South Ferry Terminal Instrumentation and Monitoring

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Abstract: Mueser Rutledge Consulting Engineers (MRCE) and Geocomp Consulting are providing professional engineering services to the Design Build Joint Venture between Schiavone Construction Co., Inc. and Granite Halmar Construction, Inc. (SGH-JV), designing excavation support walls and tunnel underpinning, and providing monitoring of adjacent structures along 1,600 linear feet of the new #1 subway tunnel. The new tunnel includes a station that crosses beneath three existing New York City Transit (NYCT) active subway tunnels. Construction involves an extensive amount of rock excavation. MRCE and Geocomp designed and implemented the real-time instrumentation and monitoring program. Deformation monitoring of the three existing subway lines (#1 and #4&5 lines) commenced in March 2005. Instrumentation included seismographs, piezometers, inclinometers, tiltmeters and robotic total stations reading hundreds of reflective prisms mounted along the existing subway walls and surrounding structures. Up to 22 seismographs are being utilized to monitor vibrations during blasting, which at times have occurred at up to four locations simultaneously four times per day.

I INTRODUCTION

Development of the South Ferry Terminal Box Instrumentation and Monitoring program commenced during the Design-Build proposal stage in the fall of 2004. Instrument installation commenced in the spring of 2005, and monitoring is in progress through April 2006. Monitoring is anticipated to continue into 2007.

A. Location

The new South Ferry Terminal Structural Box project is located at the southern tip of Manhattan about one half mile south of the World Trade Center site abutting State Street to the east, Battery Place to the north, Battery Park to the west, and the new Staten Island Ferry Terminal building to the south as shown in Figure 1.

Figure 1: Site Location Plan

B. Geology

The ground surface along the route is generally flat and at about elevation +107 (NYCT Datum), where Elev. 100 is 2.7 feet above Mean Sea Level at Sandy Hook, New Jersey. In general, the subsurface along the proposed tunnel alignment consists of miscellaneous granular fill (placed outboard of the historic Manhattan shoreline) over glacial deposits consisting of medium compact to compact sands with some silt and gravel and occasional cobbles and boulders, over bedrock. The glacial soils are generally low permeability, and bedrock varies from Manhattan schist, to the harder schistose gneiss. Groundwater levels generally range between Elev. 98 and Elev. 102.

More specifically, the South Ferry tunnel alignment transects a relatively steep northeast-southwest trending valley in the bedrock with its deepest point near where the tunnel will pass beneath the existing ④&⑤ subway. North and south of the valley, sound bedrock is generally within 15 to 25 feet of the ground surface. Overburden soils within these areas generally consist of ten to 15 feet of loose to medium compact granular fill overlying five to ten feet of very dense, predominantly granular glacial till. Occasional thin deposits of alluvial sand or organic silt are found as intervening layers between the fill and till, but significant thicknesses of compressible soils were not encountered either at the north or south end of the project.

Within the valley, the soil profile is more complicated. Rock is found at a depth between 30 and about 60 feet below ground surface, of which the upper five to ten feet are generally weathered. Overburden soils consist of about 20 feet of loose to medium compact granular fill overlying glacial till and interglacial marine deposits. The glacial till is primarily a very dense, well-graded fine to coarse sand or sandy silt. The interglacial deposits are generally finer grained ranging from a hard clayey silt to silty clay frequently with traces of shell fragments.

C. Existing Station

The existing South Ferry station, the southern terminal for the Broadway-7th Avenue subway line (#1 train), services commuters transferring from the adjacent Staten Island Ferry terminal and tourists visiting Battery Park, the Statue of Liberty, and Ellis Islands. The station was constructed in the early 1900's on the outside of a sharp curve, which renders it functionally deficient based on today's train service requirements.

Per the Metropolitan Transportation Authority's Capital Construction Company (MTACC) web site,

> The station was built in 1905, at a time when subway trains were much shorter than they are today. As a result, the platform can only accommodate the first five cars of each train, requiring customers in the rear cars to walk forward to exit, increasing the chance of train delays which can affect service throughout the entire ①②and ③subway lines. It was also built as a single loop track, which limits the number of trains that can be stored (other subway terminal stations have two or three tracks). In addition, the curvature of the platform requires the use of mechanical "gap fillers" to cover the space between the platform and the train door, and causes moving trains to generate excessive noise.[1]

The existing NYCT tunnel consists of a concrete box with bents of steel columns and roof beams on five foot centers. The columns bear on a structural reinforced concrete base slab, which is supported directly on rock or compacted soils. In some areas, unreinforced concrete exists between the steel bents to complete the walls and roofs.

D. New Station Components and Benefits[1]

Components and improvements of the new subway station include:

- A full-length straight platform accommodating two 10-car subway trains.
- Additional station entrances reducing congestion and improving access from street level, and directly to and from the Staten Island Ferry Terminal and Battery Park.

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[1] http://www.mta.nyc.ny.us/capconstr/sft/

- A new direct transfer between the 1 line at the South Ferry Terminal and the R and W lines at the Whitehall Street station.
- Station accessibility compliant with the Americans with Disabilities Act.
- Sufficient overrun track south of the platform to allow trains to safely enter at higher speeds.
- State-of-the-art switching technology for crossover tracks north of the station.
- Capacity for up to 24 trains per hour.

E. New Tunnel Configuration, Crossings, and Adjacent Infrastructure

Figures 2 and 3 illustrate the existing subway tunnel configuration and the alignment of the new subway tunnel station in reference to the existing infrastructure, respectively.

Figure 2: Existing tunnel configurations, park and surrounding infrastructure (MTACC website)

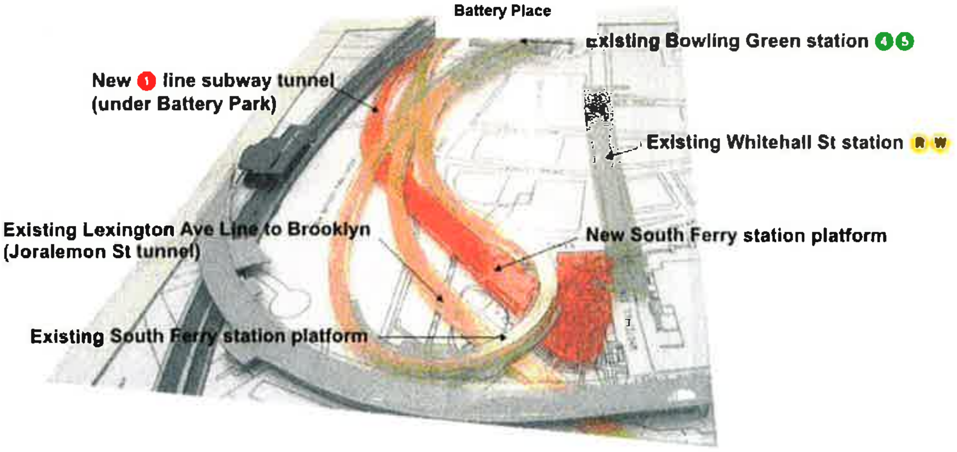

Figure 3: Existing & New South Ferry Stations and Surrounding Infrastructure (MTACC website)

