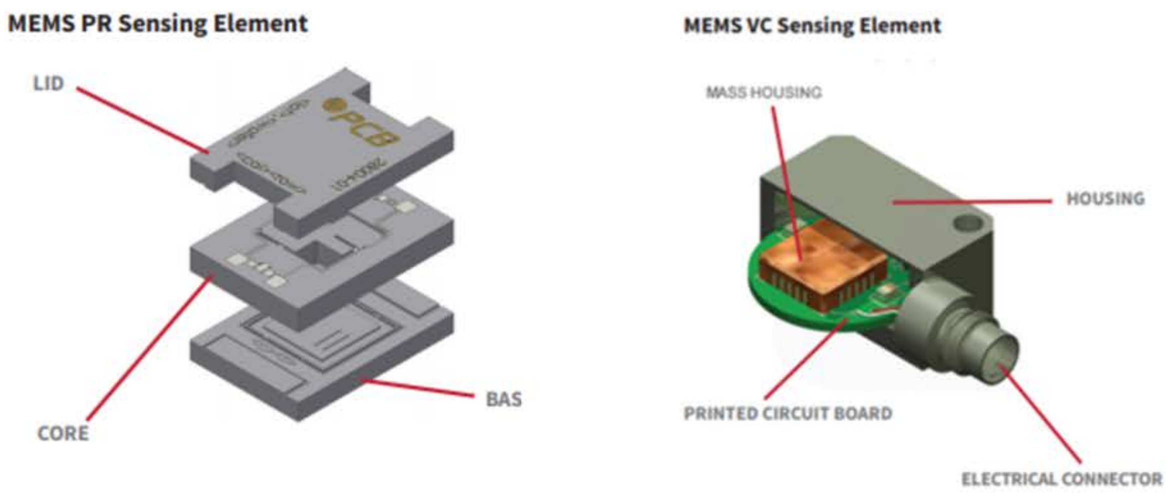

Figure 1: Schematic lay-out of MEMS Accelerometers (Courtesy of PCB Piezotronics, Inc.)

In case of a capacitive type MEMS accelerometer, a seismic mass is suspended between two parallel plates creating two air gaps. By applying an electrical charge across these gaps, capacitors are created. The applied acceleration then causes movement of the seismic mass. This movement causes a change in the air gap thickness, and thus a change in capacitance, which is directly proportional to the applied acceleration. While the range of accelerations that can be covered for VC type sensor is much smaller than that for a PR type sensor, a VC sensor has a much higher sensitivity, making it the preferred choice for monitoring vibrations due to traffic and construction activities. It should be noted that both types of MEMS accelerometers can be DC coupled, which allows them to measure down to 0 Hz (something that is impossible with geophones). In addition DC coupled accelerometers will not have an intrinsic decay function, which eliminates any error during numeric integration of the measurements.

FUNCTIONAL REQUIREMENTS VIBRATION MONITORING SENSORS

Prior to selecting the sensor to be used for vibration monitoring, it is essential that the functional requirements for such a sensor are determined. As there is no national standard in the United States for the monitoring of vibrations due to traffic and construction activities and to avoid subjectivity, the requirements included in various European standards were reviewed. The Dutch standard SBR Part A includes a typical set of requirements, which can be summarized as follows:

> *The sensors must be able to measure velocities between 0.2 mm/s and 50 mm/s (or in case of accelerometers between 1 mm/s2 and 30 m/s2) over the entire frequency range of 1 to 100 Hz*

To put these values in perspective, velocities of 0.2 mm/s are generally considered the threshold for human perception of vibrations. Vibrations at these velocity levels are unlikely to cause damage (incl. architectural damage) to buildings of any kind, and even velocities that are 10 times higher are still safe for ruins and ancient monuments (see Table 1). The accelerations values mentioned above are the equivalent of 0.1 mg and 3.1 g

Table 1: Schematic lay-out of MEMS Accelerometers (Courtesy of PCB Piezotronics, Inc.)

