

## PRECISION SURVEYING MONITORING OF SHORING AND STRUCTURES

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**ABSTRACT:** This paper provides a synopsis of the state of practice of manual total station movement monitoring. Different variables such as instrument used, accuracy under varying and challenging conditions, sources of error, establishment of accurate baseline readings, set-up and control of survey networks, and reporting, distribution and archiving of data are examined. A specific project located in downtown Toronto provides an example of practical and technical aspects of precision survey monitoring. The excavation for the project was seven-stories deep and occupied an old, open parking lot next to several sensitive and/or significant buildings. Sixty-five targets placed on surrounding structures were monitored with a total station theodolite. Inclometers, crack-gauges and preconstruction condition surveys of abutting structures were also part of the monitoring for the excavation portion of the project.

### INTRODUCTION

Surveyors involved in the monitoring field have most likely learned the benefits of monitoring structures and shoring during their career. However, due to the many variables that encroach on the physical world, surveyors must be extremely cautious with the management of errors and must have an understanding of which variables can affect readings. In field applications, precision surveying monitoring is used to protect lives, provide cost savings, verify design assumptions and reduce risks. In theory, these are simple and easy benefits to realise. In practice, these benefits may be difficult to measure and record due to site conditions, access problems, ignorance, and budgetary constraints.

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## **VARIABLES AFFECTING PRECISION SURVEYING MONITORING**

### **Instrument Selection**

While there are many Total Stations on the market, many are not sufficiently precise for most monitoring applications. A precision instrument is generally one with published specifications of  $\pm 1$ mm per 100 metres or less in the Electronic Distance Measurement (EDM) and 1 second or less in the angular measurement. Instruments with this level of precision all contain dual-axis compensators, which compensate for 3 to 6 minutes of movement. Manufacturers of these instruments include Leica, Sokkia, Topcon and Trimble. In practice, it has been found that high precision instruments with the finest accuracy do not add value to the monitoring data. Highly sensitive instruments tend to be too sensitive when used on typical construction projects, since the environmental conditions are not generally controlled. Vibrations, temperature changes, movement in reference points, and unstable ground conditions cause degradation in the observations. Whilst these are usually small errors, it is hard to determine with confidence that the results obtained are better than  $\pm 1$ mm to 2mm under the above mentioned conditions.

### **Accuracy**

In theory, any surveyor can attempt a precision surveying project. However, due to the nature of the work, the practice is much more difficult than would be expected. While the principles involved in surveying are the same for all surveyors, one experienced in precision monitoring will understand that the standard of care is much higher than the standard required for typical survey work.

By using optimal geometry for the position of reference points, it is possible to obtain an accuracy of less than 1mm over the X, Y, and Z position of the instrument. By conducting an accurate and precise re-section to known co-ordinates, the instrument will fix its position and record all the data. Precision surveyors working in the field can obtain an accuracy of less than 2mm by using at least four reference points. By using reference points attached to buildings and structures outside the zone of influence, errors can be minimized. The more reference points that are used, the more accurate the outcome.

Surveyors traditionally work within an error bar of  $\pm 5$ mm, using points in the ground close to the site. By placing precision surveying reference points far from the construction and then completing a traverse to the site, co-ordinates can be obtained without interference from the zone of influence.

### **Background Movements**

Everything moves, all the time. By keeping this in mind, it is possible to filter out the background movements on a project. Thermal loading, settlement, frost invasion, strong winds, weather fluctuations and heat shimmer can all cause background movements.

Thermal loading, even in a Toronto winter, carries a great deal of energy. As buildings and structures expand and contract due to the transfer of energy, the reference and monitoring points move with them. Energy from the sun can shift a tripod and/or instrument, as will shadows from clouds moving across the instrument whilst taking observations. To help address this problem, the instrument should be placed in either full sun or full shade. The instrument must be allowed to acclimatise on the tripod before taking observations. The effects of thermal loading can be reduced by taking observations early or late in the day.

As water is pumped from the excavation, settlement of points may occur. If control points are seen to be moving, re-surveying the affected point(s) using stable control points away from the zone of influence is necessary.