As illustrated by Figure 3, the new #1 line subway tunnel branches off from the existing #1 train at the intersection of Greenwich and Battery Place. It passes beneath existing and active NYCT tunnels three times at what we have termed the north #1 train crossing, the middle #4/5 train crossing and the south #1 train crossing (or South Loop station). Immediately adjacent to the NYCT tunnels are:

1. Brooklyn Battery Tunnel to the west (vehicular)
2. Battery Park Underpass to the west within and below Battery Park (vehicular),
3. Buildings along Battery Place and State Street,
4. NYCT R&W subway lines and Whitehall Station to the east,
5. Peter Minuit Plaza
6. Staten Island Ferry Terminal to the south

It was required that adjacent buildings be examined, monitored and maintained throughout the Contract. These crossings and adjacent infrastructure, and the need to design and implement the support of excavation for the new tunnel, and the underpinning and instrumentation and monitoring program for the active existing tunnels, were factors which influenced the decision to issue the project as a Design Build Contract. Allowing bidding Contractors to design, and then following the MTA review and approval process, select the means and methods most suitable to their available skills, equipment and tradesmen, was ostensibly the most practical solution considering the tight 24 month schedule allotted for construction.

II DESIGN AND BID STAGE

MRCE and Geocomp worked with Schiavone Granite Halmar Joint Venture (SGH-JV) during the bid stage to interpret the specifications and design, develop and price the instrumentation and monitoring program. The cost for instrumentation and 1.5 to 2 years of real-time continuous construction monitoring will be in the $3,500,000 range.

A. Instrumentation and Monitoring Contractual Requirements

The instrumentation and monitoring requirements were contained in the project specifications, and generally required that all NYCT structures within 200 ft of construction be monitored for vertical and horizontal movement at five foot intervals along the tracks. The specifications also required all adjacent existing structures and foundations within 100 ft of construction be monitored.

Upon review of the proposed tunnel configuration and the existing infrastructure, we estimated that approximately 5,200 linear feet of NYCT tunnel, with each tunnel generally containing two tracks, would be monitored at five foot intervals for vertical and horizontal movement. In addition, there was a combined length of adjacent vehicular tunnels within 100 ft of construction approaching 1,000 linear feet along the Brooklyn Battery Tunnel and Battery Park Underpass to also be monitored. As all monitoring was to be read and submitted daily, the large number of data points and the short reporting interval necessitated automation.

The following threshold and limit criteria were specified:

	Threshold	Limit	Units
Horizontal Movement	0.25	0.5	inches
Vertical Movement	0.5	1	inches
Vibrations	0.5	2	inches per second

While threshold criteria were provided, the specifications required the Design-Build Contractor to prepare and submit a Building and Monitoring Plan that proposed threshold limits. The SGH-JV requested that MRCE and Geocomp write a specification and detailed work scope based on the contract requirements, to accompany their overall bid. In this way, the MTA, as Owner, would know what was included in the price bid for instrumentation and monitoring. The instrumentation and monitoring plan together with its lower cost was a significant factor in MTA's selection of the SGH-JV.

A. Instrument Selection and Potential Movements

In selecting the appropriate instruments to achieve the goals, robotic or automated motorized total stations, tiltmeters or continuous tilt beam sensors, liquid levels, and inclinometer/extensometer combinations, including emerging technologies such as fiber optic systems were considered. The flexibility of the Contract Specifications allowed the design instrumentation engineer to consider all of the tools and instruments available to meet the underlying objective to provide real time monitoring of buildings and subway tunnels as necessary to provide a detailed record of construction impact.

MRCE developed bid stage design for underpinning and excavation support in the areas of the three crossings, which provided information necessary to consider potential modes of movement. Prior to selecting the appropriate instruments, the potential modes of movement and impact to adjacent structures/users had to be evaluated. These structures/users included:

1) Three 100 to 150 ft sections of active subway tunnel to be underpinned and then excavated beneath to permit construction of the new tunnel
2) Hundreds of feet of excavation support walls to be constructed immediately adjacent to, or within a 1:1 influence line of existing and active subway tunnels
3) Newly completed steel and glass façade Staten Island Ferry Terminal building
4) DOT Vent Shaft for the Battery Park Underpass
5) Peter Minuit Plaza, where thousands of daily commuters pass
6) Historic Landmark buildings, at 1 Broadway, 7 State Street, and the South Ferry Station itself, and
7) Other non-landmark high rise buildings including the curved 40 story 17 State Street tower and the Customs House – Museum of the American Indian

In addition, and as is typical throughout New York City, pedestrians and tourists along State Street and within Battery Park meander around and cross through the project nearly continuously, via pathways and sidewalks at grade.

At the crossings, the tunnels would be underpinned by installation of dozens of grout filled 9-5/8 inch diameter minipiles, followed by excavation of soil and/or rock beneath the tunnels and amongst the minipiles. The work potentially allows the tunnel to deform by twisting, bending, settling, racking, and/or rotating, either as a rigid body, or differentially between two points.

B. Instrumentation Components/Alternatives

1. Vibration Monitoring – Seismographs

The NYCT specification provided a threshold level for vibrations of 0.5 inches per second (ips) and a limit level of 2 ips at NYCT structures and buildings beyond. For the type of work and structures being considered we agreed that these levels were suitable. However, in order to adequately assess the vibrations resulting from construction and to provide information to the Joint Venture for controlling their work, a substantial number of locations would have to be monitored.

We proposed and installed 10 automated seismographs to continuously monitor vibrations. These sensors provide a continuous histogram of peak vibrations, and full waveforms for events above the project threshold limit. All recorded data are forwarded in real time to a project web site developed and maintained by Geocomp.

As many as twelve additional seismographs were added once blasting was implemented, as the rock was more difficult to excavate than anticipated and proved impractical to remove using hoe rams. In addition to MTACC, various other MTA organizations took part in reviewing the Contractors proposed blast plans, including Rapid Transit Operations (RTO), Maintenance of Way (MOW), and the Government and Community Relations office.

Too many fixed or automated units would have been required to cover the required blast monitoring locations for any given day to make real time remote monitoring of all seismographs practical. We added manual seismographs and moved them as necessary to adequately provide continuous vibration monitoring adjacent to blast locations as required by the Joint Venture, FDNY, MTA, and DOT. Data is collected and submitted daily to the Joint Venture and the MTA.

