Geotechnical Instrumentation for the Central Artery/Tunnel Project: An Overview

Work on developing an instrumentation program must be initiated at the start of project planning and continue through design and pre-construction phases.

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As a small but important element of a large, complex project such as the Central Artery/Tunnel (CA/T) Project, it is important to define the role of instrumentation early so that it is utilized properly. As with all important project elements, its use must be considered in the planning and design stages, then carried through construction and even through post-construction (operation) phases.

General Role of Geotechnical Instrumentation

Geotechnical instrumentation generally encompasses multiple functions on a project, achieving success through an interdependent blending of these roles. The following four features were integrated in the geotechnical instrumentation program for the CA/T Project:

Early Warning System. Sufficient instrumentation is necessary to provide an early warning if potential problems are developing. On the CA/T Project, all installed instruments have threshold and limit values set by the designers so that, as data are acquired and analyzed, trends toward "problems" can be identified early.

Record of Events. Most new projects cause some disruption to adjacent facility owners. The CA/T Project must be constructed where major facilities such as subways, high-rise structures, utilities, as well as historic and recent surface structures are in close proximity to the new construction. Accurate and comprehensive records of deformations and other pertinent changes are required to address disputes that may arise between various abutters and the project owners. These data must include pre-construction, construction and post-construction events.

Construction Control. For such a complex project, the methods of construction as well as the sequence and rate of construction could have an important effect on resulting soil deformations and the performance of adjacent structures. Thus, the proper evaluation of timely field data is necessary to control the construction process.

Evaluating Design Uncertainty. Construction of the CA/T Project combines geotechnical and structural engineering to create appropriate excavations and subsurface structures. The nature of geologic materials results in design parameters that contain uncertainty. Strength, compressibility and stress-strain properties are non-linear, and have inherent time-related aspects that cause predictions of performance to contain some risk. Calculated factors of safety are not precise in geotechnical engineering, and field monitoring can assist in the important role of evaluating the degree of this inherent uncertainty.

General Approach

The general approach to geotechnical instrumentation program for the CA/T Project follows ten steps:

1. Identify the geotechnical uncertainties.
2. Make judgments relating to geotechnical conditions and construction performance.
3. Define measurable parameters that can be used to indicate inadequate performance, and select appropriate instrument types and locations.
4. Assign response values (hazard warning levels).
5. Formulate generalized plans of action that will provide the basis for a detailed specific plan of action to be formulated later if a response value is reached.
6. Recognizing the uncertainties, observe construction events and make measurements with instrumentation.
7. Interpret instrumentation data on an ongoing basis; *i.e.,* relate causes to effects.
8. All responsible parties meet if a response value is reached to discuss any necessary responses.
9. Formulate a detailed specific plan of action to be initiated immediately.
10. Proceed with the response action.

Key Issues

The size and complexity of the CA/T Project, and the fact that it is being constructed in a complex urban setting, resulted in the careful evaluation of a number of key issues.

The Boston "Environment." Two existing conditions combine in Boston to create an unfriendly environment for subsurface construction. First, the geologic setting is considered adverse. As with most glaciated areas, the subsurface profiles vary significantly within short horizontal and vertical distances. There are large deposits of relatively soft clays and organic materials. The groundwater level is high (adjacent to Boston Harbor) and the bedrock surface is also variable in elevation and in its degree of weathering. Second, the age of the city and its infrastructure also present numerous difficulties. Project construction is adjacent to old subway tunnels and stations, water and sewer mains, and historic buildings. Construction is also located within historic fill areas that contain old wharves, piles, building foundations, etc. Instrumentation can be thought of as "insurance" to protect these facilities, as well as newly constructed facilities.

