Abstract

The first seismograph was developed around 132 AD. Much has happened since then. The “modern” seismograph (> 1920) has seen a lot of changes. From falling pin seismographs to magnetic tape units to today’s Z-curve analysis models, the blasting seismograph remains a necessary and useful tool to the blasting community.

But why so many changes? What forces drive the advancement of the seismograph? There are many answers and aspects to this question. Research, regulation, and technological advances are the primary forces behind innovation in our industry. But these three forces also drive each other.

Research drove our industry from displacement seismographs to particle velocity seismographs. Technology took us from 80 pound seismographs to units weighing less than 5 pounds. Regulation (and litigation) - the driving forces behind the Z-curve analysis units.

How have these innovations helped today’s blaster? Have there been any negatives? It is important for today’s blaster to understand how we got here and why.

The Beginning

One of the earliest recorded uses of the seismograph occurred during the Han Dynasty. An astronomer invented the device because of the large number of earthquakes in China during this time. The seismograph’s purpose was to determine the direction in which an earthquake occurred so that relief items could be sent to the stricken area.

Early History

Over the next 2000 years or so, the seismograph underwent a number of changes. However, these seismographs were designed for earthquake study. These seismographs were typically installed at monitoring stations. Size and portability were not issues. It wasn’t until the 1920’s that seismographs designed specifically for blast monitoring began to be developed.

The falling pin seismograph was designed in 1927 by Edward Rockwell of Rutgers University. This portable seismograph was designed on the principle that more kinetic energy is required to knock over a shorter pin than a taller pin. The seismograph consisted of a number of ¼ inch diameter steel pins of varying height (2 – 15 inches) with a flat bottom. The following equation was developed to calculate the amount of kinetic energy required to knock over a pin in terms of inches/sec.

\[ v = 13.9 * \frac{d}{\sqrt{h}} \text{ in/sec} \]
where:

\[ v = \text{velocity}, \]
\[ d = \text{the diameter of the pin}, \]
\[ h = \text{the height of the pin}. \]

Using this equation, a 1-inch per second velocity would be required to knock over a pin that was 12 inches high and ¼ inch in diameter. A 2-in/sec velocity would be needed to knock over a 3 inch by ¼ inch pin.

The Analog Seismograph

Advances in electronics led to the analog seismograph in the 1940’s. One of the first analog seismographs was the Leet seismograph developed by Dr. L. Don Leet of Harvard University and shown at left. This seismograph utilized a three-component geophone. A compartment held a roll of light sensitive paper. A needle for each channel vibrated from movement causing voltage changes. A mirror attached to a shaft connected to the needle reflected a bright light back to light sensitive paper. This created a displacement waveform on the advancing paper. A notable use of the Leet seismograph was during the first atomic test blast, Alamogordo, New Mexico, 1945.

There were several disadvantages to the Leet seismograph. It was not self triggering. Coordination between the blaster and the seismograph operator was essential. If the seismograph was turned on too soon, the paper supply would be exhausted prior to the blast. The light sensitive paper was the only physical record of the vibration history. Too much exposure to light and the waveform would literally disappear. The geophone was internal. This portable unit weighed about 65 pounds.

Another early blasting seismograph was manufactured by the W. F. Sprengnether Instrument Company. This was also a displacement seismograph. It was a non-electric unit that utilized weights to produce a waveform trace.

Figure 2 – Leet Seismograph

Displacement seismographs were the simplest type of seismograph to design. Regulations in the 1940’s and 50’s were minimal at best. Most of the blasting at that time occurred in quarries, mines, or for large construction projects. These activities were typically far away from housing developments. Research regarding vibration damage potential was in its infancy.

In order to calculate velocity from a displacement waveform, a seismologist would need to determine the maximum slope of the peak. Once determining the peak with the steepest slope, the height of the peak would be measured (?d) in inches. This quantity would then be divided by the length of time...
between the occurrence of the peak and the nearest zero-crossing (\( \tau \)) in seconds. This was a very cumbersome task. In order to obtain the maximum particle velocity, the steepest peak of the waveform had to be determined. This was not necessarily the highest peak. Oftentimes many peaks had to be measured to determine the maximum reading.

USBM Bulletin 442 issued in 1942 used a vibration criterion based on acceleration. My research has not produced any information on acceleration-based seismographs.