Frost invasion of control points can be a problem in cold climates. By placing control points above the ground, on structures and buildings, it is possible to minimize this problem. While points on the ground will heave and subside with a frost and thaw cycle, points on buildings and structures are more stable and adverse effects are minimal. It is also possible to install deep datum points extending well below the frost line.

Strong winds and other weather fluctuations can cause observation errors. Attempting to take observations under inclement weather conditions causes stress for the observer and can cause degradation in the accuracy and precision of the readings. One gust of wind can blow the instrument out of alignment, so it is important to keep the tripod firmly anchored. If the wind is causing errors, it is advisable to take observations at another time. If this is not an option, then considerable time, patience and persistence will be necessary to have any chance of obtaining good observations. Most other daily weather fluctuations are compensated for automatically by the advanced instruments of today.

## **SOURCES OF ERROR AND ERROR MANAGEMENT**

It is critical for a surveyor to take the time and care, both in the field and when processing data, to avoid or minimize errors. The most common errors encountered in the field include pointing errors, observation errors, vibration errors, calibration, and instrument drift.

### **Pointing Errors**

Pointing errors are caused when the instrument is not pointing directly at the target when the reading is taken. This normally occurs when the surveyor does not take the time to ensure that he/she is truly pointing at the target when taking a reading.

### **Observation Errors**

Angle of observation errors are caused by the laser being smeared over a target as it measures the distance. This normally occurs when the target is too oblique or acute in relation to the instrument.

Long observation errors are caused by too much distance between the total station and the target. This normally occurs when measurement distances exceed 100 meters.

Heat shimmer causes sighting problems when targets become a blur through the telescope. This occurs more often in summer when the atmosphere carries a great deal of heat and targets appear as wobbling, blurred smears as the day progresses.

Taking observations in the early morning is one of the most ideal options in this situation. Other options include short sighting distances (not always possible), taking observations in late afternoon (not as good as morning because of accumulated dust and heat in the air) or taking observations at night (logistically difficult).

### **Vibration Errors**

Vibrations from nearby machinery or de-watering systems on the project site can cause a noticeable degradation in observations. This normally occurs when the instrument is set up too close to a vibration source. Wind vibration is less of an issue; however, it can cause the instrument to drift or create difficulties with calibration checks. Setting up the instrument near a busy road with vehicles travelling over grates or manholes can cause the instrument to move out of alignment due to vibrations. Regular checks to reference points whilst working are recommended.

### **Calibration**

Precision total station theodolites require calibration at least once a day. Calibration is affected by temperature changes, barometric changes, and altitude changes. Transporting the instrument in a vehicle can cause vibrations and it is advisable to calibrate the instrument at the end of each journey. Yearly visits to the instrument manufacturer for cleaning and factory calibration are also recommended.

### **Instrument Drift**

Drifting of the instrument is most commonly caused by unstable ground conditions, strong winds or uneven sun exposure. By anchoring the tripod legs securely, it is possible to decrease the risk of drifting. It is also advisable to let the instrument acclimatize on the tripod for five to ten minutes, before commencing observations. A brace for the tripod legs prevents sliding when working on smooth surfaces. Even the slightest bump or knock to the instrument may cause it to drift off alignment. Care needs to be taken during observations to ensure there is nothing touching the tripod.

## **PLANNING AND EXECUTING A PROJECT**

The outline below is presented from the perspective of a survey monitoring specialist. It is always a good idea to take the time at the start of a project to confer with the site authorities about site conditions and access plans. Some of the steps involved in the precision surveying monitoring of shoring and abutting structures include:

- meetings with stakeholders, owners and engineers;

- planning the site activities;
- installing and initializing the control network and monitoring points;
- taking regular observations and processing the data; and
- reporting, distributing, and archiving the data.

### **Meet with Stakeholders, Owners and Engineers to Optimize Program**

The first step in a project is to meet with the stakeholders in charge of the construction and shoring design to plan the locations of the monitoring points, the frequency of the observations, and to define the review/alarm levels, if any.

