Automated Vibration Monitoring for Construction Applications

A Retrospective and Current Practice or… Everything Is so Much Easier Now!

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My career in vibration monitoring (VM) began in the late 1980s. At that time, the state of the practice was primarily focused on blasting operations, which was driven by a boom in highway construction and quarrying. VM projects other than those related to blasting were unusual. Today, however, vibration monitoring can be found on most civil construction projects and is not just for blasting anymore.

Recent Trends/History

Impact of RI 8507

Damage complaints from construction and mining operations increased during the construction boom. However, a lack of research on the effects of vibration on structures meant there were no definitive vibration standards to follow. In this context, the U.S. Bureau of Mines (USBM) was tasked with assessing the damage and nuisance potential from surface blasting. The result was the Report of Information, *USBM RI 8507, Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting,* published in 1980.

Prior to this report, the principal criterion in VM had been Peak Particle Velocity (PPV). PPV is the speed of the subject particle in oscillation during a passing vibration wave. Furthering the state of practice, *RI 8507* introduced the equally important variable of the frequencies in the vibration wave and established the framework for modern VM with the so-called Siskind Curve (Figure 1), named for the lead author of the report. The Siskind Curve is also known as the *RI 8507* compliance curve.

The *RI 8507* compliance curve is still very much in use today for determining safe vibration levels, not only related to blasting, but also in almost all other areas of engineering and construction that involve vibration risk. Unfortunately, no further large-scale research has been undertaken since the 1980s, and the USBM was disbanded in 1995.

Geophones

As the concepts in *RI 8507* were introduced into state and local regulations, commercial vibration monitors had to evolve from simply recording PPV to capturing full waveforms and rendering the frequency values for easy use in the field. This was not as easy as it may sound for today's digital age.

How did analog devices record full-vibration waveforms in the pre-microprocessor age? Then, as now, VM employed two major components: a geophone, which converts the vibration waveform into an electrical signal, and a recording device to capture the output of the geophone for further analysis.

The geophone is a simple harmonic oscillator. Geophone design used on VM has not changed much since its introduction. The current standard is the moving coil type, consisting of a coil of fine copper wire that is free to move around a fixed

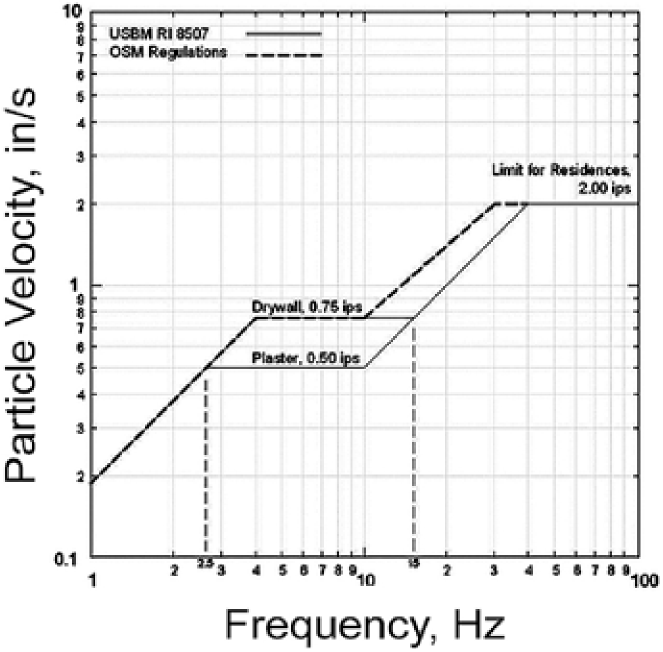

Figure 1. **The *RI 8507* compliance curve, also known as the Siskind Curve.**

magnet. As the coil moves relative to the magnet, a voltage is generated. This voltage is used to describe the waveform.

Vibration monitors typically use a triaxial geophone (Figure 2) packaged orthogonally in a weatherproof housing. Geophones need to be level and oriented correctly in order for the coil to be free to move in its range, and to describe the waveform correctly.