Contractor Priorities. The construction contractors' primary concern is building the project rapidly and at low cost. Geotechnical monitoring is not high on their list of priorities. There are various possible contractual methods for obtaining rapid and accurate field monitoring data. After some initial experiments the CA/T Project opted to have the construction contractors purchase, install and maintain the instruments, but a separate specialist contractor — who is under contract with the Massachusetts Highway Department (MHD), but managed by the project's Management Consultant (MC) — has the responsibility to read, check and transmit the data to the MC on a daily basis. This system ensures that the MC receives the data in a timely fashion for managing and controlling the project. The MC passes the data immediately to the construction contractors, who may choose to take additional readings. Of primary concern is that the data are rapidly available to all interested parties.

Mitigation Agreements. The size and complexity of this project has resulted in numerous formal mitigation agreements with city, state and federal agencies, as well as with certain high-profile abutters (*e.g.,* Amtrak). These agreements speak specifically to the "protection" of certain facilities and, in many cases, the instrumentation data will be used to judge the effectiveness of the mitigation arrangements.

Project Insurance. The CA/T Project has been successful in negotiating and putting in place wrap-up insurance policies for both construction and design liability (covering individual sections of the project). The intent of these coverages is to encourage cooperation and communication among all parties in the planning, design and construction process, and to work toward a common goal for a safe, economical and functional project. The instrumentation demonstrates to the insurers that the means to warn project participants about problems as well as the means to control the construction process are in place.

Cost of the Instrumentation Program. The cost of instruments varies from a few tens of dollars each to several thousand dollars each. In addition, the cost of reading and evaluating data usually far exceeds the cost of purchase and installation. For an urban underground project, the total cost of a geotechnical instrumentation program can vary between one and three percent of the total construction cost.

Long-Term Issues. Project construction will include excavations in clay, which may create temporary changes to groundwater levels. Altered groundwater levels will take widely varying times before they are restored to pre-construction levels. The project is divided into numerous construction contracts and will be carried out over a twelve-year period. Locations and monitoring of instruments in adjacent contracts need to be coordinated, and certain issues (*e.g.,* the consolidation of clay) may require monitoring long after construction is complete in a specific area.

Design Phase

Figure 1 indicates the flow of instrumentation tasks during the project design phase. The tasks are listed in the order in which they need to be accomplished.

The Concept Report was necessary to clarify project objectives and provide general and consistent guidance to project designers. The Design Policy Memoranda (DPMs), Standard Special Provisions (SSPs) and Standard Detail Drawings (SDs) followed, with more specific instructions to designers. Later, the series of design submittals and reviews are needed to ensure that final programs are developing in an orderly fashion and that all necessary technical and contractual considerations are being properly addressed.

Preliminary Stages. The geotechnical instrumentation Concept Report was compiled by the MC in order to present and explain the objectives of the project instrumentation program, describe each of the primary tasks associated with the program, evaluate alternatives for assignment of responsibilities for the tasks and, finally, make recommendations for the assignment of responsibilities. The report was disseminated to the final designers in order to introduce them to the project philosophy on how construction monitoring should proceed.

DPMs are short documents intended to provide guidance to final designers on specific issues. As an example, one DPM clarifies the vibration acceptance criteria and structural category descriptions to reflect existing Boston structures and to reflect other criteria such as those established by AASHTO and the U.S. Bureau of Mines.

Instrumentation SSPs serve as a model for final designers while they formulate their plans and specifications for the individual construction packages. The SSP, rather than being a true "standard," is used as a guide specification and is tailored to fit individual construction contracts.

Two SDs depict the design details for all readily foreseeable instrumentation types. The drawings are incorporated, without final designer modifications, in all design packages that require instrumentation.

