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ABSTRACT

This paper summarizes the monitoring experienced gained from several urban rock blasting projects in New York City and one just beyond the city limits. The majority of the experience was gained on the new South Ferry Terminal Structural Box project that included a new subway terminal station and section of tunnel on the number 1-line subway located in Battery Park in Lower Manhattan. The paper will review lessons learned and the limitations of using "off-the-shelf" seismographs for near-field blast monitoring. We allege that standard and widely available seismograph equipment is not generally utilized to its fullest potential, and that alternative forms of monitoring are often overlooked in favor of criteria based on peak particle velocity alone. The new South Ferry Terminal tunnel and station comprised a 1,300 ft long excavation varying in width from 25 to 60 ft and 20 to 50 ft in depth. The excavation necessitated blasting adjacent to and underneath existing subway lines at several locations. A separate project currently underway and at a site located north of New York City, is also mentioned due to its wider variation of blast parameters relative to the more typical "urban" blast projects of New York City.

INTRODUCTION

The projects of this paper are recent projects where Mueser Rutledge Consulting Engineers (MRCE) provided blast monitoring services in the traditional sense using mainly standard seismograph equipment. The Building Code of the City of New York stipulates that the Fire Department of the City of New York (FDNY), Bureau of Fire Prevention, Explosives Unit oversee all handling, transporting, and use of explosives within the city limits. Per discussions with the FDNY, these projects represent only a small fraction of the 20 or 30 construction projects per year that utilize blasting within New York City (FDNY 2007). The FDNY reports that the number of construction projects utilizing blasting is increasing as the complexity, depth, size and cost of large infrastructure improvements also expand, mostly in the transportation and utility distribution sectors. There is one series of local blasting projects in particular, constructing the city water tunnels, that has been in progress for more than 30 years and which will continue for many more years, if not decades.

Relative to other construction means and methods which are published with some regularity, a void appears to exists in the number of published case histories on blasting in urban environments relative to the number of projects in which blasting is utilized. Further, the criteria most often cited or specified to monitor effects of blasting in urban environments is widely recognized as conservative and derived from data recorded in the 1970's and 1980's in significantly different conditions (Siskind 1980a,b, 1994; Stagg 1984) than that of a typical twenty-first century urban blasting project. That is not to say that cosmetic, or even structural damage, cannot result as long as vibrations are maintained below these widely believed "conservative" limits, as each project is different. We concur with Oriard's statement, "how inappropriate it is to assume that a single number, or even a small range of numbers, can reasonably be applied to the diverse conditions that one encounters on a day to day basis for close-in blasting" (2005). Many are in favor of less stringent criteria, especially in near-field blasting where frequencies of the blast are often as high as 1,000 Hz (hertz) at 15 ft and many thousands of hertz within five feet (Lucca 2003 & Oriard 2005). The City of New York, Department of Buildings Technical Policy and Procedure #10/88 provides lower ranges of criteria and procedures for avoiding damage to historic structures from adjacent construction (DOB 1988).

While in addition to vibration monitoring, several alternative means to monitor the effects of blasting have been successfully implemented on other projects (Dowding 2002, ITI 2007), the industry as a whole seems reluctant – or at the very least slow – to react, adopt or implement new tools, or otherwise improve our means of monitoring this age old form of rock excavation. We are not blind to inherent liability issues involved in recommending "lesser conservative", "unproven" or even "non-industry standard" criteria, nor are we promoting large scale changes in the standard of the profession. We are also well aware of the inherent dangers associated with blasting, heightened as the public perceives them, and that these issues play a major role in how the industry is governed, regulated, and perceived. Claims from adjacent property owners are common, whether frivolous or warranted and whether prosecuted under strict tort liability or whether negligence need be proven which is a legal precedence (Stark, 2002). These issues have generally hampered the blasting industry and led to additional costs.

It is possible that in favor of the status quo, these and other liability issues have played a large role in hampering the further development or improvement of the way in which we monitor and determine the effects of blasting on adjacent structures. We nonetheless, encourage the profession to publish and re-examine the state of the art in blast monitoring. At least locally, we foresee advancements in future Building Codes and/or in blast regulations, as blasting remains a critical component in completing projects on time and budget. A large improvement in the way blasting is typically monitored can generally be achieved without incurring a large increment of additional cost, and the benefits of such an improvement far outweigh the costs of alternatives.