During this meeting, it is important to determine:

- concerns for the project;
- locations of any sensitive structures;
- locations of any potentially hostile neighbours;
- locations of any underground services;
- expected movements for the project;
- distribution method and list for the monitoring data;
- action plan if the measured movements exceed the anticipated movements;
- monitoring frequency;
- party responsible for reviewing the data and adjusting the monitoring program if necessary;
- contact details for the site coordinator and shoring contractor to coordinate the first site visit.

### **Planning the Site Activities**

The next step is to visit the site and conduct introductions with the site supervisor and shoring company supervisor. During this visit, it is necessary to determine the details and staging of the excavation (i.e. the gate and ramp locations, the excavation sequence and the location of a geodetic benchmark). Practical considerations to be discussed include: the location and height of any hoarding being placed around the site; sign in and out procedures for entering and leaving the site; specific site conditions relating to safety and/or set-up; and location of first-aid kit, eye-wash, and the nearest hospital.

In order to plan where to set up the total station, it is important to be aware that large pieces of machinery will be moving even larger pieces of material around the site. A key part of the planning involves obtaining information from the site supervisor regarding staging of construction activities, with respect to selecting instrument set-up locations that are safe and away from the influence of vibrations and heat exhaust. Targets used for monitoring and control are self-adhesive and reflective, and are attached directly to the structure to be monitored. Targets are available from various suppliers. A small amount of cleaning is normally required to affix the target to a structure or pile. Quite often, it is beneficial to place targets well above ground level on structures, to facilitate their observation and to keep them out of the reach of the public.

Before precision surveying monitoring points or reference points are placed on structures around a site, it is good idea to obtain permission from the owners or managers of these structures. It is also recommended to meet with building owners or managers to gain access to the structure and answer questions about the project. If your client (or your client's client) is in the process of negotiating tie-back encroachment agreements, then coordination and communication are critical. This will reduce potentially upsetting hostile neighbours and/or replacing targets that have been removed by owners and managers through ignorance or anger.

### **Installation and Initialization of Control Network and Monitoring Points**

The control network is the anchor that ties the whole survey-monitoring package together. See figure 3. Without strong control, the observations taken are of no practical use. Control points should be placed on sound, rigid structures not prone to movement due to thermal loading, frost invasion, etc. For example, targets on structures with visible expansion joints or cracking typically do not make good control points.

All control points must be placed outside the zone influenced by the excavation, but in a location where access through the gates is possible without placing anyone in danger, including the public. A good rule of thumb is to multiply the final depth of the excavation by a factor of 1.5. Therefore, if the excavation is to be ten meters deep, then the zone of influence will extend at least fifteen meters from the edge of the excavation. For very large excavations, the effects from ground relaxation due to the amount of material being moved can result in counter intuitive movements i.e. neighbouring buildings may tilt away from the excavation.

Control points should be placed on at least two axes with a minimum of six points. It is always a good idea to set one wall of the excavation either as a North-South baseline or as an East-West baseline. This allows the lateral movements to be shown in relation to moving into or out of the excavation. On most projects, due to line-of-site constraints, it is necessary to utilize temporary control points that are within the zone influenced by the excavation. The position of these points must be checked relative to stable benchmarks each time they are to be used.

Once the control points have been installed, they can be surveyed using the total station. By measuring the distance between two points along one wall, it is possible to calculate local co-ordinates for them. It is much easier to set a baseline along the shoring wall in the field, rather than utilizing rotations and/or co-ordinate shift calculations during processing. By using the height difference, an assumed height may be calculated for the points. Once an observation is taken to a benchmark, the height difference between the starting points and the benchmark can be calculated to assign the geodetic elevations.

The co-ordinates for these two points can be used to calculate a re-section solution. This is typically done by the on-board computer on the total station using a least-squared adjustment program. This solution should give values very close to zero, if not zero (measured to 0.1 of a millimetre). If the solution is not less than two millimetres, then the instrument should be moved to a better position relative to the points.