The full time presence of our field instrumentation engineers during months of blasting proved a valuable service, as our field sketches and daily and weekly reports clearly illustrate blast locations and corresponding vibration monitoring locations for each blast, thus documenting distances as well as tabulated peak particle velocities for evaluation by interested parties.

2. Ground and Excavation Support Wall Deformation – Inclinometers and Survey Targets

Inclinometers and survey targets were included in the monitoring program to provide data for evaluating the performance of the support wall during construction, and to assure the Owner that adjacent subway tunnels were not translating laterally and adjacent streets were not in danger of settling more than the allowable tolerance.

Determining optimum location to monitor lateral deformation required location specific consideration. Monitoring within the support wall yields wall deflection for each stage of excavation, while monitoring immediately behind the support wall shows the ground response to the wall deflection. Further, monitoring immediately in front of the nearest structure to the excavation support wall indicates the ground deformation and dissipation thereof where it may reduce earth pressures acting on an adjacent structure. Inclinometers within or immediately behind the wall are often preferred as they serve two functions: 1) they monitor wall deformation to allow early correlation with structural analysis and thus overall site safety and 2) they provide maximum lateral deflection, as soil deformations, both vertical and lateral, are known to diminish with distance from the wall.

To provide adequate data for the Joint Venture most inclinometers were installed within the support wall itself during wall installation. The instruments were initially monitored using manual inclinometer probes, and later with in-place inclinometers and data loggers, remotely and automatically delivering data every 3 hours to the project website.

3. Groundwater Monitoring – Piezometers

Groundwater piezometers equipped with dataloggers that relay data to the real time project web site were also included in the monitoring program to monitor changes in groundwater levels during construction. Location of the groundwater monitoring was discussed with the Contractor's dewatering subcontractor.

Original plans were to provide a "water tight" excavation support wall with minimal external drawdown (less than 3 ft), to protect adjacent structures from potential settlements that may have resulted from area wide groundwater drawdown. Our analysis indicated that recompression settlement of less than ¼" might result from complete groundwater drawdown to the rock surface beneath adjacent structures. Moreover, adjacent structures within an assumed radius of influence of site wide dewatering are mostly high rise buildings bearing directly on rock. Also, the subsurface was previously excavated and dewatered on at least three occasions, from original construction of the #1 train, the #4/5 train tunnels, and the vehicular Brooklyn Battery Tunnel (BBT) and Battery Underpass. While the #1 and vehicular tunnels are shallow, the #4/5 and the BBT are a similar depth to the new construction. Based on this analysis, the Joint Venture requested and obtained a waiver to the "water tight" requirement and thus received authorization to dewater the site ahead of excavation using a deep well induction system.

Although the criteria for less than 3 ft of groundwater drawdown was relaxed because of the waiver, several piezometers were installed and datalogged to provide feedback to the dewatering subcontractor and to document groundwater response. Groundwater readings are currently collected remotely on three hour intervals and relayed by wireless modems to a base computer which then uploads the data to the project website.

4. NYCT Structure Deformation – Total Stations, Tiltmeters, Extensometers, Fiber-Optics

While other instruments were considered to monitor structural deformations, we were unable to advance alternatives to equal the flexibility and coverage afforded by robotic total stations reading reflective prisms. Robotic total stations are theodolites similar to those used in manual optical surveying. They are equipped with high quality automated gears and an internal computer that once programmed, activates the instrument on a pre-selected schedule, reads a group of prisms in series, relays the data to an external computer, and then rests until the next reading. Also equipped with automatic target recognition, they focus in on the absolute center of the reflective prisms and as a result, obtain increased accuracy over traditional survey, especially in repeated monitoring tasks. Once programmed through a manual set of initial or baseline readings, the instruments can be set to automatically read a group of prisms on a set frequency, say every 2, 4, or 6 hours as conditions may warrant.

This automation was both critical and necessary, as access to the tunnels would not be possible on a daily basis, especially as the majority of the work does not take place within the active subway tunnels, but adjacent to and eventually, beneath the tunnels. A stable reference, anchored point, or backsight in this case, is required. A single total station was designed to be located on each side of each crossing, with stable reference or backsights positioned in the tunnel beyond a distance of 125 to 150 ft from the crossing, where no movement is anticipated. The total station itself may move, but automatic processing of the backsight data allows for the re-determination of the current instrument location based on the measurements of distance and angle to the stable reference points (via triangulation). Thus, data collected accounts for movement of the total station if it were to occur.

The total station alternative was optimum for following reasons:

- The change in three-dimensional location of targets affixed to the tunnel structure can be determined with time to a high degree of accuracy
- Additional monitoring prisms can be easily added to refine readings in areas showing movement

- Multiple prisms on close spacing, 5 to 10 ft, can be monitored individually, giving excellent resolution to evaluate structural response
- Redundant coverage achieved by using multiple robotic total stations to monitor each crossing
- Minimal locations requiring power, very few cables, and few moving parts
- Limited access to tunnels, as regular access is unnecessary

Concerns with the total station alternative were:

- Train clearance and sight lines within the tunnels, especially considering the frequency of passing trains
- Heat vectors and air flow and their potential disturbance to infrared signals
- Power and communications options and their potential interference with train signaling devices, including reliability of wireless communications in the busy tunnels
- Adequate redundancy if one or multiple total stations failed simultaneously
- Backup power
- Damage or theft
- Dust buildup and other routine maintenance
- Long term stability of readings, i.e. drift
- Limited access to tunnels, for maintenance if and when required
- Reliability of the total stations in the project environment

Tiltmeters or tilt beam sensors, where a string of sensors could be mounted in series along tunnel walls, end to end, were considered as an alternative to the total station. Uniaxial or biaxial angle changes of fixed length rods connected to common bolts at pivot points over time would provide the necessary data to determine if vertical or horizontal movement occurred along the crossings, respectively. This system likewise required fixed reference points beyond the anticipated zone of movement. This was a viable alternative, but offered less redundancy, required more power connections and cabling, and had many more operating parts when compared to total stations. We were also uncertain that there would be continuous evenly spaced runs of tunnel available for which to mount the rod sections as protrusions from the wall would require boxing out the string or other details for which we could not plan in advance of installation as sufficient access was not available prior to implementation.

Individually mounted tiltmeters would not provide an equivalent system. Hypothesizing tunnel deformation from individual tiltmeters requires knowledge or at least an assumption of a point of fixity or a hinged point around which the structure rotates. As such knowledge could not be known in advance of interpretation, the risk of obtaining multiple interpretations from the same tilt data was considered too great and more direct measurements of tunnel deformation were sought.