This paper reviews valuable experience gained on several projects in which we utilized the equipment we already owned to record, evaluate and interpret as much information as was necessary to improve our understanding of the blasting performed, and to answer to concerns of the project team and third parties. Widely available equipment that represents only a modest upgrade from standard "off-the-shelf" seismograph equipment was procured and used to supplement the data more traditionally obtained. For reasons unknown, equipment upgrades such as these and improvements in data interpretation which directly result from such an upgrade are much less commonly implemented than warranted. We have observed significant improvements in the quality of data collected, resulting in an increase in the project team's confidence in the means and methods implemented for the blasting which allowed the projects to proceed with fewer delays and interruptions.

SOUTH FERRY TERMINAL

Project Description

The South Ferry Terminal project was the construction of a new terminal station and section of tunnel on the New York City Transit (NYCT) number 1-line subway located in urban Battery Park in Lower Manhattan as shown on Figs 1 and 2.

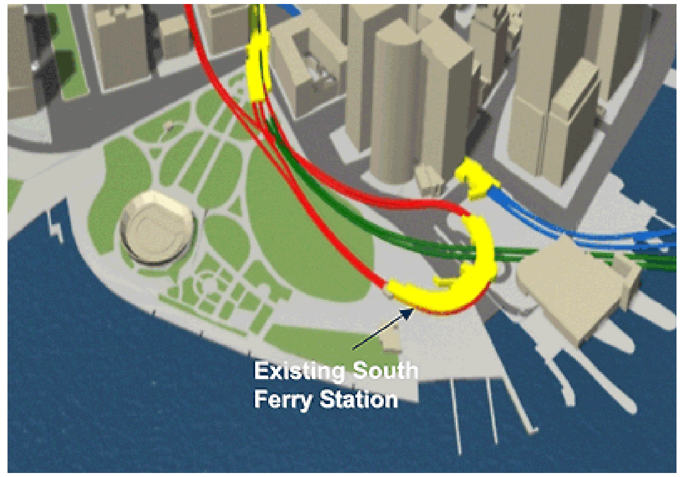

Fig. 1. Project Location and Infrastructure
[Source: MTA 2006]

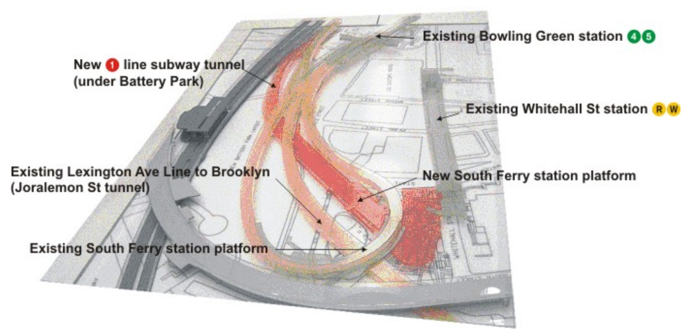

Fig. 2. Project Location – New Tunnel Configuration
[Source: MTA 2006]

The new tunnel and station comprised a 1,300 ft long excavation varying in width from 25 to 60 ft and 20 to 50 ft in depth. The excavation necessitated blasting adjacent to and underneath existing active subway lines. The total amount of rock excavated was on the order of 77,000 cubic yards, approximately 80 percent of which was removed by blasting. Up to 22 seismographs were used to monitor localized vibrations from blasting in and around adjacent structures including a subway control room, subway tunnels, a vehicular tunnel, and three nearby historic buildings. Pre-construction condition surveys of adjacent buildings were performed by others to document conditions prior to blasting. Crack monitors were installed where determined appropriate by the Engineer performing the condition surveys. The majority of the rock was characterized as schist by NYCT, and as schistose gneiss by the Contractor, with moderately weathered regions. The 10-month blasting program included 198 days of blasting and 1,679 individual blasts. All blasting products used were manufactured by Austin Powder of Ohio.

Limiting vibration levels were established by NYCT between 0.5 and 2.0 inches per second depending on the sensitivity of the adjacent structure. Frequency ranges of conventionally available seismographs were exceeded during close-in blasting due to the proximity of the blasts to the seismographs and the resulting dominant ground frequencies that occurred at these locations. Though these limitations were acknowledged, data recorded suggests that the typical criteria of 0.5 to 2.0 inches per second may be conservative and can be periodically exceeded without structural damage to surrounding structures, especially but not limited to buried structures such as tunnels. Further, this conventional criterion may require re-evaluation when in such close proximity to a network of buried structures or mixed ground conditions (i.e. soil on rock).

Blasting for the new South Ferry Terminal Station began with a series of test blasts in October and November of 2005. Test blasts assist in assuring that blast parameters such as hole spacing, depth/burden, powder factors, charge weights and the number of delays result in acceptable rock breakage and vibration attenuation into the surrounding ground and adjacent buildings. The Contractor preferred the rock break into boulder size block fragments that are small enough to be excavated with ease using typical excavation equipment, but not so small that the rock cannot be reused as a construction material on rock fill projects.