Typically, observations of the control points are now made. By taking multiple readings to each point and calculating the average position, it is possible to set strong baseline readings for each point. These sets of observations should fall within at least two millimetres of each other. With the control points co-ordinated and stored in the instrument, initial readings to monitoring points can commence. It is important to maintain the control network by taking regular check observations while doing resection setups. If the solution error is growing, it will most likely be that one or more of the control points is not stable (i.e. it is moving). By creating a solution and checking through the computed co-ordinates, it is possible to find the point or points that may have moved. Then by re-surveying these points and using the new co-ordinates obtained, they may be used again in the network.

On most projects, the precision survey monitoring points on neighbouring structures are installed before the pile target monitoring points. The initial position of the precision surveying monitoring points should be observed before any excavation/construction commences. In addition, it is typically desirable to establish baseline readings that capture the magnitude of background movement, prior to any construction influence.

Once pile target installation has commenced, it is a good idea to use the same targets as temporary control points on a regular basis. By doing this, it is possible to identify quickly if those targets are moving. Pile target installation should start before the excavation exceeds 1.5 meters. Be alert to the fact that piles may be trimmed down after installation and therefore targets may be destroyed. Once the targets are installed, baseline readings are taken. At least two sets of initial observations are typically used to calculate the initial location of the pile monitoring targets.

### **Conducting Regular Observations and Processing the Data**

Regular observations are typically taken on a weekly basis for the pile targets and on a monthly basis for precision targets. If unexpected movements are discovered, the stakeholders will quite often request more frequent readings of areas of concern. If significant movements are measured, then extra observations should be taken to verify that the movements are true and not due to error. Close attention should be paid to the co-ordinates of any temporary control points. Verification of a movement outside of the alarm levels should trigger a response which normally involves contacting stakeholders and notifying them of the movement.

Once observations are completed, processing can commence. By using a planned procedure for processing, results can be processed and calculated in a structured way, which saves time while creating verifiable data. While processing, doing check comparisons between temporary control points reading to reading, is one way to help identify errors. A constant difference between a series of points is normally a sign of an error.

Observations can be processed using a common spreadsheet program. See figure 2. Typically, data is transferred from the instrument to a computer, which could be a hand-held, laptop, or desktop computer. Observations can be checked, averaged in the processing spreadsheet, and used in the creation of a report in an agreed-upon format.

## Reporting, Distributing, and Storing Data

On completion of the processing, the data can be imported into a spreadsheet. While the spreadsheet itself may be many columns wide, with a bit of patience and skill, a format is possible that displays the data in a concise and clear way. By incorporating visuals, such as a graph into the report, it is possible to convey information in an easy-to-understand format. Many calculations can be performed in the spreadsheet, and environmental conditions can also be recorded and plotted.

After compiling the report, it is normally sent to concerned stakeholders in whatever communications format requested. Reports should be sent as soon as possible after the observations and processing are completed. A cover letter is normally included in the report and can be used to explain any problems reading targets on site or other concerns, such as extreme weather conditions, access problems or safety issues. A sketch showing target locations is commonly sent with the report.

After reporting the data, it is typically stored by creating a digital copy and a hardcopy. The digital copy is burned to a physical disk, while the hardcopy is filed the traditional way. It is important to remember that the report is the only work product that the client receives. The report creates an impression with respect to quality of data contained within the report. Simple spelling errors or wrongly numbered reports produce doubts regarding the standard of care taken during collection and analysis of the data.

An excellent summary of planning, designing and construction phases of an overall monitoring program can be found in chapters three and four of *Geotechnical Instrumentation for Monitoring Field Performance*, Dunnycliff (1988).

## THE PROJECT

The project outlined permits discussion of the physical installation and layout for precision survey monitoring.

Dig an excavation seven stories deep adjacent to several noteworthy and/or delicate structures. Do it with as little impact on the neighbourhood as possible and as economically as possible. Do it in reclaimed soil sitting on top of shale geology close to a Great Lake. Sounds like a challenge.

