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Summary

This paper focuses on the extensive geotechnical instrumentation program developed to monitor and control the effects of construction of MHD's Central Artery (I-93)/Tunnel (I-90) Project in Boston.

1.0 Introduction And Background

Boston's massive and complex CA/T Project must be designed and built with minimum disruption to existing infrastructure including buildings, subways, railroads, utilities, bridges and viaducts. From project inception, integration of design and construction were emphasized, and a proactive philosophy of designing to prevent soil deformations was pursued. To ensure that strict control and monitoring criteria were achieved, an extensive instrumentation system was designed and is being implemented.

This paper presents an overview of the project and defines the technical instrumentation needs generated by the adverse geological settings, old infrastructure, and abutting structures. Key monitoring criteria are stated, along with current experience of designing and implementing the monitoring system. Since portions of the system have been in place for some time, several valuable "Lessons Learned" are discussed, and several planned future developments presented.

2.0 Project Description And Instrumentation Requirements

The CA/T Project represents a challenging endeavor from a geotechnical engineering standpoint. Few, if any, single projects in the United States encompass both the variety and magnitude of underground construction as the CA/T. Significant features include: approximately 4 miles of cut-and-cover tunnel construction within a heavily congested urban environment where dozens of buildings lie within the zone of influence of construction. There are six locations where tunnels will be constructed either above, below, or adjacent to active underground rail transit facilities, an immersed tube tunnel, and viaduct piers with vertical and horizontal loads in the thousands of kips.

The instrumentation program is the primary means of monitoring construction activities which can result in detrimental impacts to surrounding facilities. Accurate and timely reporting of data is essential to meeting the objectives of the instrumentation efforts.

The generally adverse ground conditions found in the Boston area make the geotechnical efforts even more challenging. The high groundwater table, deep deposits of soft soils, and the presence of permeable strata combine to create an environment with the potential for large deformations resulting from excavation activities. In addition, virtually the entire project alignment falls within reclaimed land, filled by numerous processes and materials, many of which are not well documented.

The generalized profile consists of fill, soft organic and silty clay deposits, dense glacial deposits, and bedrock. In some areas, the soft silty clay extends to depths in excess of 150 ft. The bedrock properties are extremely variable, ranging from totally decomposed to very hard and massive.

Control of deformations and maintenance of prevailing groundwater levels represent the primary geotechnical objectives in CA/T tunnel construction and thus define the role of the geotechnical instrumentation program. Soft marine clays and organic deposits encountered throughout the alignment are particularly sensitive to changes in groundwater conditions. Structural foundations founded above, on, or within these strata become subject to potential deformation. Additionally, existing timber pile foundations exposed to air for extended durations as a result of lowering of the groundwater table will likely deteriorate.

Many buildings are designated as historic, and must be protected from even architectural damage, century-old transit tunnels must have structural and waterproofing integrity maintained, and multistory office buildings must not experience deformations that could over-stress structural members. In all cases, tolerances for allowable deformations are very small and thus deformations must be measured to a high degree of precision.

Construction vibrations represent another source of potential distress to adjacent structures and business activities. Buildings in poor structural condition, with attached facades, or housing sensitive electronic equipment must be protected by near real time monitoring and reporting of vibrations. The geotechnical instrumentation program is the key element of the mitigation effort protecting adjacent facilities.

3.0 The Monitoring System: Design And Implementation

Initial geotechnical site investigations were performed by Area Geotechnical Consultants (AGCs). The AGCs produced investigative data and engineering reports identifying and evaluating possible impacts of construction and subsurface conditions on adjacent facilities.

Section Design Consultants (SDCs) used these reports to create final designs for particular sections of roadway and also to design the geotechnical instrumentation program. The geotechnical instrumentation program was incorporated into the construction documents and consists of specifications and drawings. The drawings show instrument locations and installation details, and specifications include selection, installation and maintenance criteria, monitoring frequency, response values, and data reporting requirements. The SDCs based their designs on recommendations of the AGCs, as well as guide specifications and directive drawings prepared by the Management Consultant, Bechtel/Parsons Brinckerhoff (B/PB).

The geotechnical instrumentation program is designed to achieve the following objectives:

- Monitoring ground and facility deformations resulting from construction,
- Monitoring of changes in groundwater levels,
- Providing preconstruction baseline data for comparison with construction and post construction data.

The construction contractors are responsible for purchasing, installing, and maintaining the majority of the instruments. Before the construction contractors can proceed with instrument installations, they submit plans for review by B/PB to insure conformance with contract requirements. B/PB performs quality assurance of the contractors' work, reads the instruments (using a subcontractor), analyzes and reports the data.