Design Submittals. Design stages are those milestones along the development of a final design where the Section Design Consultant (SDC), a firm retained to carry out the final

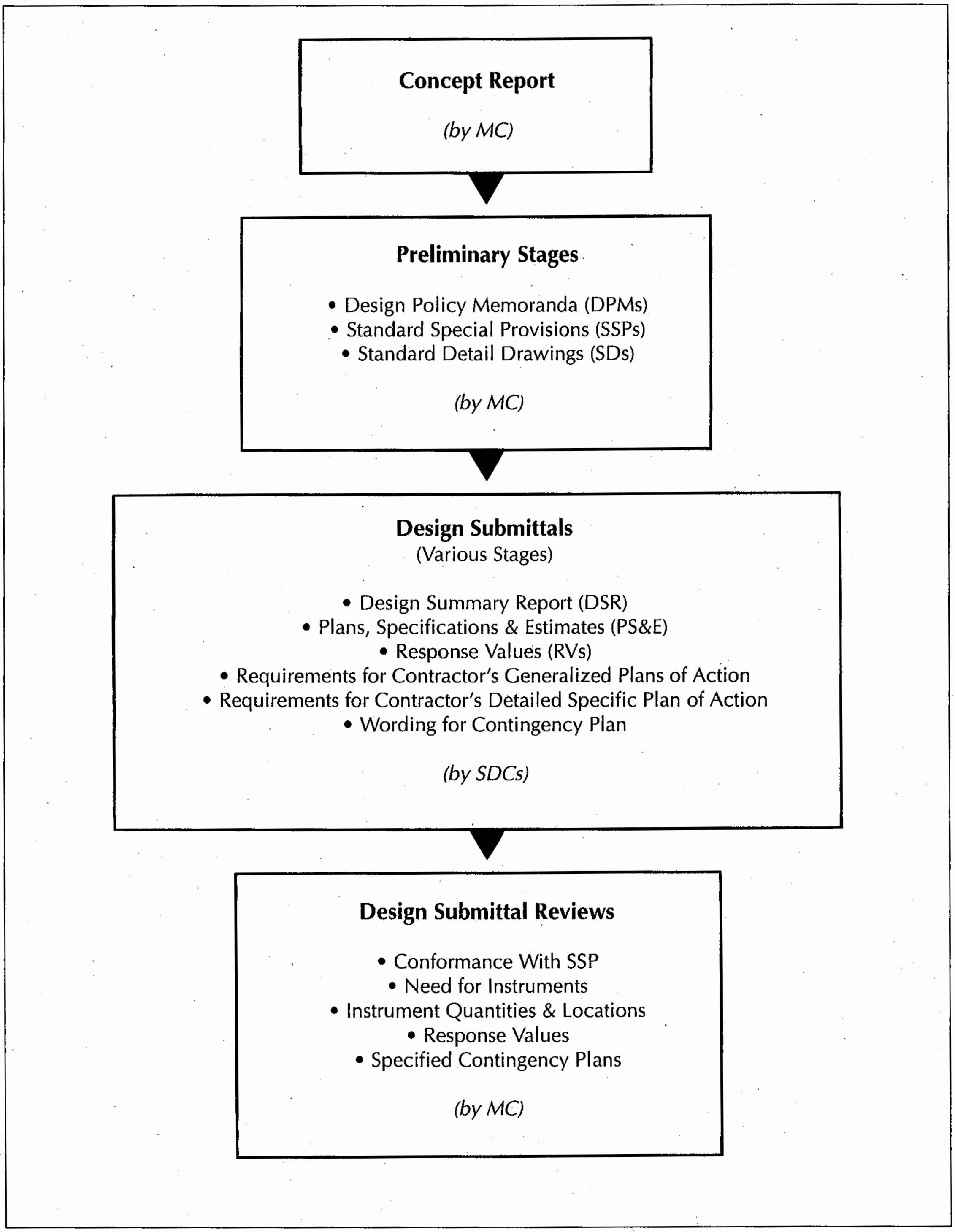

FIGURE 1. Instrumentation tasks during the design phase.

design for a particular segment of the CA/T Project, is required to submit the documents for review by the MHD and the MC. Submittals normally fall at the 50, 75 and 100 percent stages of design, then culminate with the Plans, Specifications and Estimates (PS&E) documents (the final design submittal prior to advertising for bid).

A Design Summary Report (DSR) is a document prepared by the SDC to indicate major geotechnical and structural design assumptions.