Many steps outlined in the *Installation and Initialization of Control Network and Monitoring Points* section of this paper were greatly simplified due to the prior relationships between members of the project team, as both the shoring engineering firm and contractor had worked together on many projects. The shoring engineer had an exact idea of the monitoring plan, therefore planning of the installation required minimal input with respect to monitoring point locations, etc. Additionally, the alarm and review levels, report format, reading frequency, and distribution lists were easily agreed upon. Sign-in procedures, safe access to instruments, and scheduling of work were all covered during start-up meetings.

Figure 1 outlines the location of the survey monitoring points. To the north of the site, precision survey target installation began just below the roof level of the eight-storey theatre, facing south and west at three different levels to check for lateral and vertical movement and twist. There was also a six-storey building monitored on a

laneway on the north side of the site. This laneway was too narrow to obtain accurate observations on the south facing wall therefore targets were installed on the window and door frames, facing west. To check for north-south movement, the bearing was used instead of the distance. Across the road to the west was another theatre. Targets were installed on the east face of this building; four stories above ground and at an angle approximately sixteen degrees out of the local grid alignment. This was also the situation for the restaurant on the eastern boundary of the site, which had sixteen targets installed on its north, west and south faces.

By choosing a surveyed point located perpendicular to the point being monitored, a reference distance was calculated between them. When the observations are reported, a calculation is performed in a spreadsheet using the new co-ordinates. A new reference distance is calculated, showing the direct movement towards or away from the original reference point. This method is commonly used on most structures or shoring that is not perpendicular to the local grid.

On the south side of the site, four targets were installed on the north face of a condominium. Adjacent to this, twelve targets were installed on the north face of a hotel. Targets placed on the restaurant, condominium and hotel were all approximately 2.2 metres above ground level.

### **Observed Movement**

Data collected in the field recorded movement of the restaurant's west wall at the very start of drilling. Concerns mounted as daily observations showed more and more subsidence. As pile holes were drilled, the wall adjacent to the drilling began to subside in the centre and show lateral movement towards the drilling. A graphical representation of the movement is shown in Figure 2. Remedial action was undertaken by placing structural support under the wall. Other movements noted were within acceptable parameters and no further concerns were raised. At time of writing this project had received fifteen months of ongoing monitoring and would continue with monitoring for several more months.

### **CONCLUSION**

Careful planning of any monitoring program is highly recommended. As part of a comprehensive monitoring program, precision surveying monitoring provides accurate data, verifiable against other instrumentation installed on site. With many variables to contend with and errors to manage, precision surveying monitoring is a challenging undertaking. Errors are a constant that must be dealt with on a regular basis with forethought and an open mind. An understanding of what causes errors goes a long way towards avoiding or minimizing them. Presentation, reporting, transferring, and storing of data are very important steps in the program.