Production blasting began with opening shots shortly before Thanksgiving 2005. An opening shot is one in which the starting point is a horizontal or planar surface which results in the "opening" of a void or relief hole within the rock surface. Opening shots are important to differentiate from non-opening shots (bench shots) as the increased confinement can result in more energy (higher vibrations) transmitted into the surrounding ground. Opening shots commenced near the north end of the new running tunnel alignment following overburden soils removal.

Seismograph Monitoring Equipment

Three brands of seismographs monitored the project, namely SYSCOM, Geosonics and Instantel. NYCT subway tunnels are hostile environments in which to monitor due to limited access, high electro-magnetic interference and AC power, where available, is unreliable due to periodic power interruptions. Equipment is also prone to vandalism and moisture as well within the tunnels.

Ten SYSCOM model MR2002CE seismographs manufactured by SYSCOM from Sainte-Croix, Switzerland were permanently mounted on adjacent structures throughout construction as part of the general construction monitoring and instrumentation contract shared by Mueser Rutledge Consulting Engineers (MRCE) of New York, NY and Geocomp of Boxborough, MA.

The SYSCOM units were highly robust and the easiest to database due to their open-source programming. The units are considerably more expensive than the others and lacked the portability for monitoring multiple locations as they are generally designed for longer term or permanent installations. The seismograph can record up to 800 samples per second and has a frequency range up to 350 Hz. Overall, the SYSCOM seismographs proved very rugged for long term tunnel monitoring in that they did not false trigger and rarely required troubleshooting.

Most geophones were bolted to tunnel walls or adjacent structures as necessitated by contract or structural sensitivity. Seismographs were generally installed at distances between 5 ft and 50 ft from adjacent proposed rock blasting. Eight SYSCOM units were bolted in adjacent active subway tunnels, one on a vent shaft for the adjacent vehicular Brooklyn Battery Tunnel and one on the southwest corner of an occupied historic multi-story office building located at One Broadway. These seismographs were connected to the iSiteCental Online Database maintained by Geocomp by either wireless radio to a field computer to the website or by an internet protocol modem. Data were available for periodic download and review throughout the day or by special request following a blast.

Up to twelve additional portable seismographs were used to monitor subway tunnels or adjacent structures. Four to six of these seismographs were either Geosonics 3000 EZ Plus or 3000 LC models manufactured by Geosonics Inc, out of Warrendale, PA. These were equipped with the standard Geosonics triaxial geophones capable of measuring up to 5 inches per second (ips) peak particle velocity (PPV) at frequencies up to 250 hertz (Hz). The maximum sampling rate of these seismographs was 2,000 samples per second. Limitations are that these particular units were older, manufactured in the early to mid 1990's and thus are not easily adapted for real time automation or notifications via remote connection by cellular modem. They have a long track record and have proven durable and robust for construction use with extended battery life of a month or more. These geophones were either bolted to structures or sandbagged at desired manual and accessible monitoring locations. In some cases, particularly in the existing 1-line as it paralleled the new running tunnel, several geophones were bolted along the tunnel and only those nearest the blast were monitored by use of extension cables, some exceeding 600 feet in length.

At the beginning of blasting one Instantel Minimate Plus seismograph manufactured by Instantel Inc. of Ottawa, Ontario, Canada, with an internal triaxial geophone was also used as a mobile seismograph. As construction progressed and there were more blasts per day over two shifts, additional Instantel Minimate Plus seismographs were purchased, one 4-channel unit and two 8-channel units capable of monitoring two triaxial geophones simultaneously. The geophones used with the Instantel Minimate Plus units were the standard ISEE

(International Society of Explosive Engineers) type capable of measuring vibrations up to 10 ips per channel at 250 Hz. The 4-channel seismograph records a maximum of 4,096 samples per second while the 8-channel maximum sampling rate is reduced to 2,048 samples per second because of the doubled number of input channels. The Instantel Minimate Plus seismographs were portable, versatile, and user-friendly, though their size advantage sacrifices internal battery life. Other models with larger internal batteries are available through the manufacturer. As installed, they were somewhat susceptible to false triggering from electrical interference, a problem in subway tunnels due to the live third rail and urban tunnel environment. We later minimized false triggers from electrical interference by using Instantel DIN geophones (meeting specifications for the Deutsches Institut fur Normung) for tunnel monitoring applications as opposed to ISEE geophones and we minimize lengths and use double shielded signal cable where possible.