Response Values (RVs) are instrumentation readings specified by the SDC that, if reached, mandate a response action by the construction contractor to arrest increasing movements, stresses, vibrations, etc. An RV has two components: an early warning threshold value and a not-to-exceed limiting value.

Generalized Plans of Action are required as an early submittal from the construction contractor stating in general terms the mitigative measures (response actions) that will be taken if an instrumentation reading reaches an RV.

Detailed Specific Plans of Action are submitted by the construction contractor if an RV is reached. The plan must be prepared within 24 hours of reaching an RV, and the response action must be initiated within another 24 hours.

Contingency Plans are response actions pre-engineered by the SDC and the MC and are included in construction specifications. They are implemented where it is appropriate to specify response actions rather than to delay decisions until the construction phase.

Design Submittal Reviews. These reviews are carried out by the MC at the 50, 75 and 100 percent stages of design as well as at PS&E stages to ensure that the developing design documents conform to project criteria and needs. The process involves the assignment of a tracking number to each review comment. The SDC writes a response, and the reviewer writes a later evaluation of that response.

Construction Phase

Figure 2 indicates the flow of tasks during the project construction phase.

Early Construction Submittals. Construction contractors are required to purchase and maintain the instrumentation. Because these tasks are paid for as part of the lowest responsible bid, there is a need for strong quality assurance to ensure conformance with the specifications. Construction contractors are therefore required to submit, for review by the MC, proposed instrumentation materials and procedures. Particular emphasis is given to detailed step-by-step installation procedures. The contractors are also required to submit generalized plans of action, stating in general terms the response actions that will be taken if an instrumentation reading reaches an RV.

Data Collection and Reporting. Data can be grouped into two categories: causes and effects.

Causal data consist of all construction and environmental events that may create changes to instrument readings. Construction contractors have the primary responsibility for gathering and reporting causal data (referred to in Figure 2 as Construction Data).

Effect data consist of instrumentation readings that are gathered and reported by three separate entities:

- Geotechnical instrumentation data are the responsibility of a project-wide Monitoring Contractor, selected on the basis of the lowest responsible bid, with pay items per reading.
- Survey data are the responsibility of a project-wide Survey Contractor, also selected on the basis of the lowest responsible bid, with pay items per crew-hour.
- Contractor's Data are instrumentation or survey data that the construction contractor may choose to collect in addition to data received from the MC. Specifications stipulate how Contractor's Data must be collected, tabulated, plotted and reported in order to be acceptable to the MC. No separate payment is made for Contractor's Data.

All these three sources of effect data are made available by the MC and the construction contractor in a timely manner.

Relating Causes & Effects – Response Actions. The task of relating causes to effects constitutes interpretation. Steps and responsibilities are as indicated in the last box of Figure 2. The tasks are arranged to maximize communication among all the parties involved, and to foster an interactive response process.