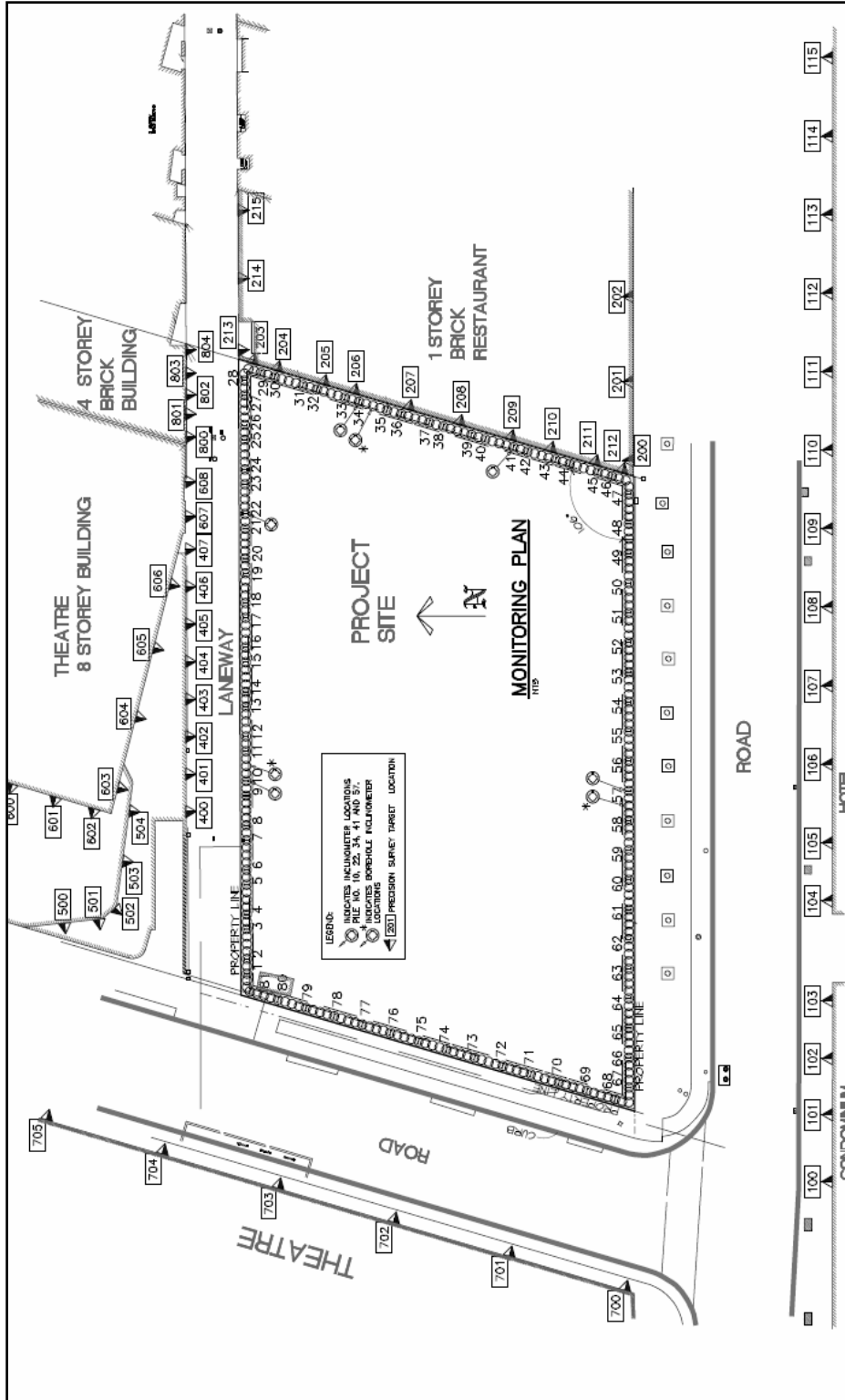


FIG. 1. Monitoring plan showing structures, shoring, and target locations

Target	Initials - 2006-02-22			2007-02-02 - R08			2007-03-09 - R09			2007-04-09 - R10			Movements (mm)	
	Eastings	Northing	Elev.	Eastings	Northing	Elev.	Eastings	Northing	Elev.	Eastings	Northing	Elev.	Lat.	Vert.
200	606.941	520.109	80.354	0.942	0.110	0.354	0.940	0.110	0.353	0.942	0.111	0.354	2	0
201	615.467	520.113	80.304	0.469	0.116	0.305	0.467	0.115	0.304	0.469	0.117	0.305	4	1
202	626.841	520.129	80.230	0.842	0.132	0.231	Target Unavailable			0.843	0.134	0.231	5	1
203	620.220	566.089	80.441	0.213	0.097	0.436	0.212	0.098	0.437	0.211	0.100	0.434	9	-7
204	618.627	560.538	79.946	0.621	0.541	0.936	0.623	0.543	0.936	0.619	0.544	0.933	6	-13
205	617.546	556.836	80.583	0.541	0.837	0.568	0.541	0.837	0.567	0.540	0.838	0.566	6	-17
206	616.159	552.051	80.661	0.151	0.054	0.639	0.153	0.054	0.640	0.151	0.054	0.637	8	-24
207	614.938	547.815	80.667	0.932	0.824	0.642	0.932	0.823	0.641	0.932	0.824	0.640	5	-27
208	613.572	543.117	80.684	0.566	0.128	0.666	0.566	0.127	0.665	0.566	0.129	0.665	8	-19
209	612.532	539.575	80.672	0.526	0.586	0.656	0.525	0.584	0.655	0.527	0.586	0.654	4	-18
210	610.894	533.971	80.023	0.887	0.981	0.014	0.888	0.981	0.011	0.888	0.981	0.011	7	-12
211	609.036	527.622	79.976	0.030	0.629	0.968	0.033	0.631	0.968	0.033	0.632	0.966	1	-10
212	606.926	520.405	80.743	0.925	0.406	0.743	0.926	0.409	0.742	0.926	0.409	0.740	0	-3
213	624.484	566.056	80.482	0.485	0.052	0.478	0.486	0.053	0.476	0.485	0.055	0.477	1	-5
214	630.528	566.339	80.848	0.527	0.334	0.847	0.526	0.337	0.845	0.527	0.336	0.845	3	-3
215	637.509	566.391	80.853	0.511	0.386	0.851	0.510	0.387	0.848	0.510	0.389	0.848	2	-5