Unusual Monitoring Locations

One of the most unusual monitoring locations at South Ferry was an electronic relay room that controlled the unique movable platform extensions at the loop station and train signals on a section of the line. NYCT had set an initial vibration limit of 0.5 ips on the racks containing the electro-mechanical relays, many of which were over 30 years old and sensitive to vibrations as they were mounted on steel spring bearings. As the new station crossed under the existing station and was seated directly on rock, blasting was to be performed directly underneath the relay racks. This location, like others in active subway tunnels, was inaccessible except when accompanied by a NYCT authorized employee and thus required a remote connection to its seismograph. Initially one Instantel ISEE geophone was bolted directly to one of the racks and a second geophone was anchored to the floor. The two geophones were monitored using an 8-channel seismograph with data downloaded via radio from across the platform.

As the new tunnel alignment crossed beneath the existing tunnel in three locations, blasting and vibration monitoring beneath an existing station, subway tunnel, relay and other mechanical rooms was performed to not only avoid damage to these active existing structures, but also to the underpinning piles installed to support these structures. These underpinning piles were a combination of wide flange bracket piles and drilled and grout-filled 9-5/8” outside diameter by 0.5” thick wall steel pipe typical of minipiles (see Fig. 3). They were installed prior to soil or rock excavation from inside the tunnel, and in some cases from above and through the existing tunnels. The underpinning piles extended through rock that needed to be excavated, where they provided support in rock that would not be excavated for the new tunnel construction. As such, controlled blasting was successfully performed within feet of these structural elements. The underpinning piles were designed and configured in bents spaced approximately 15 ft on center along the tracks such that horizontal blasting rounds needed to be configured within the widths of these pile bents. Closely spaced horizontal line drill holes were used to reduce or eliminate over-break and minimize damage to these adjacent underpinning piles.

Fig. 3. Blasting beneath subway, between underpinning piles

Minimizing resulting vibrations on the racks in the electronic relay room proved difficult, and NYCT approved the Contractor’s proposal to install elastomeric isolation bearings to further isolate the racks from the floor at which point the second geophone was moved such that two of the three racks were being monitored. This option of isolating a sensitive piece of equipment is often overlooked and ought to be more commonplace where sensitive laboratory or other equipment are in use. It may often prove more practical to isolate sensitive equipment or exhibits than to limit the Contractor to lower vibration criteria which significantly drives up the cost of urban blasting. Incidentally, the isolation bearings were able to noticeably reduce vibration to the relay racks.

Vibrations exceeding 0.1 ips were sent directly to the installed computer using the Auto Call Home feature of the Instantel seismograph and then transmitted by text message to the cell phone of the blast monitoring Resident Engineer. After numerous test blasts it was determined that the amount of powder used to limit vibrations on the relay racks and the corresponding rock burden removed was not a viable solution. The Contractor implemented an extensive drilling and hoe-ramming operation to improve the horizontal relief zone between the structural box of the existing platform and the rock below it. Once sufficient rock had been removed and additional separation was achieved, controlled blasts beneath this structure resumed with acceptable vibrations recorded in the signal relay room.

These techniques of channel drilling, line drilling or in this case a combination of drilling and hoe-ramming to form a physical separation or relief zone, are often not initially performed to sufficiently reduce the vibrations transmitted across this boundary. The effort is time consuming, labor intensive and therefore expensive and as a result, Contractors often prefer an observational approach in which the resulting vibrations are evaluated to determine if additional separation is needed. On many urban blast projects, the costs of constraining the Contractor by forcing smaller and smaller blasts parameters outpace the costs of improving the separation between monitored structures and the blasts, which may achieve the same desired outcome of transmitting lower vibrations to adjacent structures. These decisions are best left to experienced blasters and engineers with a full understanding of both the theory but also the "art" of blasting in which there will always remain unknown factors including but not limited to, local structural geology, joint spacing, orientation, joint material, rock type, degree of weathering and decomposition, hardness, distance to the monitoring point, geometry, and confinement.

At the request of NYCT and two adjacent property owners, two adjacent buildings of note were monitored continuously, namely a Chapel at 7 State Street and a museum and a courthouse building at One Bowling Green (between State Street and Whitehall Street). A seismograph recording a continuous 15 minute histogram was installed in the basement of the Chapel along State Street opposite the main station excavation. The Elizabeth Anne Seton Chapel – the Shrine of the first American born Saint – dates back to the 18th century and is a registered historic Landmark building still serving a small congregation in lower Manhattan with a live-in clergy member. The Landmark status of the building limited vibration to less than 0.5 ips. Vibration data were downloaded periodically using a wireless radio and peak vibrations remained below threshold criteria, at values of 0.3 ips or less.