We only briefly considered liquid levels systems, where very accurate settlement profiles can be obtained using a hydrostatic and stable reservoir controlled by an overflow chamber, continuous tubing or piping and periodically spaced pressure transducers that measure the static head at each measuring point over time. If a measuring point settles, the height and thus pressure between the reference elevation within the reservoir and the pressure gage increases, and the elevation of the sensor can be read to within a fraction of a millimeter. We abandoned this alternative primarily because an additional system was required to monitor horizontal movements, and we had concerns about maintaining the piping and reservoir system.

We considered a fiber optic alternative, which is capable of providing dynamic strain measurements at a much greater frequency than either of the alternatives. A network of fiber optic lines can be orientated and installed such that a change in the strength of reflected or refracted light transmitted through and received at measurement points indicates changes in length between measuring points, as light travels at a constant speed. It did not appear to us however, as capable of providing an equal number of measuring points or an equal redundancy to either the total station or tilt beam sensor alternatives described above. Our main concern with this system was finding stable reference points in two planes, as it appeared cost prohibitive to run profiles as far out as would be necessary for either the tilt beam sensors or total station alternatives. A local reference point considered, but later dismissed as impractical due to schedule and access, was to anchor fiber optic rods into rock adjacent to, or beneath the tunnel, where it may not be disturbed by construction. We believe this technology has advantages over more traditional monitoring systems where dynamic measurements, hundreds if not thousands of readings per second, are warranted due to constantly changing loading conditions, as in the loading of structural members on a bridge for example.

The results of our proposed program are illustrated in Figure 5, where the originally proposed instruments are located and the ranges for which the total station would monitor reflective prisms are shaded. The new #1 tunnel is cross-hatched for clarity.

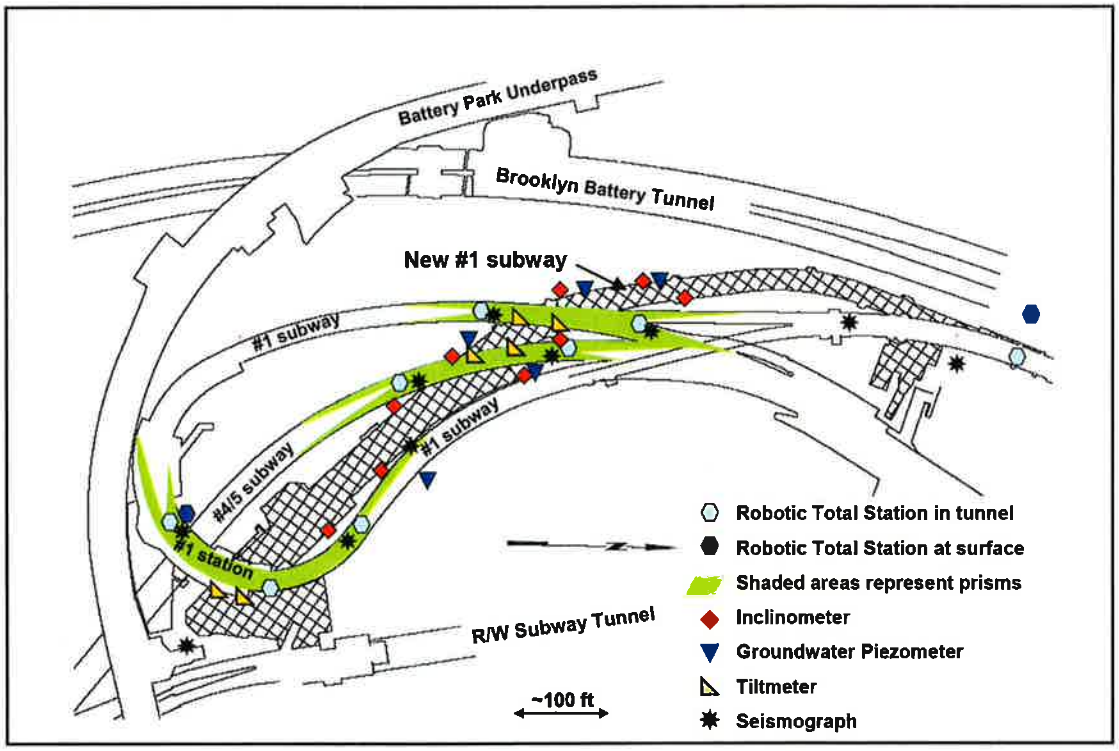

Figure 5: Instrumentation Plan

III IMPLEMENTATION AND INSTALLATION SCHEDULE

The NYCT subway system runs non-stop 24 hours per day, 7 days per week, 365 days per year. By observation, trains on the #1, #4 and #5 line typically pass every five to 10 minutes between 5:00 am and 8:00 pm, with train gaps gradually widening to every 15 to 20 minutes between midnight and 5:00 am.

At the start of construction, access became available either under night or weekend flagging during active train service where work is interrupted every five to 15 minutes to allow trains to pass, or during night or weekend General Orders (GOs). GOs are the NYCT's temporary track outages where the third rail is de-energized and work can progress without impact from passing commuter trains, though diesel powered work trains may still operate. The nightly work shifts are generally limited to the hours of 11:00 pm and 5:00 am (6 hours), while weekend shifts generally run from 12:00 am Saturday morning to 5:00 am Monday morning (53 hours). The actual time available for progressing the work within these shifts, after accounting for shift changes and confirmation of either track outages in the case of GOs, or setting up the tracks in the case of flagging, is reduced by 15% to 30%. SGH opted to work 12 hour shifts through the weekends, in efforts to maximize efficiency. It was not unusual for weekend work to consume 18 to 24 hours.

Communication and coordination was of the utmost importance. Survey layout work, utility relocation, temporary lighting and power drops, and other tasks commenced immediately in constrained dark and dirty work areas, complicating instrument installation and squeezing an already short baseline period. Demolition and minipile drilling commenced as soon as locations became physically accessible.