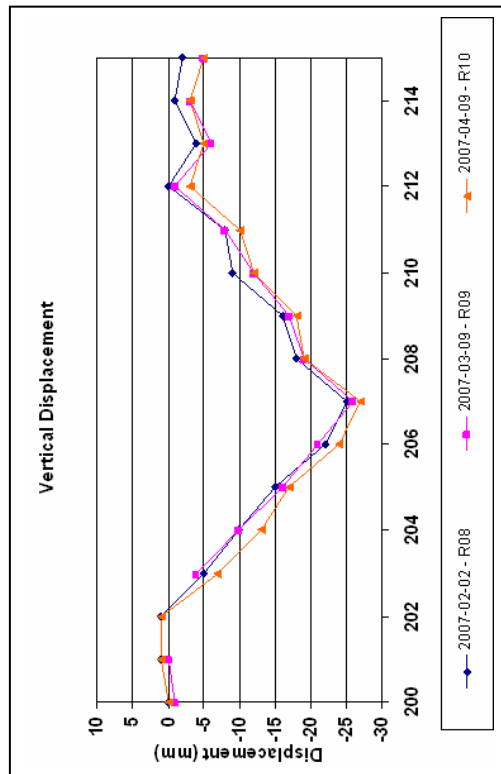
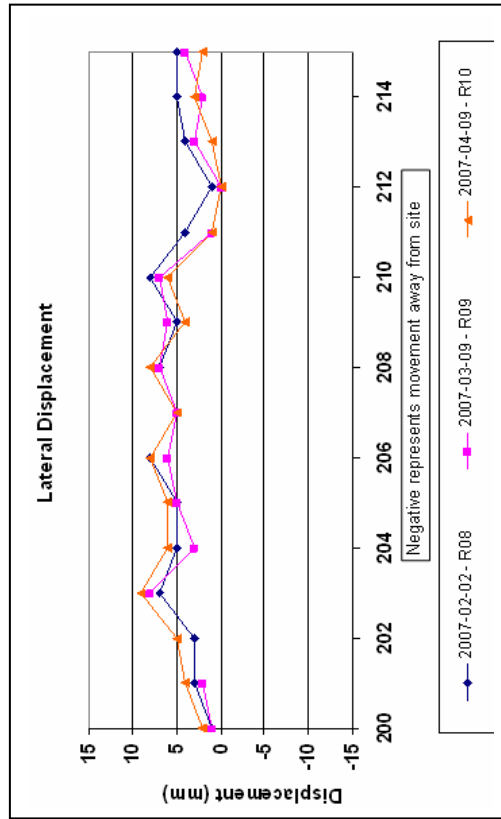