Following a reported incident in the adjacent museum in which a small artifact had reportedly tilted off of its base without causing any damage, NYCT directed the Contractor to monitor the building; the Landmark United States Custom House designed by the famed architect Cass Gilbert and constructed around the turn of the 20th century. Purchased and restored by the General Services Administration, it now houses both the National Museum of the American Indian and an active Federal Court House. Although the nearest construction activity seldom approached within 100 ft of the basement, a Geosonics seismograph recording a 1 minute histogram was installed in the basement and vibration data was downloaded for review on periodic basis and as directed following particular blasts.

The primary area of concern in vibration monitoring was where the new running tunnel ran parallel to or crossed beneath the existing active subway tunnels. As trains were running throughout the construction period on the weekdays, monitoring locations could only be added or moved when train service was suspended for construction on the weekend. Through careful coordination between the Contractor and NYCT personnel, blasts were shot in the several minutes lead time, known as headway, available between trains. Where headway was insufficient and/or a train was waiting at the station to depart, NYCT would hold the trains during the blast and then perform a post blast tunnel inspection before allowing the train traffic to resume. While this led to an overall work slow down, it was mandated by NYCT to ensure safety. Such tasks were usually performed only twice a day at off-peak times specified by NYCT. The tunnel monitoring proved to be an interesting challenge as blasting would eventually come to within 10 ft from the existing tunnel. These near-field shots resulted in near-field ground motion frequencies that exceeded the ranges of the standard geophones manufactured by Instantel, Geosonics and SYSCOM.

Data Interpretation and Evaluation of Waveforms

Figure 4 shows a waveform for a typical blast event, which is a time history of peak particle velocity versus time. Blast monitoring is best performed by recording waveforms of the blast events for both verification of instrument function and structural response. Irrespective of frequency, acceptance criteria often rely only on the magnitude of the peak particle velocity alone (peak component preferred, peak vector sum typical). A time history evaluation provides additional feedback to the blasting and engineering teams in which to evaluate blast parameters and structural response.

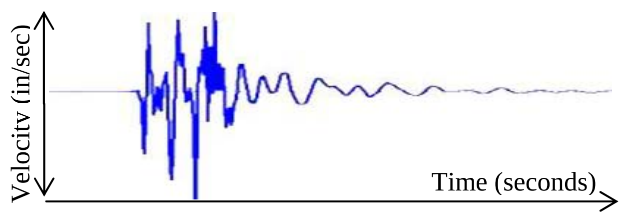

Fig. 4. Waveform (time-history of particle velocity) for a typical blast event

It is important to collect and examine waveforms where applicable to provide quality control of the monitoring data, especially when blasting occurs in close proximity to seismographs, as the following waveform is indicative of a potential problem with the instrument, and may result in false readings if this effect is not recognized. Figure 5 is an example of an event that exceeded the frequency monitoring range of the seismograph.

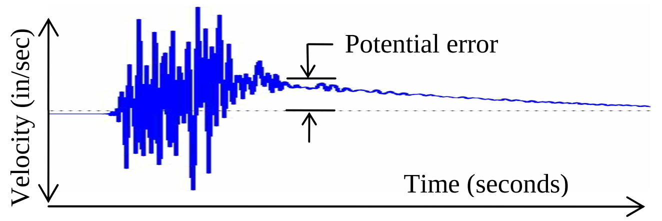

Fig. 5. Waveform, example of faulty seismograph reading

As a matter of practice, the dominant frequency of the recorded waveforms resulting from blasts should be reviewed for comparison to the natural frequencies of adjacent structures. Dynamic excitation is likely to cause damage to a structure when resonance occurs, i.e., when the dominant frequencies of the excitation are close to the natural major frequencies of the structure. In practice of dealing with vibration problems, the dominant frequencies of the recorded waveforms should be compared to the natural periods of the adjacent structures to understand preliminarily the potential for damage. An estimate of the first natural period (the inverse of the frequency) of a regular building is simply 0.1 times the number of floors. More detailed analysis would be required to analyze the actual dynamic response of a structure to a vibration input. This level of analysis would normally be reserved for the most sensitive of blast monitoring applications.

The location of the seismograph on the structure is also critical, as one must consider whether to monitor ground motions at the point of contact with the structure, or structural response within the structure itself. As was done on the racks in the relay room where the primary concern was the vibration transmitted into the relays. Vibrations of structural members within a building may vary considerably from one point to another, and certainly from one floor to another, as stiffer members in the building may attract energy while more flexible members may not, causing vibrations to either attenuate or amplify as they move throughout the structure (Volterra 2006). In urban areas, especially in near-field blasting, consideration should be given to both the measured distances from a blast, horizontal and vertical, as well as the medium through which the vibrations travel. Near-field blasting is defined as "within meters of the construction blast holes" (Dowding 2000).