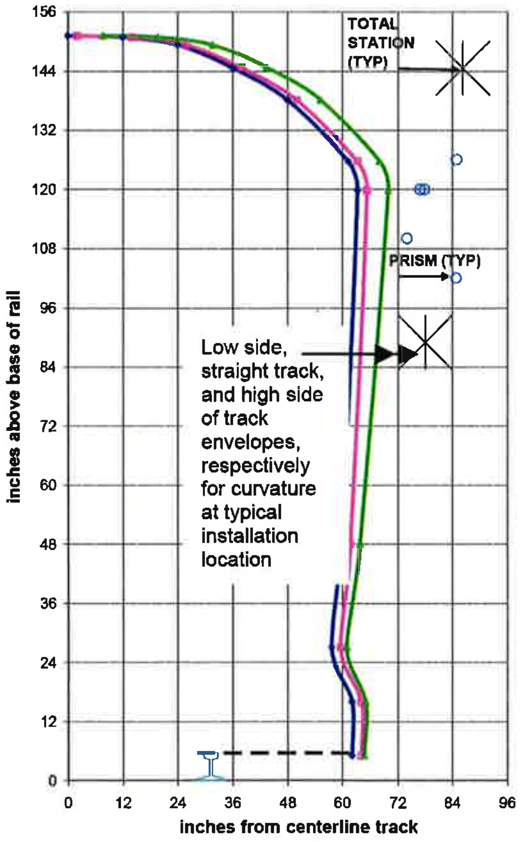

Figure 6: Typical train envelope and clearance diagram showing instrument locations

hile the instrumentation components re determined, actual locations for total stations were not selected until tallation. Sightlines were checked m multiple potential instrument ations to determine which would ovide the greatest tunnel coverage, fficient overlap to provide the ended redundancy, and a visible ed reference point far enough from active work zone. Each potential ation had to be checked against the CT train envelope, to assure that the trument would not be struck by a ssing train. Formulae provided by the CT allowed for computation of the nimum clearance from the rail at rying heights above top of rail as a ction of superelevation and rizontal and vertical radii. As strated below, often only a few spare hes were available, warranting ditional independent measurements. sample diagram and resulting arance for a robotic total station and veral reflective prisms is provided in gure 6, the three lines representing low side and high side clearance es for the track alignment and rvature at a specific location, and that straight level track.

IV RESULTS TO DATE

The project web site and central data storage system provides for real time data access and review of large quantities of data in multiple forms. Databasing, organizing, and sorting data are necessary in large instrumentation projects such that data evaluation can be performed routinely and efficiently. The majority of the data collected to date is from blast vibration monitoring, as excavation beneath the tunnels has just commenced.

A. Vibration Monitoring – Seismographs

Figure 6 provides a one year histogram of peak particle velocity at one specific location. The data represent a grouping of raw data collected at four minute intervals. It shows pre-blasting baseline during normal train service (May through November), and typical blasting vibrations between November and February and again between March and April. Other seismograph locations affixed to tunnel walls, especially the more flexible center crash walls, experienced baseline vibrations from passing trains as high as 0.3 ips, illustrating the variability of vibrations at different points along the structure and the importance of sufficient baselines.

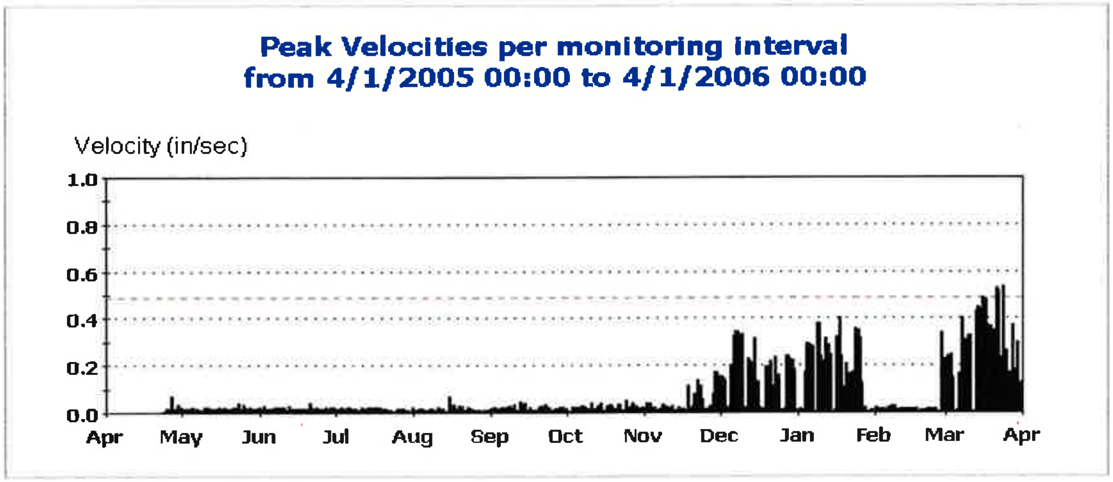

Figure 7: One year histogram of seismograph data

Concurrently with recording histograms, individual waveforms are recorded and uploaded to the project website for evaluation whenever a vibration event exceeds the preset trigger level of 0.5 ips. An example waveform from one blast is provided as Figure 7. This information is available to project staff within three hours of the event.

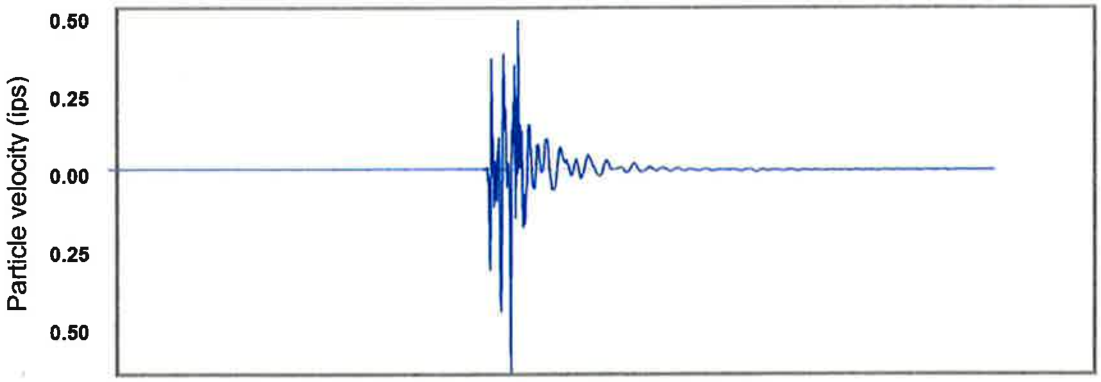

Figure 8: Typical waveform for blast vibration event exceeding 0.5 ips

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 high readings if this effect is not recognized.

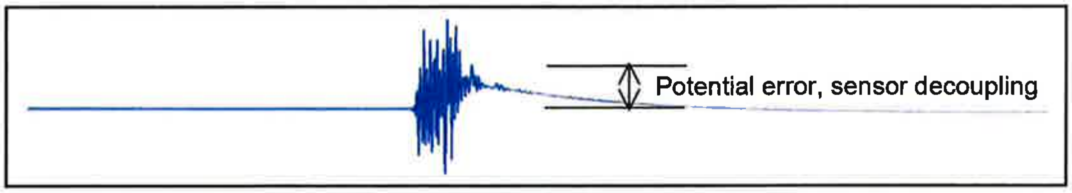

Figure 9: Decoupled waveform, example of an inaccurate seismograph reading

In addition, specifics of the construction events that resulted in the above vibrations are necessary to allow engineering interpretation. For the Contractor and their blaster to incorporate the monitoring data in their blast design and make the blasting more efficient, i.e. increase rock removal while minimizing the number of vibration events that occur above threshold, they need scaled distances, blast configuration data, and estimated versus measured peak particle velocities from regression analyses. To obtain this information requires careful recordkeeping and constant communication between the Contractor, blaster, engineer and Owner. With this information, the blaster can then make use of the monitoring data and adjust blast design parameters daily as site conditions warrant.