The US Bureau of Mines issued Report of Investigations 5968, *Review of Criteria for Estimating Damage to Residences from Blasting Vibrations* in 1962. As the name suggests, this report reviewed research by the Bureau and other researchers. It “suggested” that particle velocity be considered rather than displacement or acceleration. USBM Bulletin 656, *Blasting Vibrations and Their Effects on Structures*, was issued in 1971. This report concluded that “damage to residential structures from ground vibrations from blasting correlates more closely with particle velocity than with acceleration or displacement.”

Sprengnether manufactured the first particle velocity seismograph in the 1960’s. It was marketed as the SSU I. It weighed approximately 35 pounds or 30 pounds less than the Leet seismograph. The SSU I had a three-channel geophone and a microphone for recording air overpressure.

Like the Leet seismograph it used photo-sensitive film to record the waveform traces and did not have a trigger mechanism. It was common for the seismograph operator and the blaster to meet before the shot and “set the watches.” Each would have a stopwatch and they would start the watches simultaneously. It would be determined that the shot would go off in exactly \( x \) number of minutes. The seismograph operator would hop in his car, drive to the recording site, set up the seismograph, and a few seconds before the shot time, turn on the unit. If all went well, the shot would go off before the seismograph ran out of film. A DC milliamp meter would display the highest reading for each channel. These monitor readings would be converted to particle velocity. In order to get the “official” readings, the seismograph operator would develop the film, get out his magnifying glass, straight edge, and ruler, and “read” the record.

Later in the 1960’s, Spengnether developed the SSU II. The significant advancement of the SSU II was the replacement of the DC milliamp meter with an LED readout that provided monitor readings in inches per second. The SSU II was also housed in a metal attaché-type case, making it much easier to transport.

Figure 3 - SSU II
After Bulletin 656 was issued, many states began developing regulations based on particle velocity. Soon cassette-based seismographs began to appear. These seismographs recorded the waveform data onto cassette tapes. These tapes were run through reproducing equipment that transferred the waveform onto photo-sensitive paper. The record was then read by hand. Although the photo-sensitive paper could still fade over time, the waveform could be reproduced using the original cassette tape. Cassette tapes also ran for 30 minutes. This was considerably longer than the film in the Sprengnether seismographs.

Dallas Instruments developed several models. Early models were not self-triggering. They were also not auto-ranging. The seismograph operator would have to estimate the amplitude of the particle velocity and set the range to the appropriate level. If the range were set too low, the tops of the waveform peaks would be cut off. If the range were set too high, the waveform would be so compressed that it would be nearly impossible to read the record. A single meter provided particle velocity readings in inches per second, as well as air overpressure readings in decibels.

ETI also manufactured a tape machine. Marketed as the Vibra-Tape, the seismograph was housed in a large yellow box. It had dual meters to provide both particle velocity and air overpressure readings.

Cassette tape machines also provided operators with the ability to add blast information verbally onto the tape. Prior to the shot - “This is Jim Smith for ABC Stone Company. The date is July 9, 1979. I am set up at the Miller residence, 1433 Quarry Road. Skies are clear; the temperature is 84 degrees. Judy Miller is my witness. I am calibrating the unit now . . . . Shot 3 to follow.” Following the shot – “Time of the shot was 1:32 PM. Peak particle velocity was 0.83 inch per second, airblast was 114 decibels.” This information was important because it was the only way to document this information on the tape. While meters provided particle velocity and decibel readings following the blast, once the meters were reset for the next shot, the only way of retrieving this information was by running the tape through a reproducer and reading the waveform by hand. The date, time, recording location etc. was only available through the operator’s written or verbal notes.

The Dallas ST-4 cassette tape machine provided a huge step forward. This was the first (or certainly among the first) self-triggering seismograph. A binary code stamp was also placed on each recorded event. The date and time could be extracted from this code once the tape was reproduced. The unit also had an LCD that displayed peak particle velocity for all three channels and the air overpressure in millibars. Most seismograph operators traveled with charts and tables so they could quickly convert millibars to psi and psi to decibels.
Frequency data was not available in the field. This was not a problem as most regulations limited particle velocity to 2.0 inches/second. Also, many of the cassette seismographs had 6-hertz microphones. Little research had been done on the effects of airblast. Any airblast that did not break a window was considered safe.