MEMS Sensors

A new development in geophone technology is called the Micro-Electro-Mechanical System, or MEMS sensor. MEMS sensors are becoming more common as quality improves and cost is reduced. MEMS accelerometers are used for countless applications, from smart phones to automobiles, to aerospace, and now, even to geotechnical sensors. MEMS-based geophones have some advantages over traditional geophones. They offer better frequency response, and some commercial designs provide a virtual self-leveling option, eliminating a field variable that often causes issues when least expected.

Recording Devices

The devices used to capture the output of the geophone have also evolved. The direct-writing oscillograph (DWO) was first patented in 1929 (Figure 3). The DWO's principle of operation, adapted for use with a geophone, was complicated, but very clever and provided very good results. The geophone would generate output to the DWO, controlling a light source that would shine to photosensitive paper moving at controlled speed. The result was a waveform captured on the photosensitive paper. Despite the fact that the paper needed to be kept out of the sun and had a limited storage life, this methodology was very good at rendering a useful waveform in the field.

Field use of the DWO was a great way to introduce the concepts required in basic VM waveform analysis. To render results, the user had to scale the waveform peaks to determine PPV, and count the zero crossings to determine frequency, directly off the trace recorded on the photosensitive paper. Once you've done several of those by hand, you get very good at it!

Versions of DWO were used until the late 1980s, when they were replaced by magnetic tape, thermal printers, pen plotters, and, later, cheap solid-state chip storage. The technology introduced in the late 80s advanced the art, but was not always convenient. Analog circuits were, by necessity, large and power hungry, requiring massive batteries that (fingers crossed!) would work for one full day in the field. Once a processed waveform was stored on solid-state memory (if it would fit), or on magnetic tape, it could be printed to thermal tape, or uploaded to be further processed via another major development of the 80s — the personal computer. Although PC processing was not nearly as labor intensive (or error-prone) as manual reduction of waveforms, the systems of the 80s still required a lot of work.

VM systems with integrated field plotters rendered a very good summary of the event and a nice waveform trace, but were ill-suited to field use and always required attention. State fire marshals on blasting operations liked them because they provided an immediate record of the event in the field. Many are still in use, but it's the exception rather than the rule today.

These were great first steps, but left much room for improvement. Compare the state-of-the-art engineering seismograph with today's typical system in Figure 4 (picture of the S3 next to the MicroMate).

Miniaturization

One trend in VM has followed that of other electronics: miniaturization. Riding the digital wave, VM manufacturers have been able to reduce the size and power draw of today's systems to a fraction of those in the 80s. Think ENIAC vs. a MacBook Air. Not only do the new systems have ample storage for weeks of monitoring, but they also have the battery capacity to do it.

It's interesting to note that on many applications today, users are taking small VM systems and packaging them inside larger enclosures to be able to protect them in the field, provide a platform for solar power collection and storage, and to house other instruments.

Automation

The most recent trend in VM is automation. In this context, automation refers not to autonomous operation of the vibration monitor itself, but to automate complete tasks that would otherwise require a technician. For example, a manual system requires a technician to visit the vibration monitor to offload recorded data, but an automated system automatically transmits data offsite at scheduled intervals or whenever an exceedance event occurs. A manual system would require processing the retrieved data on a PC; an automated system would process the data, transmit alerts by SMS or email, and generate reports night and day with no human involvement. Automation has provided a significant boost in efficiency, reduced costs, and monitoring opportunities.

However, automated systems are not fully evolved yet. There is some latency in the system — a delay of minutes between detection of an exceedance event and reporting that event on smartphones. Real-time reporting is not so far off. Consider that earthquake warning systems in Japan can provide 15 to 30 seconds of warning before damaging shockwaves arrive. It's a different system to be sure, but an example of what could be done.

Applications

Modern VM systems are used for many applications. The most common application is compliance monitoring, verifying that the monitored source is staying within prescribed limits. Common vibration-producing activities include pile driving, ground-improvement operations, blasting, demolition, building implosions, roller compaction, and dynamic compaction. Modern VM systems are also used in structural studies, to identify dominant frequencies, isolate nuisance vibrations, or to determine whether a location is suitable for vibration-sensitive medical or manufacturing equipment.

Many VM applications are driven by proximity to sensitive utilities, structures, or operations in the proximity of planned work. Vibration monitoring is useful through all phases of a construction project, from the time a project site is selected, though demolition, and then during construction. VM can help builders avoid litigation and needless schedule slippage, while providing a safe project environment.