Vibration summary tables are submitted daily, with more detailed weekly blast summary reports providing the tabulated data for the week along with blast location plans showing all seismograph monitoring locations and daily field reports for our site engineers. The automation process streamlines data collection and greatly improves archiving and managing the data, but the field presence remains a necessary and invaluable tool to allow incorporation of the monitoring data into the blast design.

In the past five months, blasting has occurred on more than 95 days with more then 900 individual blasts. To date, we have collected, tabulated, and reported more than 4,000 peak particle velocities and frequencies, providing distances from each seismograph to each blast. Monitoring data from a typical blast are provided in Table 1, and several summary plots of vibrations versus log distance are illustrated below in Figures 10A and 10B, with "typical intensities of vibration from the operation of construction equipment" from Wiss (1981) superimposed for comparison.

Blast #	Date	Time	Seis #	Structure	Dist (ft)	Estimated PPV (ips)	Measured PPV (ips)	dB	# holes	Depth (ft)	# Explo.
79C	4/1/2006	14:17	S-7	NYCT signal room	10	2.7	1.7	104	9	4	7
			S-1	NYCT tunnel	45	0.2	0.4	114			
			S-6	NYCT signal room	45	0.24	.53				
			S-4	NYCT roof	50	0.2	0.3	136			
			S-3	NYCT tunnel	245	0.02	<0.1				

Table 1: Typical data collected for an individual blast

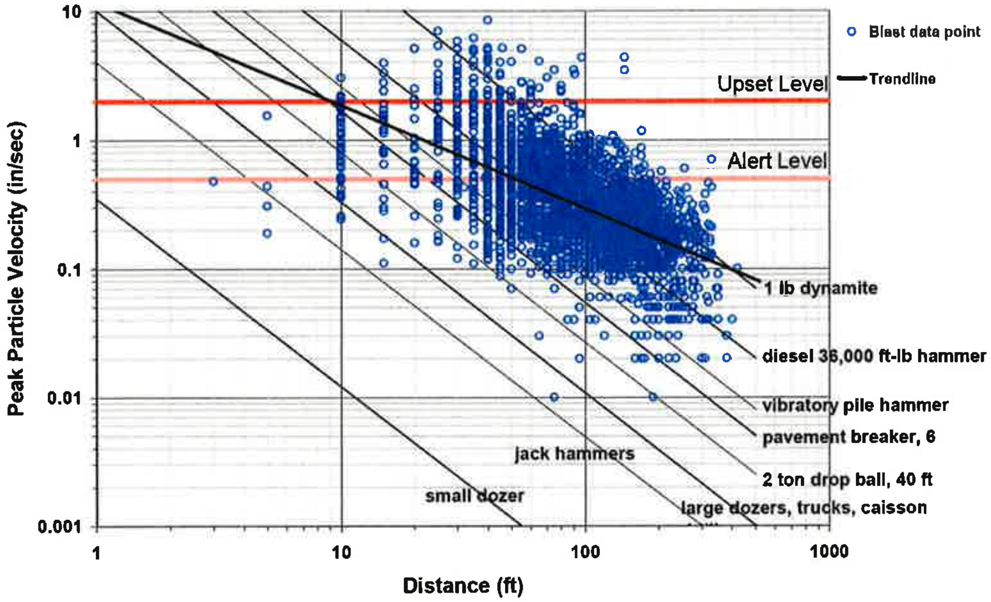

Figure 10A: All data to date, includes non-structural monitoring data, i.e. points not on structures

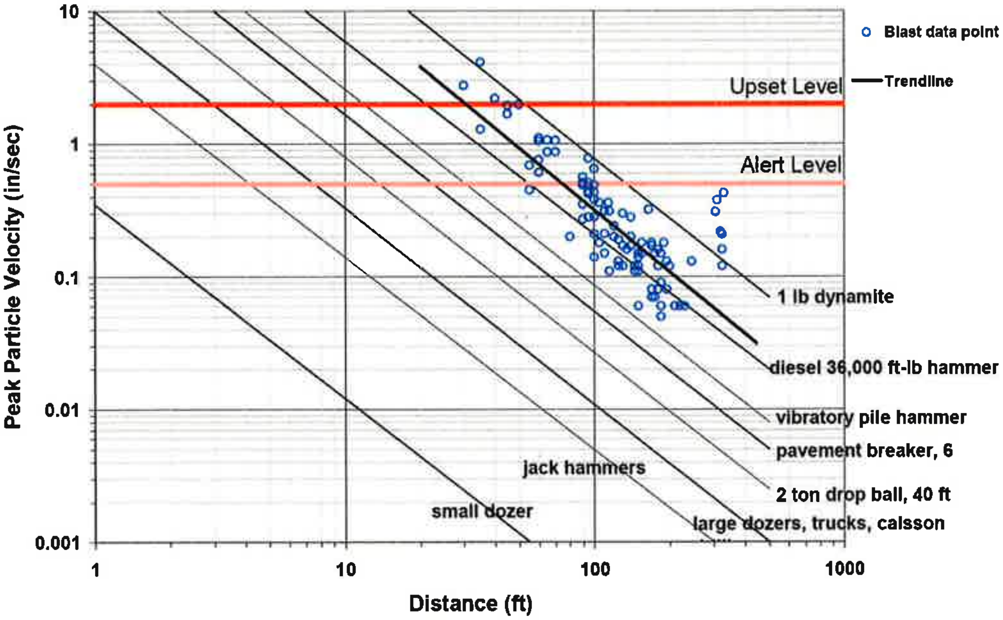

Figure 10B: All data from one specific location, note better trend line correlation with reference data

As seen by comparing the linear best fit trend lines in Figures 10A (all data) and 10B (one specific location), the scaled energy correlation is highly dependent on similar ground conditions between the blast and the seismograph. This example illustrates that blast vibrations are not significantly different than those from a 36,000 ft-lb pile driving hammer. It is thus prudent to look at each seismograph location individually, and to consider how the vibration travels from the source to the instrument, through rock, through soil, or through structure.

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. 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. In urban areas, especially in "close-in" 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. Close-in blasting is defined by Dowding (2000) as "within meters of the construction blast holes."

Waveforms should be reviewed where appropriate to verify instrument function and to identify commonly ignored or unnoticed malfunctions caused by "aliasing" and/or "decoupling". 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 "close-in" blasting. These phenomena may result in false high readings.