It is important to differentiate normal attenuation of vibrations through a homogeneous soil or rock mass, from that which may or may not occur once the vibration energy enters a structure. The specifications often do not differentiate whether the criteria applies to measured vibrations in or on the ground surface directly outside the monitored structure, or at a particular monitoring location within the structure. Thus and in the absence of additional information, it is often assumed to apply to both. The structure's response and the location of the sensor within the structure can significantly alter the recorded vibration, resulting in either attenuation (typical further dissipation of energy or decrease in vibration) or in some cases amplification (rare convergence of energy or increase in vibration). For example, there are large differences in the stiffness of slabs on grade, structural columns, beams and floors, and block or timber framed drywall partition walls, and thus differences in how vibrations will travel through these members. Stiffer structural members attract load, and also energy or vibrations. It is not uncommon however, to witness geophones hastily installed on or affixed to any of these surfaces without consideration to the impact of the decision. Further, the geophone's specific location on a particular member, close to a braced connection (relatively stiff) or mid-span (relatively flexible), can also affect the recorded magnitude of the vibrations significantly.

Waveforms should be reviewed where appropriate to verify instrument function and to identify commonly ignored or unnoticed malfunctions caused by "aliasing" and/or "decoupling" as shown in Fig. 5. In aliasing, the frequency of the source vibration exceeds the instruments limit and the instrument provides false data, usually with very low frequencies as the instrument is unable to sample fast enough to closely track the actual movement. In the case of decoupling, the geophone sensor moves out of sync with the structure on which it is mounted. While this would occur most frequently in the case where geophones are sandbagged, it can occur with bolted installations if the vibration source is close enough to the sensor, as may occur in near-field blasting. These phenomena may result in false readings.

Careful review of waveforms is not a new recommendation in the field of blast monitoring, but to date it seems rarely performed in practice and even more rarely specified. One earlier case history we did locate regarding blasting in the urban New York City area made similar recommendations. Blasting for the North River Pollution Control Plant and underground sewage treatment plant on the Upper West Side of Manhattan included a 4.2 mile section of 10 to 15 ft diameter tunnel opening in rock created by drill and blast (Oriard 1971). The referenced paper titled "Monitoring Tunnel Blasting in the Urban Environment: A Case History", includes discussion on, 1) pre-construction condition surveys, 2) seismograph monitoring equipment, 3) analyzing and interpreting seismograph data, 4) blast design consultation and, 5) preparation for defending claims in the event of litigation. By today's standards, the seismograph equipment and available communication options for data transmission were rudimentary, but yet the process described therein was one of getting the most out of the data, and using it to better understand the blasting and protect all parties from frivolous claims. These remain valid points today. The process they described is one that in our opinion was performed with more attention to detail than is common in today's blast monitoring projects. Ultimately, poor attention to detail becomes a deterrent in promoting successful use of blasting in urban construction.

One last comment on this paper for which the writer's should be commended and which remains uncommon in today's practice, is their interpretation of data in which they plot peak particle velocity versus square root scaled distance (distance divided by the square of the charge weight per delay, commonly SD, where SD = $D/W^{0.5}$) on a log-log scale. We presented data from our blast monitoring projects in this format and provide one such plot in the last of three case histories included in this paper. Another well known publication describing these and other factors including comparison of various damage criteria and human response, regarding construction vibrations was later published by John F. Wiss in the Journal of the Geotechnical Engineering Division (1981). This state-of-the-art presentation remains a valuable resource and likewise made the call for further research to improve our understanding of blasting and blast monitoring.

Criteria for the South Ferry project relied on peak particle velocity alone, irrespective of frequency, without consideration of the quality of the recorded data (evaluated by reviewing waveforms), and without acknowledging the limitations of the equipment. We provided these additional services to provide a better understanding of the effects of blasting on adjacent structures, and to facilitate project completion as efficiently as possible.

Seismograph Monitoring Equipment & HF Geophones

To gain more experience, knowledge and a better understanding of the blast vibrations recorded in near-field monitoring, we installed two types of geophones on the same shelf. While both geophones were manufactured by Instantel, one geophone was a DIN geophone with a maximum range of 10 ips and 315 Hz per channel monitored at 4,096 samples per second and the second was a special high-frequency (HF) geophone designed for near-field monitoring. HF geophones are required in near-field blasting because the higher frequencies attenuate at short distances from the blast whereas lower frequencies travel farther from the source. Oriard made the following comparisons, "a very small charge may generate a frequency up to 20,000-25,000 Hz 8-12 inches away in hard rock…A half-pound charge might register a frequency of several thousand Hz out to a few feet, and a frequency of several hundred Hz within the first 10-30 feet. If the instrument has an upper frequency in the range of 150-250 Hz, it will not respond properly to small charges at very close range, and the results could easily be misinterpreted. The failure of the instruments to respond properly could give the impression that the vibration does not increase in intensity as one approaches the source" (2005).