Central Place residential tower in Rosslyn, VA, is one example of an urban monitoring application that made effective use of VM. The site for this project rests on top of the WMATA Metrorail station at Rosslyn. The work required demolition of existing structures and blasting for new elevators in close proximity to the existing WMATA tunnels.

Monitoring included fixed VM in the tunnels (Figure 5), at the surface, and at sensitive structures. Strain gages were installed on the existing tunnels to measure the actual structural effects of the blasting and excavation. Inclinometers and extensometers were used at the surface to monitor the support of excavation. All VMs, strain gages, inclinometers, and extensometers were connected in near real-time to a cloud-based server to provide automated report processing.

The project-specific website was established and populated with plan-view overlays and context-relevant data display,

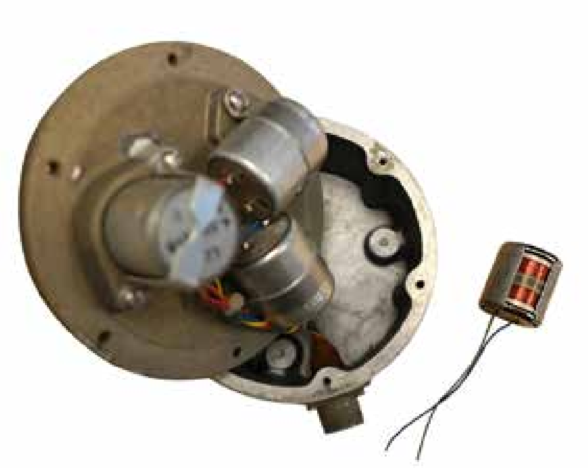

Figure 2. The triaxial geophone is actually three sensors.

Figure 3. Direct-writing oscillograph. (Photo source: Google.)

Figure 4. Example of device miniaturization.

Figure 5. **Automated vibration monitoring of Metro tunnel while construction occurs nearby.**

to easily orient users' viewing results. The automated system efficiently provided real-time reports of exceedance events to a diverse group of stakeholders via SMS and email alerts. The web-based system eliminated tedious report compilations, provided an easy collaboration vehicle, and archived all data for later access, if necessary.

The project team used the data to optimize blast design, minimizing potential vibration damage to tunnel structures. After each blast event, the recorded vibration, strain, and displacement results were reviewed to modify the excavation plan, powder factor, and hole spacing. This critical feedback was essential to an efficient system to assist the contactor and engineers in minimizing impacts on the structure and other risks.

Best Practices

Although VM has become very common, it is surprising how many users cannot obtain good measurements. Successful monitoring is not difficult if users follow these basic steps:

1. Consider what's being monitored. What's at risk? What question must be answered?
2. Read the operator's manual.
3. Check that the systems are calibrated according to the manufacturer's guidelines.
4. Always ensure that the geophone is leveled and firmly connected to the subject material. Bolt the geophone to the structure, bury the geophone, bond the geophone to the structure with plaster of paris, or prevent lateral and vertical movement of the geophone with carefully placed sandbags.
5. Orient the geophone toward the expected source. Document this orientation for later analysis of the waveform.
6. Protect the geophone from being disturbed.
7. Check that the unit has a reliable source of power or a fully charged battery.
8. Test remote connections and system functions before leaving the site.

Remember that monitoring is important. It may affect public safety or provide information necessary for important decisions that may affect project schedules and costs, or in the worst case, become evidence in the event of litigation.

Into the Future

Now, 30 years later into my career, nearly all construction projects in urban environments have some form of VM. The instruments and automation that are available today were just science fiction when I first began. Today's VM technology goes far beyond the scope of *RI 8507*, and it is clear to me that our current compliance standards are becoming obsolete. The advancement of measurement technology has been truly amazing and will no doubt continue to evolve.

If real-time, latency free, remote monitoring is not far from being a reality, can we also visualize realistic damage criteria for all types of works? Why are we still using research intended to understand the effects on wood frame structures to project masonry or concrete structures? Today, we need more solid research, of the type inspired by the USBM in the 70s and 80s, to provide more comprehensive models for commonly found construction in urban environments. I wonder who will come up with the next "Siskind Curve(s)" and where the state of the practice will be in the next 30 years?

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