Vibration Level (Peak Particle Velocity)*			
mm/s	**in/sec**	**Human Reaction**	**Effect on Buildings**
0.15 - 0.30	0.006 - 0.019	Threshold of perception; possibility of intrusion	Vibrations unlikely to cause damage of any type
2.0	0.08	Vibrations readily perceptible	Recommended upper level of the vibration to which ruins and ancient monuments should be subjected
2.5	0.10	Levels at which continuous vibrations begin to annoy people	Virtually no risk of "architectural" damage to normal buildings
5.0	0.20	Vibrations annoying to people in buildings (this agrees with the levels extablished for people standing on bridges and subjected to relative short periods of vibrations)	Threshold at which there is a risk of "architectural" damage to normal dwelling - houses with plastered walls and ceilings Special types of finish such as lining of the walls, flexible ceiling treatment, etc., would minimize "architectural" damage
10 - 15	0.4 - 0.6	Vibrations considered unpleasant by people subjected to continuous vibrations and unacceptable to some people walking on bridges	Vibrations at a greater level than normally expected from traffic, but would cause "architectural" damage and possibly minor structural damage.

Source: Whiffen and Leonard 1971

The Dutch standard also requires that over the entire frequency range the sensor has an accuracy of 10 % (which is equates to 1 dB). As long as these requirements are met, the sensor is suitable for vibration monitoring. This means that the standard does not mandate a particular type of sensor, but simply defines the parameters a sensor must meet (as is stated explicitly in the commentary).

For comparison purposes, the generic vibration criterion curves for vibration sensitive equipment as standardized by the Institute of Environmental Sciences and Technology (IECF) are shown in Figure 2, together with the International Standards Organization (ISO) guidelines for the effects of vibration on people in buildings.

From this figure it shall be clear that monitoring for vibration levels defined by IECF are much more challenging than that for vibrations due to traffic and construction activities.