B. Tunnel and Structure Deformation Monitoring (total stations and reflective prisms)

Group plots of height vs. time, northing vs. time and easting vs. time are provided on the project web site for engineering evaluation. The plot below shows three months of data from 11 reflective prisms read by one total station in relation to threshold and limiting criteria of 0.5" and 1" respectively. The one outlying point at +0.15" was never re-zeroed following installation, but as is aids in illustrating the system repeatability for a typical individual sensor, say 0.05" in this case. Clearly, there is no measurable settlement or sloping trend lines. Plots such as the one shown in Figure 11 are reviewed by engineers daily.

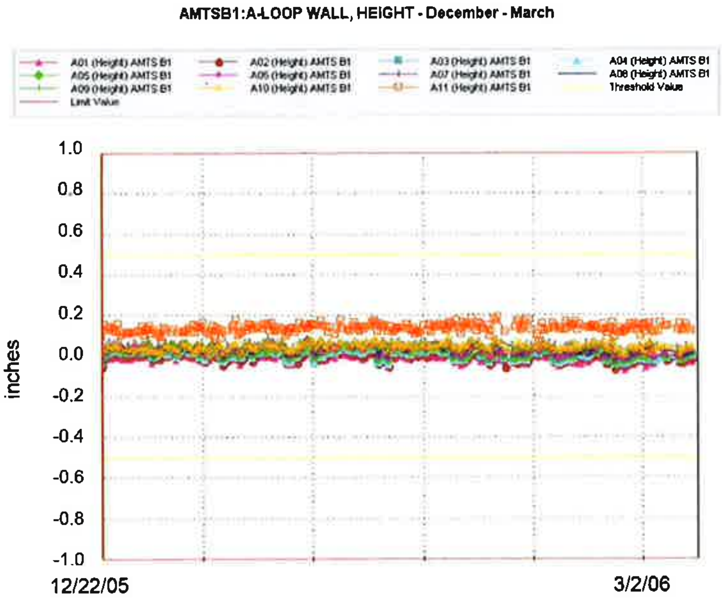

Figure 11: Tunnel Deformation Plot, height versus time

In-place inclinometers and automated real time tiltmeters and piezometers show little or no unusual trends to date worthy of highlight in this paper. Construction progress records, however, to allow engineering interpretation and evaluation of the data or to confirm or justify observed movements are strongly recommended. These snapshot images of construction progress provide documentation for record purposes, and allow the engineer the ability to go back into the files and determine what stage of excavation was present at any time. A small portion and example of one such construction progress plan is illustrated in Figure 12. This information is essential to the effective interpretation of measured data.

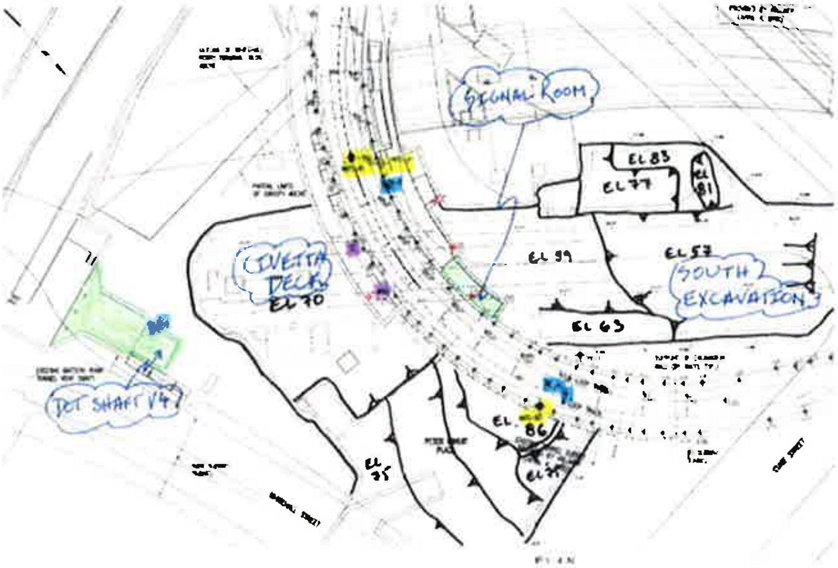

Figure 12: Portion of construction progress plan

V ISSUES TO CONSIDER IN INSTRUMENTATION AND MONITORING DESIGNS

The following thoughts and recommended topics for further discussion or development within the field of instrumentation and monitoring:

- Labor relations – How much direct experience do most engineers have with unionized labor? Surveyors are unionized in New York City. They consider all activities involving a total station to be their work. Using total stations to monitor deformations is not surveying in the typical sense of the word, as we are not laying out points for construction. It is deformation monitoring, where the instrument, once set up, is frequently and remotely, unmanned, re-shooting angles and distances to reflective prisms. However, when a union survey chief sees an Engineer looking through the lens of a robotic total station, they see a surveyor's job potentially in jeopardy. We recommend that the practice of requiring a licensed surveyor to oversee automated total stations used for deformation monitoring be stopped. Licensed surveyors generally do not perform survey to the accuracy required for monitoring deformation during construction.

- Education of Labor Force – We struggled with how much to inform everyone of details of the tasks we were performing. When tens of thousands of dollars of equipment are housed in containers small enough to be packed up in backpacks, how much do you want to broadcast it? On the other hand, the overwhelming majority of workers do want the project to succeed and do take pride in performing well, and helping the greater cause. Knowing for instance, that we were not installing video cameras within the tunnels to make sure the laborers are not taking too many breaks, as one laborer inquired to his foreman, cannot be an adverse side effect of educating the laborers.

- Working for a contractor as part of a Design-Build team – Accepting terms and responsibility of working directly for a contractor, the hours and demands, meeting schedules, responding to short term needs to keep the project moving forward and the equipment and crews on schedule, i.e. delays = time lost = money spent. These are not unusual or atypical considerations for contractors, as they are ingrained in the psyche of every executive, superintendent and foreman, but they are often not given enough thought by engineers. Typical "lost days" for a contractor, for a crew of say a couple dozen workers, a dozen or so heavy pieces of equipment, some rented, some owned, may result in a cost of hundreds of thousands of dollars per day, not to mention the impact on schedule and hence, one more day lost during which they can't start a new project. If an engineer can prevent such a loss by adding a $6,000 seismograph and an inspector to appease an adjacent property owner, or a dozen or so overtime hours or a weekend or a night shift to prepare a submittal or report that may result in engineering fees on the order of one to two thousand dollars, is there any question in a contractor's mind as to whether or not an engineer should do so? This requires the willingness of engineers to adapt to a contractor's work ethic and hours. Many a weekend and or night shift were sacrificed by dozens of engineers who assisted in making this project a reality. It has become an unfortunate reality that what one believes will take but a few hours to achieve on a weekend or night shift, ends up consuming an entire day, or two, once that person enters the MTA tunnels and becomes just a piece of much larger tasks, where your priority is but a speck in the overall picture of things.