Most blasting and explosives companies did not have the capability to reproduce tapes onto paper. Typically, the tapes would periodically be sent to a consulting firm for analysis. It was common for weeks to pass between a shot and the analysis.

Cassette seismographs were the standard in our industry for over 20 years. Technological advances, research in building response, increasing demands for housing, infrastructure, and energy sources, coupled with public outcry, would soon change both the blasting and the seismograph industries.

**Digital Seismographs**

By the late 1970’s housing developments were moving closer and closer to mines and quarries. Public demands for more and better roadways, often in suburban and urban areas, necessitated large road cuts in populated areas. The escalating cost of oil increased the need for domestic coal. As blasting operations moved closer and closer to residential areas, the public’s concern over blast vibrations increased.

In 1980 the US Bureau of Mines published RI 8507, *Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting* and RI 8485, *Structure Response and Damage Produced by Airblast from Surface Mine Blasting*. RI 8507 concluded that “Particle velocity is still the best single ground motion descriptor.” But it was also the first comprehensive report to evaluate damage potential based on both particle velocity AND frequency.

In 1984 ETI introduced the first digital seismograph, the Everlert Vibra-Tape 5000. This was still a cassette tape machine but recorded the event digitally on magnetic tape. These magnetic tapes allowed for future computer analysis. The seismograph also had a sleep/wake feature that allowed the operator to set the instrument to activate and de-activate itself for any pre-set period of time.

Nomis developed the first printing seismograph with on-board analysis in 1985. Known as the SSU 1000D, this seismograph was equipped with a thermal printer that produced a strip chart recording in the field. The strip chart also included a summary providing the operator with peak particle velocity, acceleration, displacement, and frequency for all three ground motion channels. Header data, such as operation, location, and operator was included on the printout. Air overpressure data was provided in both psi and decibels. Particle velocity, frequency data and a full waveform printout were now available within 10 minutes of a blast. The unit was housed in a Pelican® case making it much easier to carry than the bulky cassette machines.
In the late 1980’s ETI introduced the Everlert II. This was a digital seismograph with a 3.5 inch floppy disk drive. A distinct feature of this unit was an LCD screen in the lid that displayed the particle velocity and airblast waveforms after a blast. The unit also provided on-board RSVP analysis.

The 1980’s brought desktop computers into the workplace. The 1980’s also brought another major manufacturer to the seismograph industry. Instantel produced the MultiSeis V. The MultiSeis had an internal memory. DOS base software facilitated analysis.

In the early 1990’s GeoSonics entered the seismograph manufacturing business with the SSU 2000DK. This seismograph had a fax-type thermal printer and a 3.5 inch floppy disk drive. A USBM Z-curve analysis could be added to the strip chart. DOS based software was available for analysis. A strip chart with Z-curve analysis was now available in the field within 90 seconds of a shot.

The next trend in digital seismographs was “smaller”. As housing developments moved closer and closer to mines and quarries and litigation and regulations increased, multiple recording locations became more common. Smaller, more economical seismographs were needed to meet the needs of the blasting industry. GeoSonics developed the MicroSeis and Instantel produced the MiniMate. These seismographs did not have printers. The data was stored internally and downloaded to a computer for analysis.

As technology advances so does the blasting seismograph. Internal memories have replaced floppy disks. Print speeds have increased. Windows® based software is more user-friendly. Most microphones have a range of 2 – 250 hertz. The days of one size fits all are gone. Most manufacturers offer multiple models with multiple options: printers, small units with internal geophones, expanded memory, various keyboard configurations, and specialty designs.

The Future

Connectivity options are increasing as well as the availability of customized accessories. Remote access, seismographs that “call in” after a shot, PDA compatible, hydrophones, and custom geophones/mounting systems all point to the fact that seismograph research and development is moving forward.

Leet, Sprengnether, and Dallas Instruments have moved into the history books of blasting seismographs. Major manufactures today include GeoSonics, Instantel, Larcor/White, Nomis, Oza, and Thomas.
Where will the future in seismograph design take us? The future, like the past, will be consumer driven based on technological advances and regulatory pressures. One thing is for certain. Just as the welcome advances of years gone by, such as a self-triggering seismograph that weighed less than 65 pounds, today’s innovations will one day be considered commonplace. Seismograph manufacturers will continue to develop more complex machines with the goal of making blast vibration monitoring less complicated.