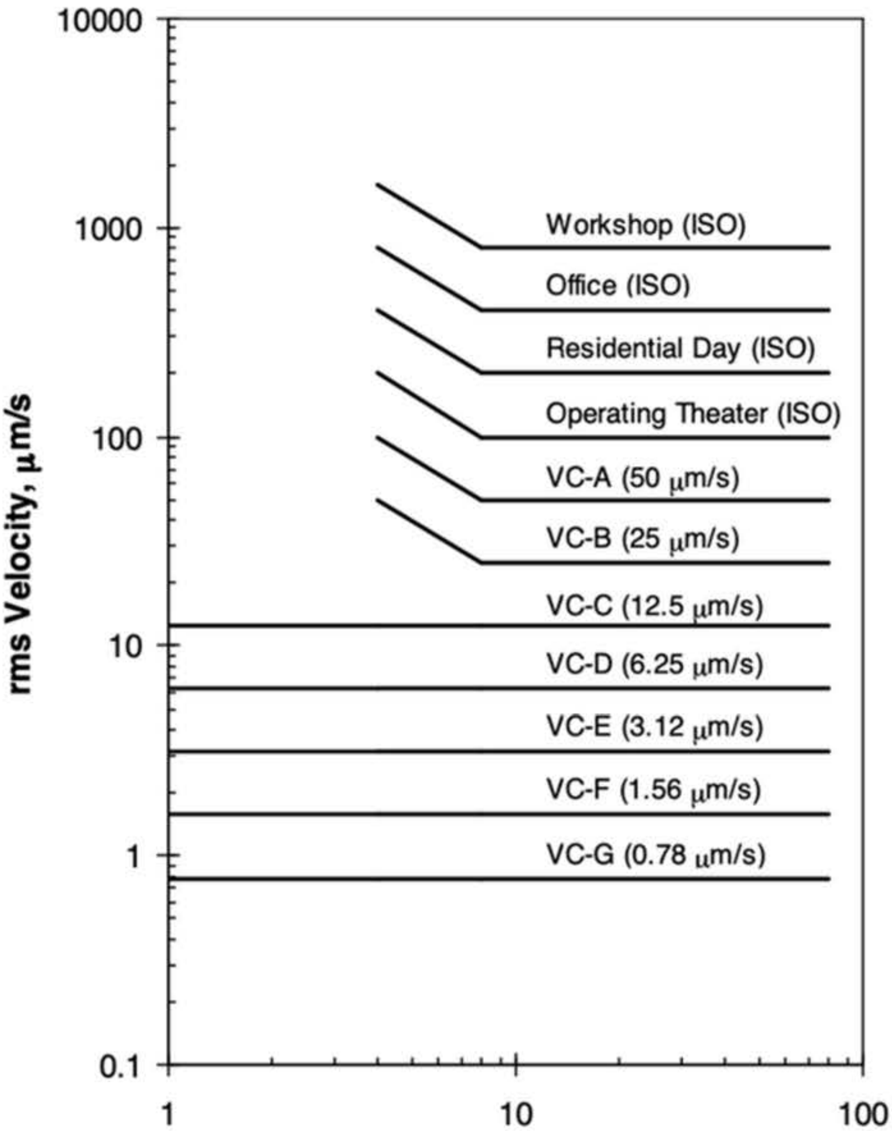

Figure 2: Vibration criterion curves for vibration sensitive equipment as standardized by the Institute of Environmental Sciences and Technology

ACCELEROMETERS VS. GEOPHONES AS THE VIBRATION MONITORING SENSOR

Even though the various standards do not specify a specific sensor type, geophones are commonly used to monitor vibrations due to traffic and construction activities. While this selection is purely subjective, quite often it is attempted to justify this selection by claiming that accelerometers cannot be used. In case of MEMS accelerometers such claims are based on "common wisdom", which holds that at high frequencies MEMS sensors register very high vibration levels compared to a geophone and that at low vibration levels the precision simply does not match that of geophones. For those reasons it is argued that MEMS accelerometers cannot be used for vibration monitoring.

While this "common wisdom" may have been true in the past, after all the MEMS technology has made great progress since it was first introduced some 55 years ago, there is no evidence that it is true today.

To demonstrate this Van Delft and Ostendorf reported in a special issue on foundations of the Dutch Geotechniek magazine in 2018 the outcome of a comparison of different types of vibration monitoring equipment, using both geophones and MEMS accelerometers. The equipment was exposed to vibrations due to two common construction activities: pile driving with an impact hammer (resulting in short periods of vibrations) and vibratory driving of sheet piles (resulting in continuous vibrations). It was concluded that in both cases the measured vibration levels and the derived dominant frequencies (approx. 10 Hz in case of impact driving and approx. 30 Hz in case of vibratory driving) were basically the same.

It should be noted that the authors did note that the dominant frequency did depend on the analysis method (in this case the Fourier analysis for the equipment using the geophones and the zero crossing analysis for the equipment with the MEMS sensor) and therefore the equipment reported slightly different dominant frequencies.

The authors also covered their views on the current trend in vibration monitoring. They mentioned that the sensors will get smaller, the number of sensors will increase (to provide more detailed monitoring) and that the sensors will be connected directly to the internet to enhance the availability and analysis of the generated data. Obviously MEMS accelerometers with a digital output will allow this more easily than the traditional geophone, and therefore the authors concluded that in time geophones will be replaced by MEMS accelerometers.

Apart from the arguments covered in the article, there are two other aspects that need to be considered as part of the sensor selection process. First,there is no perfect sensor type that is suitable for every situation. It is important that limitations are recognized, and that includes the fact that for vibration monitoring below the VC-A level shown in Figure 2 MEMS accelerometers cannot be used: with the current technology they are simply not sensitive enough. That does not mean, however, that they cannot (or should not) be used for vibration monitoring at all. For monitoring vibrations due to traffic and construction activities this type of accelerometers is perfectly suitable. Secondly, the sensor selection should take into account the required operating envelope and the sensor behavior should meet (all or most of) the requirements associated with that operating envelope. This is especially relevant when considering certain aspects of a sensor type that are often addressed in general terms. One good example of this is the frequency response issue.

As illustrated in Figure 3 this response is very different for a typical geophone and a typical accelerometer. Obviously, any sensor used for vibration monitoring must have sufficient bandwidth (i.e., a maximally flat frequency response curve where there is no more than 10 % or 1 dB variation) for the frequency range within the desired or specified operating envelope. This could preclude the use of certain geophones as the variation especially at low frequencies may be excessive. Another example is the issue of the Vibration Rectification Error (VRE) of MEMS accelerometers, which is caused by various resonances and filters within the accelerometer. The obvious approach to address this is the careful selection of a sensor where this phenomenon is not an issue for the frequency range within the operating envelope. The fact that VRE would be an issue at higher frequencies is then simply no longer relevant.