- Usefulness of large quantities of data and its impact on both design and construction decision making – Large quantities of data can provide redundancy and confidence in observed trends, and provide backups for obscured sightlines, damage or temporary service interruptions. As for impact on design or construction, we attempted to locate the instruments at the most critical locations such as to verify design loads. We as engineers must continue to set aside time to review all the data, as once it is put on line and made so readily available, it is easy to let days go by without really evaluating the data. Is simply putting too much trust in an automated alarming system a dangerous thing? After weeks, or months, or years as the case may be, of no significant movements, does it become too easy for the instrumentation engineer to evaluate only the electronic data, and as such, visit the site less frequently, which is arguably the only way to truly understand what is, or should be happening, or what to look for in the data?

- Getting your money's worth – The quintessential problem with instrumentation and monitoring remains though, that contractors generally feel as if the monitoring data, more often than not, is used to "police" their work as they are expected to build the project within the established threshold limits and any breach of the thresholds is considered a "failure". As such, the instrumentation and monitoring are seen merely as a headache and chalked up as part of an insurance type cost. Something they absolutely agree they must have to prevent unsupportable claims. Seldom are monitoring data used to allow a contractor to speed up construction or to take more risk, to widen spacing between braces for example, ultimately saving time or cost, while often data evaluation results in construction slowdowns as others decide if the magnitudes of movement are acceptable. To the MTA and design team's credit, results of blast vibration monitoring has been continuously evaluated, discussed, reevaluated, and then used to improve the blast design, implementation procedures and effectiveness of the blast program without unduly restricting the Contractor.

- Exceeding threshold values – In most cases, exceeding a threshold value is ultimately accepted by the Owner as long as safety is not compromised and damage to an adjacent structure resulting from such an event is unlikely. It is our job, as engineers, to determine a way to use this very valuable data to benefit a contractor such that a more positive view of instrumentation and monitoring spreads throughout the industry. Widespread use of real time instrumentation is here to stay and is becoming more and more "user friendly", so we must find a way to maximize its effectiveness. The speed at which newer types of instruments, or at least ways of communicating with the instruments and obtaining more and more data, is expanding and improving with increasing speed every year. Consolidation of technologies and systems integration is imperative in solving construction's instrumentation needs cost effectively.

- Data Presentation – Instrumentation engineers must avoiding information overload and present data in a manageable way. We must avoid collecting large quantities of data and forwarding it without providing enough information for the receiver to make sense of the data as a stand alone document. We should obtain, prepare and present construction progress diagrams, sketches or other information with the monitoring data to help validate and interpret recorded movements.

- Emerging and improving technological advances – real time monitoring, cabling vs. wireless technology, computer interfacing, programming, integration, the pace of emerging technologies are accelerating. We, as engineers, have to continue to adapt to an ever increasing number of options to make the instrumentation and monitoring more effective for Owners at reduced costs, or provide more value for similar costs. For example, most people will tell you that radios are unreliable in tunnels. However, by using some of the latest wireless technology, we are able to move data from instruments in the tunnels to the web very reliably, even with trains disrupting lines of sight between wireless units.

- Contract Document Specifications – With emerging and improving technologies mentioned above, there needs to be more emphasis on creating clarity in the specifications for instrumentation and monitoring. Older versions of specifications will become obsolete more rapidly, and updates should consider allowing greater flexibility in the systems to allow for ingenuity in the interpretation of the specification as long as the resulting objective is maintained. We urge more performance based specifications for instrumentation and monitoring to permit the instrumentation specialist to use the most appropriate technology. More discussion between engineers, owners and manufacturers are necessary as the field matures and newer technologies are incorporated at increasing rates. The instrumentation, monitoring and evaluation should under many circumstances, be undertaken and under the direct control of the Owner, not a contractor, as the Owner carries the longer term responsibility of answering to the needs or complaints of adjacent property owners. The process of selecting appropriate instrumentation and monitoring means, perhaps even to the extent of pre-installing and baselining instruments in a separate contract prior to some major construction projects, should be considered by the engineer during preliminary design.

- Criterion – Often the criterion for deformation does not differentiate between specific instruments in question. Why should a contractor or engineer design an excavation support wall to deflect less than ¼" or ½" horizontally, or even three inches for that matter, when there is nothing but parkland within the active earth pressure zone behind a length of support wall? More often than not, the strictest criterion along the length of a project is determined, perhaps along a length of wall that needs to support an adjacent structure, and that criterion is applied to the entire project. Perhaps these requirements are carryovers from historical projects, with too little time or too little attention given to revising criteria for each project. As such, Owners pay an unnecessary premium for "rigid" wall designs with earth pressure coefficients approaching at-rest pressures.

VI CONCLUSIONS

This example case history summarizes the development of a real time instrumentation and monitoring program for a complex geotechnical construction project in Lower Manhattan. As of the date of writing this paper, construction is entering the most critical excavation phase where dead and live loads on the existing tunnels will be transferred from its original bearing on soil or rock from 100 years ago, to the newly constructed minipiles. We are confident that we have designed and implemented an efficient monitoring program that will continue to provide the necessary data to evaluate the impact of construction on adjacent structures, if any. We look forward to monitoring the work through to completion of the new #1 train subway tunnel construction and will consider an updated publication, with MTA and client approval, to provide additional monitoring data.

The real time monitoring system developed by MRCE/Geocomp for the South Ferry project has already provided significant value to the project. Some of the benefits include:

1. Reliable monitoring of the movement of many points located on structures several times a day with a repeatability of less than 0.05".
2. Detailed monitoring and evaluation of the effects of blasting to help the contractor maximize the blast pattern at each location without damaging nearby structures.
3. Ability to detect small movements of excavation support system within hours and thereby greatly reducing the risk of an unexpected collapse.
4. Sufficiently robust and responsive to satisfy the Owner's extensive requirements; but at a sufficiently low cost to help make our Design-Build team's proposal the winning one.

The authors would like to thank many people for assisting in the design, implementation and ongoing monitoring for this project as the information summarized within is the product of many hours worked by those other then the authors. Those people include but are not limited to, D. Cacoilo, R. Ellman, W. Kaeck, A. Arana, E. Delossantos, N. Abi Saab, A. Peltz, S. Johnson, A. Ciamei and D. Busick of MRCE, and R. Nyren, J. Tripp, R. Drefus and M. Hawkes of Geocomp. We would also like to thank ASCE for the opportunity to present this paper, the MTA, as Owner, and the Schiavone-Granite Halmar Joint Venture for their confidence and support of our team.

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