Types of Instruments Used

Table 1 indicates the basic types of instruments

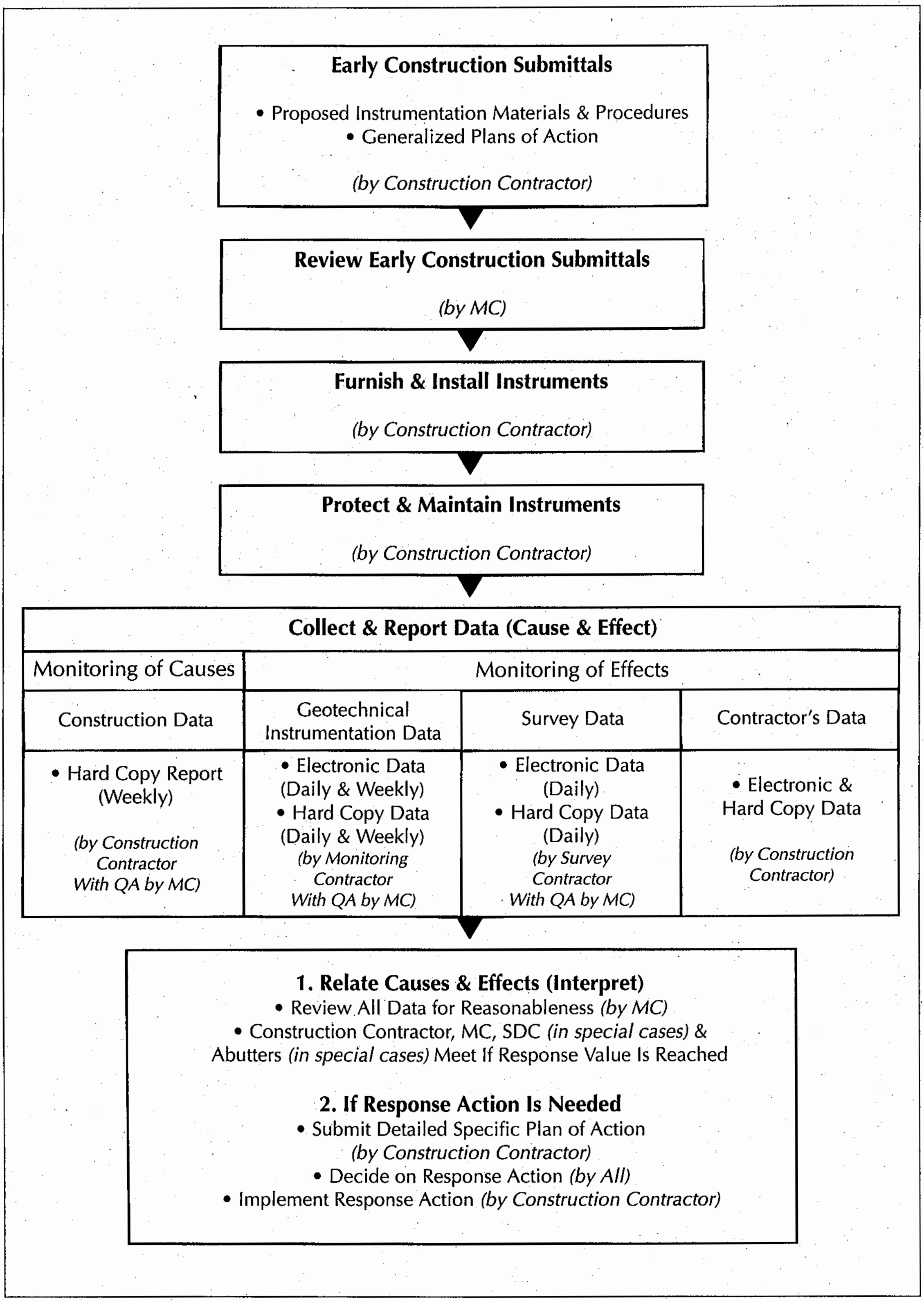

FIGURE 2. Instrumentation tasks during the construction phase.

TABLE 1.
Types of Instruments Used

Instrument Type	What Is Measured	How Measured
	Deformation	
Deformation Monitoring Point	Surface Vertical & Horizontal Deformation	Optical Survey
Convergence Gage	Convergence Across Excavation or Tunnel	Portable Mechanical Tape Extensometer
Utility Monitoring Point	Vertical Deformation of Utility	Optical Survey
Borros Point	Subsurface Settlement: Single Point	Optical Survey
Settlement Platform	Settlement of Original Ground Surface Below Fill	Optical Survey
Probe Extensometer	Subsurface Settlement: Multi-Point	Electrical Probe
Inclinometer	Subsurface Horizontal Deformation	Electrical Probe
Multi-Point Heave Gage	Heave Below Bottom of Excavation	Electrical Probe
Crack Monitor	Opening & Closing of Crack in Structure	Portable Mechanical Gage or Fixed Grid Gage
Tiltmeter	Rotational Deformation	Plug-In Electrical Readout Unit
	Groundwater Pressure	
Observation Well	Groundwater Level in Granular Fill	Electrical Probe
Vibrating Wire Piezometer	Groundwater Pressure in Other Materials	Plug-In Electrical Readout Unit
	Stress & Load in Temporary Supports	
Vibrating Wire Strain Gage	Strain on Surface of Steel (From Which Stress Is Calculated)	Datalogger or Plug-In Electrical Readout Unit
Load Cell on Tieback	Load in Tieback	Plug-In Electrical Readout Unit
	Vibration	
Seismograph	Vibration	Automatic Recording

used to acquire data for the various construction contracts. For special circumstances on the project, additional instruments were used (see the following section).