The range of the high-frequency geophone was 100 ips at 1,000 Hz per channel. This geophone was monitored at 8,192 samples per second and increased gain such that it monitored up to 12.5 ips instead of 100 ips using Instantel's Blastware Advanced Module. The Advanced Module facilitates monitoring a triaxial geophone up to 16,384 samples per second or 65,536 samples per second with a uniaxial geophone.

Often the design of the blast coupled with the number and length of delays used, requires the use of a seismograph that could record for three to five seconds or more at a high sampling rate. We used 8-channel Instantel seismographs to monitor high-frequency geophones for up to 13 seconds of data at 8,192 samples per second opposed to a maximum of three seconds using a 4-channel seismograph at the same sampling rate.

The difference in the quality of the recorded data between an ISEE or DIN geophone with more typical specifications and a high-frequency geophone with increased range and sampling rates was immediately discernable. Offsets such as those shown in Figure 5 did not occur with the high-frequency geophones. The high-frequency geophone at the higher sampling rate recorded much cleaner data without decoupling.

An extended blast event with multiple delays recorded with a seismograph monitoring in histogram mode alone would provide only a single value of peak particle velocity as opposed to a time history which identifies individual peaks of each delay within the blast sequence. This may satisfy many specification requirements where data are compared to limiting values, but provides little additional information from which to evaluate the blast.

These data allow the engineer and blast team to review and evaluate the efficiency of the blast parameters. Counting the individual peaks in a waveform allows the blast team to evaluate the delay sequence within this particular blast event which all occurred within a four second time interval. This adds value to the monitoring data.

While the peak component particle velocities between the high frequency geophone and the standard geophone have shown generally to be within 10 to 25 percent of each other, no clear trend has been identified after several projects of comparisons, meaning one was not always higher or lower than the other. As such, we believe it prudent to collect the "cleanest" data possible, by using higher frequency geophones for near-field blast monitoring, say within 30 to 50 ft of a blast. This concept is supported and described in detail by Oriard (2005).

Other recorded waveforms documented an increase in energy transmitted to the geophone by approximately a factor of two at time during the blast detonation sequence, followed by a longer than average delay between detonations.

It can be hypothesized that energy dissipated in the form of seismic waves from the later delays somehow merged and arrived at the monitoring location in sync or in-phase with other seismic waves. In the event that those peaks were to exceed a project's criteria while others did not, the Engineer may review the waveform, exercise some judgment and consider the peaks acceptable as most fall below the threshold and only a small portion exceed the criteria. If the Engineer determined the peaks were unacceptable, changes to the blast design are required. If changes need be made, the blaster has some valuable information from which to base his changes to achieve a lower peak particle velocity in future blasts. They may consider for example, 1) altering the delay sequence at the end of the blast, or 2) reducing the charge weight per delay and maybe as a result have to alter the hole layout for the last third of the shot to assure acceptable breakage. Accepting or reviewing only the peak value of the vibration data in this case would not provide the blaster with as much information from which to solve the problem and reduce future peaks. This example shows how a small increase in effort on the monitoring side can provide valuable information from which to lower overall construction costs which is the all too often overlooked aspect of the instrumentation and monitoring programs.

MULTI-USE DEVELOPMENT

Project Description

A multi-use development is currently under construction North of New York City. The site encompasses approximately 85 acres with bedrock exposed for much of the northern section of the site. The contractor has been performing an extensive blasting program to bring the site to the proper grade elevations. It is estimated that 400,000 cubic yards of rock will be removed during construction. At the northern end of the site, the closest existing structures have typically been on the order of 200 or more feet from the blasting locations. The area immediately surrounding the site is mainly woodlands although there are two highways more than five hundred feet away. There are only three structures on the site, a water tower and two buildings. One of the buildings will be occupied throughout the construction. Running adjacent to the site, but often hundreds of feet from the nearest blast, are several high-voltage feeder lines and transmission towers on which the utility company has imposed a vibration limit of 2.0 ips.

The more remote nature of the site, as compared to those in New York City, has allowed for large and open blasts. Some blasts performed at the site have exceeded 250 lbs/delay with a site average of about 55 lbs/delay. As a comparison with South Ferry Terminal, the maximum was about 40 lbs/delay and the site average was about 5 lbs/delay. There is also greater freedom for the type of explosives products used outside New York City. The contractor used Dyno Nobel products including dynamite, bulk ANFO (ammonium nitrate and fuel oil), emulsion sticks, and repump emulsion.