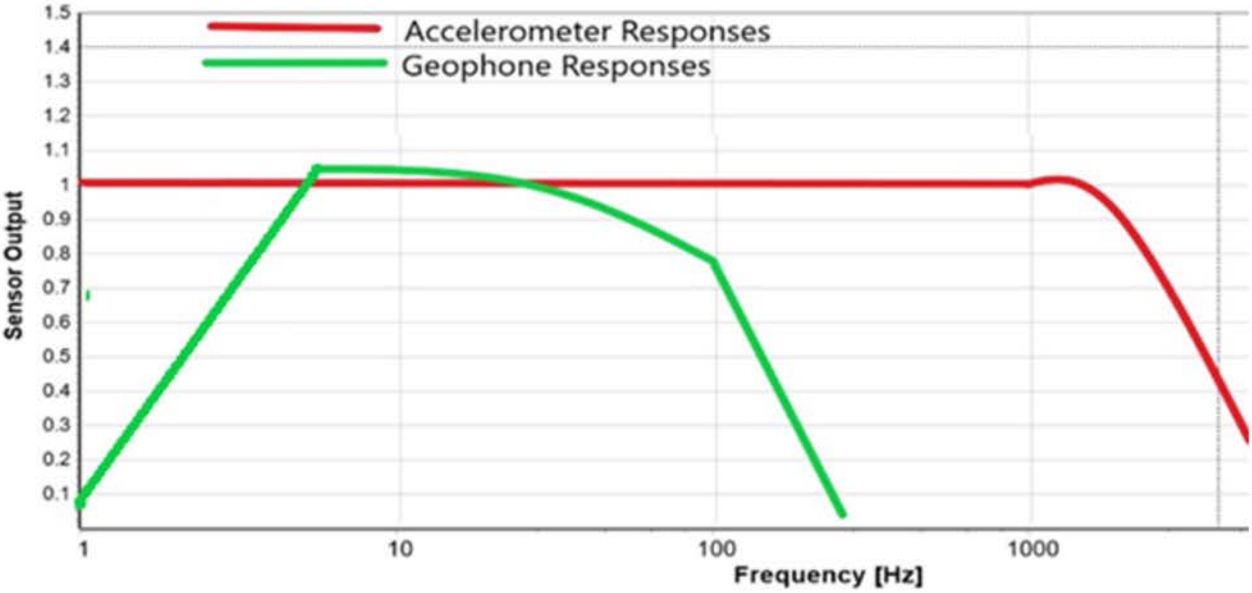

Figure 3: Indicative frequency response seismic sensors

CONCLUSION

The purpose of this paper is not to make a convincing argument that only MEMS accelerometers are suitable for monitoring vibrations due to traffic and construction activities, nor is it to claim that MEMS accelerometers can be used for all vibration monitoring activities. Instead the main objective is to highlight that the most important step in any vibration monitoring program is to define the functional specifications for the sensor(s) to be used and then to ensure that the selected sensor meets these specifications.

Using a typical functional specification for sensors used for monitoring vibrations due to traffic and construction activities, there is no doubt that there are MEMS accelerometers that are suitable for this application. Similarly there is no doubt that MEMS accelerometers cannot be used to monitor the more challenging IECF vibration levels, but as the technology advances further sensors for those applications may well become available at some point in the (near) future.

Gerald Verbeek received his BSc in Civil Engineering from Delft University of Technology in 1981 and his MSc in Structural Engineering from the same university in 1983. After spending about 20 years in the Oil and Gas industry, Verbeek started a management consulting business, Verbeek Management Services (VMS), in 2004. One of the activities of his firm is helping European companies with their business in North America, and as part of that he has been active in promoting soil and foundation testing philosophies and equipment. In the area of foundation testing this is done through Allnamics USA, which provides a wide range of foundation testing equipment and services (incl. vibration monitoring). Verbeek is active in various organizations, such as DFI (where he previously served as the chair of the Testing & Evaluation Committee), TRB (as a member of AKG70, the standing committee on foundations of bridges and other structures), PDCA (where he serves on the Technical and the Education Committee) and ASTM (where he is a member of D18, the committee on soil and rock and the chair of D18.01, the committee for surface and subsurface characterization).