Two additional instrument types were used during early construction contracts, but their use has been discontinued. Open standpipe piezometers had been subject to freezing problems. Combined inclinometer casings and probe extensometers, installed together in one borehole, resulted in poor-quality inclinometer data due to conflicting grout performance requirements for the two instruments.

Special Cases

Several unusual cases along the project alignment have a different instrumentation approach. In these cases, the depth or complexity of the excavation, the complex and unique nature of the adjacent facility, or the extreme closeness of the facility to the planned excavation combined to require substantial revision to the

TABLE 2.
Additional Instruments Used in Special Cases

Instrument Type	What Is Measured	How Measured
Deformation		
Borehole Extensometer	Subsurface Vertical Deformation	Mechanical Readout Unit & Plug-In Electrical Readout Unit
Dial Gage	Relative Deformation Between Two Parts of a Structure	Observation of In-Place Gage
Shear Displacement Gage	Shear Deformation Between Two Parts of a Structure	Portable Mechanical Gage
Jointmeter	Opening & Closing of a Joint	Datalogger
Liquid Level Gage	Surface Vertical Deformation	Datalogger
Electrolevel/Beam Sensor	Surface Vertical Deformation	Datalogger
Bending Stress in Structural Columns		
Mechanical Strain Gage	Strain on Surface of Steel (From Which Stress Is Calculated)	Portable Mechanical Gage
Spot-Weldable Vibrating Wire Strain Gage	Strain on Surface of Steel (From Which Stress Is Calculated)	Datalogger

standard instrumentation specifications. In addition to modifying the specifications, construction methods and/or sequences were also changed in order to meet strict mitigation criteria. Table 2 lists the additional instruments used or planned for three special cases (described below).

Federal Reserve Bank (FRB) & One Financial Center (OFC). These two facilities are located on opposite sides of the Central Artery excavation where it passes under the Red Line subway station at South Station. The Central Artery requires a 115-foot deep braced excavation at this location. For the FRB, the tunnel alignment actually cuts through a portion of the existing underground garage. The 32-story main FRB tower contains critical control and communication systems for member banks throughout New England.

OFC comprises a 42-story high-rise structure, featuring an external "tube" design of closely spaced, stiff columns and beams for resistance of lateral loads. This structure and its two-level garage rest on a mat foundation about 40 feet below grade, and only 25 feet from the Central Artery slurry wall planned for the support of the excavation. The structure contains many high-profile, high tech firms with sophisticated communications systems, including regional offices for the largest stock brokerage in the United States. The combination of building configuration and its proximity to a very deep excavation made structural integrity of OFC of prime concern to the monitoring program designers.

Both structures are very sensitive to vibrations, and even to modest horizontal and vertical movements. For both structures, special mitigation agreements were negotiated, and force accounts were established for the installation of selected instrumentation up to one year in advance of construction to permit adequate baseline data to be developed. Consultants to the building owners worked with SDCs and the MC to develop monitoring plans, specifications and pre-designed contingency plans that were acceptable to all parties. Instrumentation, in addition to some of the types listed in Table 1, includes spot-weldable vibrating wire strain gages, mechanical strain gages, borehole extensometers, shear displacement gages and dial gages (see Table 2).