The instrumentation program includes a Geographic Information System (GIS) consisting of Oracle and GDS. It was developed by the Project staff to improve the conventional methods of data processing and retrieval, which are too slow for the large volume of data generated. The system helps provide an early warning, so that mitigating actions can be implemented rapidly. This partially automated system provides readily accessible data to the contractors, construction managers, and other interested parties.

The GIS application consists of textural and graphic components. The textural component is an Oracle relational database. The Oracle database allows for quick and accurate entry, storage, processing, and retrieval of data and ensures that duplication of data does not occur. As soon as the data are entered and checked, they are available to many users linked by a computer network. The database has controlled access limiting users to verified/released information only, thus eliminating false alarms from data that has not been verified, while authorized users can insert, update, and delete data. The controlled access allows users unfamiliar with the system to view data, without inadvertently altering records. With the exception of a few instruments (seismographs and inclinometers), which currently have their own database programs, all the geotechnical and structural instrumentation observations are contained within the Oracle database. Oracle accepts data entered by hand, remotely monitored data and electronic data from a data logger in ASCII format transferred using bulk loading procedures.

The instrumentation monitoring program currently includes 10,000 instruments of 22 different types. The primary purpose is to provide data for construction control. The system creates a database that serves the needs of the Management Consultant (MC), the construction contractors, and the owners of adjacent properties (i.e., the abutters).

The instrumentation data would be of little value in construction control unless reduced and evaluated accurately and quickly. At the inception of the program, CA/T instruments were both installed and monitored by the construction contractors. Monitoring has since been assumed by the MC's subcontractor to collect the data and report them on a daily basis. Reduced and checked data is ready for analyses by the MC at 8:00 a.m. the day after they are collected. The MC then rechecks, analyzes, and provides copies to the Resident Engineers for forwarding to the construction contractors and selected abutters by 4:00 p.m. the same day. These hard copies provide the contractors with the information needed to monitor construction operations. When readings indicate the development of apparent problems (exceeding a predetermined Response Value), additional data are collected on an accelerated schedule and the data turnaround time is shortened to a few hours. In special cases the construction contractors can tap directly into the MC's Oracle database to facilitate rapid responses to changing conditions.

Data use requires a knowledge of when to take mitigative action. Every construction contract specification contains predetermined Response Values for each instrument. Each Response Value consists of a lower Threshold Value and a higher Limiting Value. Threshold Values provide a warning that ground or structure responses to construction operations are reaching levels of concern, and that action must be taken to prevent additional deformation. If, despite these efforts, deformation continues and the critical Limiting Value is reached, more stringent measures may be taken to bring the situation under control, including stopping construction and partially backfilling the excavation in the most serious cases.

The accuracy of the instrumentation readings is checked through a several-tiered QA/QC system, including: checking the current reading against the previous readings in the field, redundant readings by the field superintendent and others, and checking the monitoring reports for errors and consistency of data with similar type instruments in the area.

4.0 Lessons Learned

The "Lessons Learned" during implementation of the instrumentation program on the Central Artery/Tunnel Project range from broad based, such as, how to measure the potential damage to an abutting structure during construction, to very specific, such as combining two different instruments in one borehole.

Lessons specific to instrument types, locations, and installations:

- Inclinometer/Probe Extensometer - This instrument combined an Inclinometer and Probe Extensometer in the same borehole. The Inclinometer measures lateral movement of the soil mass. The Probe Extensometer measures consolidation of a soil mass. Combining the two instruments in one borehole saved installation time and cost. But, the type and shear strength of the grout required in the borehole after installation for each of these instruments differs. The Inclinometer requires a stiffer grout than the Probe Extensometer. A compromise grout did not serve the purpose, the precision of measurement for both instrument types was compromised, and the combining of these two instruments in a single borehole was discontinued.

- 'Dry' Observation Wells and Vibrating Wire Piezometers with collection zone or piezometer tip installed above the level of groundwater - Either the designed elevation for groundwater collection or measurement is above the level of groundwater after dewatering started or the interpolated geology was incorrect. The designer may not account for the amount (depth) of dewatering the contractor performed, resulting in a 'dry well' during construction. Alternatively, the geology may be different from interpolated by the designer in areas with glacial deposits or areas with human generated fill. In differing geology cases, during installation a technical person can observe the strata in the proposed collection zone, knowing the designer's intent, and make a 'field decision' to insure installation of functioning observation wells.