Seismograph Monitoring Equipment and Data Reduction

Monitoring of blasting and vibrations at the site was provided mainly by the Contractor and others, but MRCE took the opportunity to again utilize the high-frequency geophone to collect data. The range of the HF geophone allowed ground motion vibration monitoring of large shots at various distances. The data collected from those shots was plotted as scaled distance versus peak particle velocity (PPV) as shown in Fig. 11. That data allowed for the establishment of upper and lower bounds of confinement factor, K, for the site. The confinement factor can be used to estimate the peak particle velocity at a given location if the distance from the blast and the maximum lbs/delay are known following the equation:

$$PPV = K(SD)^{-1.6} \quad (1)$$

Using this information, MRCE was able to establish contour lines of max lbs/delay around the transmission towers to aid the contractor in designing blasts and ease concerns of the utility provider.

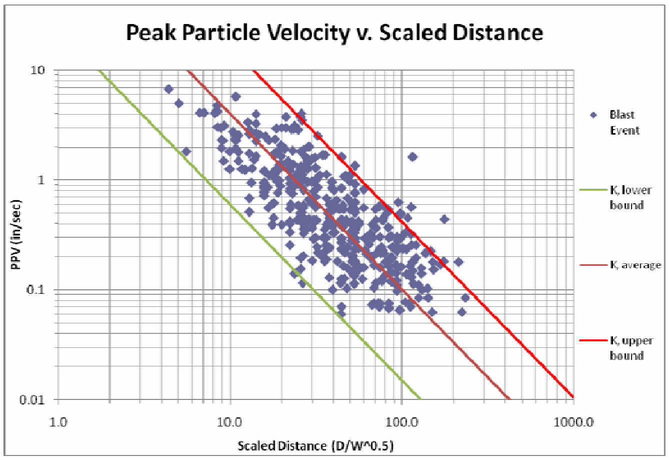

Fig. 11. Scaled distance log-log plot of data

CONCLUSIONS

These example case histories summarize the vibration monitoring techniques used on several urban blasting projects in and around the City of New York. The projects used various monitoring equipment to provide feedback to the contractors and the regulatory authorities on the blasts. The final case history was a brief overview of a larger blasting project outside of the city in a considerably “less urban” location.

Widely available monitoring equipment may not be suitable for urban blast monitoring where structures may be only feet away from a blast location. The use of more specialized equipment has proven to provide better and more useful data.

Current vibration criteria and typical reporting techniques may also not be suitable for the urban environment. We recommend blast vibration monitoring include not only reporting of the maximum peak particle velocity in relation to a pre-established threshold value as is typically specified in most current blast monitoring projects, but also:

- Including quality construction records documenting the blast parameters with the submitted vibration data as is necessary for evaluation purposes,
- Use of high-frequency geophones and/or accelerometers for near-field blasts,
- Recording time-history (waveforms) and not just histograms, to allow review of the variation of peak particle velocities throughout the blast event,
- Quality assurance/review of the recorded data for potential errors such as aliasing or decoupling,
- Review of dominant frequencies and their comparison with those of adjacent structures,
- Plotting peak particle velocity versus scaled distance to facilitate comparison of blasts performed at varied energies,
- Estimates of peak particle velocity using a site-specific confinement factor (regression analyses) developed from test blasts and revised following early production blasts,
- Improving alternative means of monitoring the effects of blasts, e.g. condition surveys, strain gages, crack monitors (static and dynamic measurements),
- Establishing improved site-specific vibration threshold criteria, which may include alternative forms of minimizing potential damage, such as isolating sensitive structures or equipment from dynamic ground motions.

We recommend consideration of strengthening specifications to require these tasks at a mutual benefit to all parties as it will facilitate:

- Better documentation of the blast events and resulting vibrations,
- A better understanding of the recorded blast effects,
- Use of engineering judgment in evaluating individual portions of recorded waveforms and as such, providing feedback to the blasters as to how the shot progressed,
- A rational approach to adjust and thus optimize blast parameters in future blasts either where preferred, necessary, or required,
- Effective successful use of blasting where appropriate, minimizing costly construction delays and frivolous claims.

A limited literature search reinforced that the criteria most often cited or specified to monitor effects of blasting in urban environments are widely recognized as conservative and are based upon research performed over 25 years ago and for a different purpose. To even approach criteria that may be acceptable for the urban environment, additional research must be undertaken. This research should not be strictly vibration based but must consider effects of frequency and include the use of strain gauges and dynamic crack monitors.

Improving both the equipment used and the analysis techniques will help to provide more accurate criteria and help in the design and execution of future urban blasting projects. Still, further research should be performed to establish criteria for near-field urban blasting and case histories need be published.

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