Red Line Subway Tunnel. In another part of the project, a tunnel will pass over an existing Red Line subway tunnel in Fort Point Channel, a branch of Boston Harbor. An immersed tube tunnel (ITT) design was chosen for this crossing. In ITT construction, prefabricated tunnel sections are floated into place, immersed and moved into a pre-excavated and leveled trench, and then connected and backfilled. The water is then pumped out of the completed tunnel and finishes are applied.

To maintain vertical highway alignment, the trench needs to be excavated to within 5.5 feet of the top of the existing subway tunnel. These twin-tube tunnels were mined from 1915 to 1916 in the Boston Blue Clay using compressed air techniques. They are circular, cast-in-place concrete with 24-inch thick walls. The tunnels carry heavy rail, 10-car trains that run every 10 minutes from 5:00 A.M. to 1:00 A.M. daily. Service cannot be interrupted under any circumstance. The tunnels were cast in 15-foot sections with only modest reinforcement, and essentially no continuous longitudinal reinforcement. Dredging of about 20 feet in Fort Point Channel will lower the factor of safety for buoyancy of the existing tunnels, and will result in a net unloading and potential for floating of the existing tunnel structures.

Again, detailed discussions with the subway tunnel owners and their consultants produced a jointly acceptable instrumentation plan that acts as an early warning and construction control system. Testing and analyses prior to the design of the monitoring system looked into concrete strength and modulus, location and type of rebar, leak surveys and special operating criteria. A full-scale in-place verification testing program was conducted on various types of instruments — including vibrating wire strain gages and jointmeters, tiltmeters and convergence gages — before acceptable commercial versions were selected for the full installation. A unique liquid level gage was also developed and tested in place. The full instrumentation system will be in place to collect up to four months of baseline data prior to the beginning of trench excavation.

Railroad Tracks Near South Station. South Station is the end of the line for commuter trains coming from the west and south. Just south of the station, the CA/T Project will connect the Massachusetts Turnpike (I-90) and other surface roads with an I-90 extension to the airport, and must cross beneath an array of seven sets of railroad tracks. These tracks are on a curve as the trains enter South Station.

The construction method chosen for this part of the project is jacked tunnels, which are large cast-in-place tunnel boxes constructed in pits adjacent to the tracks, then jacked beneath the operating tracks. Clear distance between the top of rail and the top of the tunnels varies between 15 and 20 feet. The tracks must be operational at all times, with operating hours from 5:30 A.M. to 12:30 A.M. daily. There is a need for real-time monitoring of vertical track alignment to ensure that the trains can operate safely. As with other special cases, all parties worked together from early planning stages to evaluate all important operating parameters, and jointly developed an instrumentation system that will provide acceptable construction management and control capability.

Electrolevel/beam technology was chosen as the keystone of the monitoring system. Because these instruments have not been used previously on active main line railroad tracks and have not been subjected both to the temperature extremes that occur in Boston and to track ballast tamping and regulating, a full-scale in-place demonstration program is being undertaken. The full instrumentation system will also include deformation monitoring points, probe extensometers, Borros points, vibrating wire piezometers and inclinometers. Electrolevel/beam sensors will be installed directly on the ties between the tracks and will give a continuous picture of the vertical profile along areas that will be subject to tunneling activity. Output from the monitoring system will be available to railroad owners, the MC and the tunneling contractor to ensure acceptable communication and control of the operation.

Summary

The role of an instrumentation program has numerous facets that must be tailored to the site-specific needs of the project. These facets — to be both cost-effective and efficient — need to be worked out over time, starting with project planning and running through design and pre-construction phases. Four critical functions filled on the CA/T Project were:

- Early warning system;
- Record of events;
- Construction control; and,
- Evaluating design uncertainty.

Every instrument needs to have a clearly defined justification for its use, as well as established Response Values for use in managing and controlling the construction process. A successful instrumentation program must have the cooperation of the construction manager and the various construction contractors. Special/unique cases require extensive input from the affected abutter(s)/owner(s) to ensure that acceptable levels of "control" are present.

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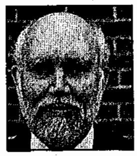

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