FIG. 2. Report and Graphical representation of movement

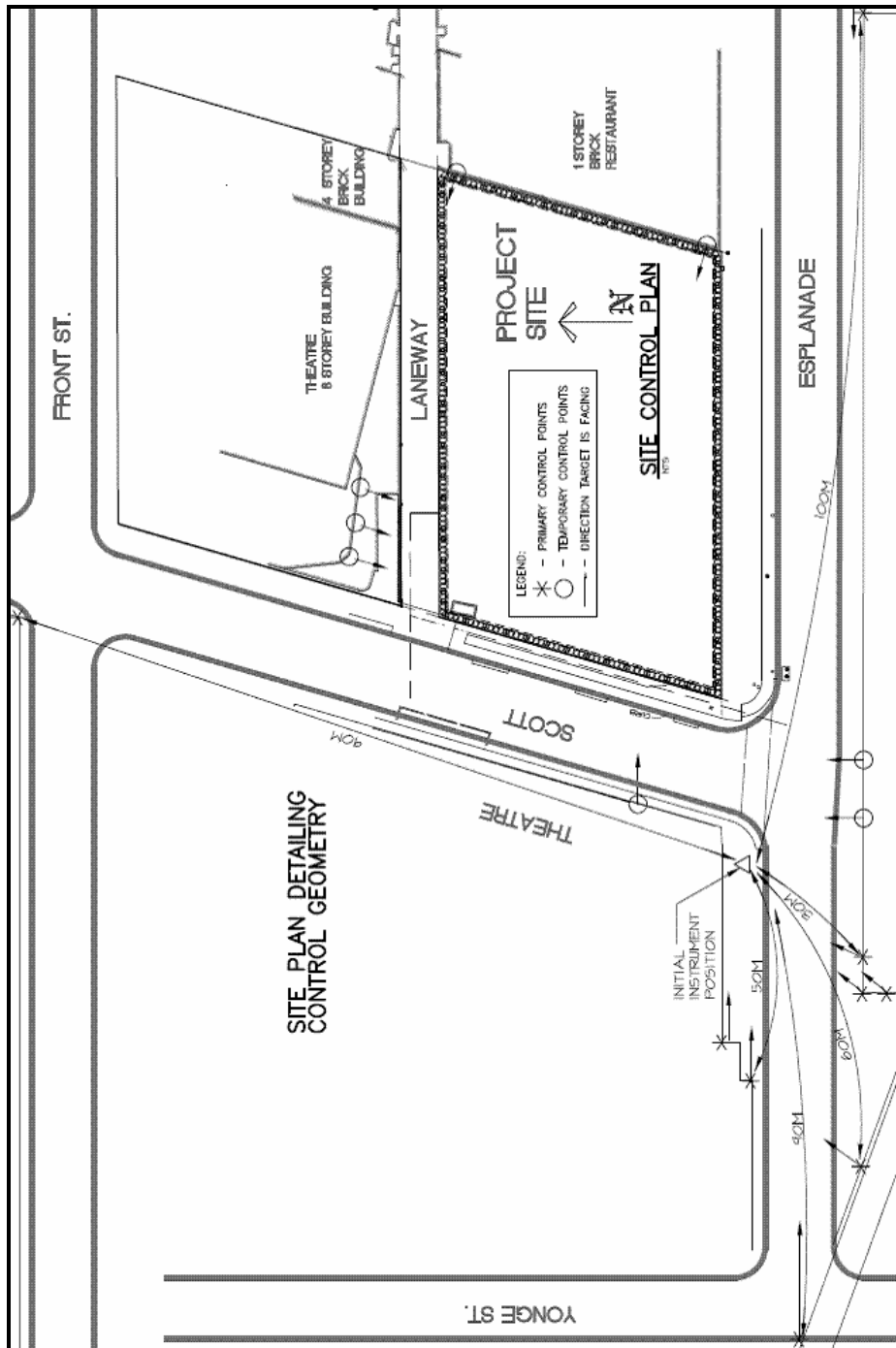


FIG. 3. Site Plan Showing Control Point Location

APPENDIX I. WORKS CITED

Dunncliff, J. (1988). “Benefits of Using Geotechnical Instrumentation” and “Systematic Approach to Planning Monitoring Programs Using Geotechnical Instrumentation”. *Geotechnical Instrumentation for Monitoring of Field Performance*, John Wiley & Sons, Inc., New York, NY, pages 33 to 44.