- Instrument base fixity established in a zone of construction's influence: Inclinometers, Probe Extensometers, and Multi Point Heave Gages - The base fixity zone, which serves as datum for each of these types of instruments, must be placed in a stratum that will not be affected by the construction activity. In cases where this is not done, there is lateral movement or settlement in the zone of anticipated fixity making it difficult to measure true movement when the data are tabulated and plotted. The base fixity zone needs to be placed approximately 10 feet below the bottom of the excavation support wall into a stratum suitable to provide base fixity, such as a till or bedrock. Further, if in fractured bedrock, the base fixity zone needs to be pregrouted.

- Deep Benchmarks (DBM) - are another example of instruments affected by construction activities. DBMs are critical for achieving accuracy for optical surveying methods. The specification for the installation of Deep Benchmarks must insure that the deep benchmark will not be subject to movement even during deep dewatering. This may require installing the tip of the DBM even deeper than a few feet into competent bedrock. During CA/T deep dewatering a few DBMs apparently moved laterally or settled, resulting in optical monitoring points referenced to these DBMs showing no settlement.

Lessons related to the effects of weather on instruments:

- It is well known that strain gages should not be read in direct sunlight. Other effects of weather that need to be considered include: freezing of water inside inclinometer casing, deformation monitoring points installed into asphalt being ripped out during snowplowing, and spurious data from tiltmeters. In some cases, the temperature can be measured and a correction factor applied to correct the instrument reading for the change. In other cases, installation of a different instrument type is necessary. During one prolonged cold spell and groundwater infiltration inside an inclinometer casing, ice built up prevented inclinometer readings from being taken. The specifications need to be written to hold the contractor responsible for maintaining the inclinometer.

Lessons related to setting realistic Response Values for instruments on abutting structures:

- Depending on instrument type, RVS are based on parameters relating to a structure, groundwater regime, loads, or allowable deformations. When a RV is exceeded, the Contractor is required to perform an action defined in the specifications or in an action plan. In some cases the designers specified the expected amount of deformation resulting from construction rather than amounts actually permitted for an abutting structure. Generally, this leads to unduly restrictive response values and evaluations. The designer's analyses must determine the permitted deformations for each abutting structure.

Lessons related to collection of data:

- Preconstruction Monitoring Data: some structures abutting construction undergo changes due to non-construction activities, e.g., seasonal weather changes, tidal changes, age of the structure, condition of the foundation. These changes require documentation by installing instruments to provide Preconstruction Monitoring Data. There are numerous late 18th century structures abutting the Project that have shown settlements prior to construction. Also, there are daily tidal fluctuations of up to 10ft between high and low tide. These data were collected, analyzed, and then used in setting the allowable deformation limits for abutting structures and water monitoring instruments

- Monitoring of instrumentation during construction must be carried out by representatives of the owner rather than the construction contractors. Under the previous monitoring arrangement for data collection and reporting two general problems occurred: 1) reduced and plotted monitoring data were not received by the MC in near real time, and 2) obtaining additional readings on instruments usually required days to implement. Therefore, rapid evaluation by the MC of changing conditions that arose from construction activities was difficult. The responsibility for collection and reporting of instrumentation data has been transferred to the MC and its subcontractor, resulting in development of a rapid and responsive monitoring system (Oracle/GDS) and collection, reduction, analyses and distribution of instrumentation data happen in near real time.

As the Project continues the lessons learned are being implemented into newly awarded contracts.

5.0 Future Developments

The project has another seven years of construction before completion. The monitoring system must continue to effectively function to 2004 and beyond. Some issues, e.g., temporary lowering of groundwater levels, and time-related deformations associated with clay subsoils, demand that monitoring continue beyond the project completion date. The system is designed to be both responsive and flexible. As we evaluate actual construction experience with the monitoring system, we seek means to modify and improve its overall performance. The Oracle/GAS combination has proven effective at providing quick and varied ways to display and plot data; relate local project geometry and geology, assess facility performance, and generate groundwater and settlement contours.

Our experience to date has also permitted us to evaluate numerical performance criteria, and instrument response values. In some cases, these were proven too conservative, and have been cost-effectively relaxed. We will continue to make these evaluations.

Another area that has advanced is data entry, manipulation and distribution. We have utilized more electronic components in accomplishing these tasks. Improved speed in these portions of the work has permitted more staff time to be available for analyses, correlations, and evaluations of interface problems. We are expanding the capability for more people, (both on project, and approved third parties) to access and read data at various stages.

Other future developments include: generating digital images of instruments and buildings they are installed in, and live camera views of the ongoing construction coupled with simultaneous viewing of instrumentation data. We consider the system a "living" entity that can be continuously modified and improved to meet the evolving monitoring needs of the largest infrastructure project in the U.S.

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