Measures to Minimize the Effects of a Deep Excavation on Two Adjacent Office Buildings: The Abutters' Perspective

For a large-scale excavation project, effective communication provides the foundation to lessen the impact on adjacent structures.

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The main feature of Section C11A1 of the Boston Central Artery/Third Harbor Tunnel (CA/T) Project consists of a 630-meter (2,065-foot) long, three- to five-lane cut-and-cover highway tunnel for the northbound central artery (CANB), which is overlain by a bus transitway tunnel. Along this excavation route, the intersection of Atlantic Avenue and Summer Street (Dewey Square) presents a number of challenges in addition to a dense array of utilities typical of many urban intersections (see Figure 1). The excavation for the CANB tunnel alignment along Atlantic Avenue reaches its greatest depth — approximately 34 meters (110 feet) — in order to pass beneath the Massachusetts Bay Transit Authority (MBTA) Red Line, an active subway line carrying more than 300 trains per day beneath Summer Street. Major structures located at this intersection include:

- South Station Headhouse, a terminal for commuter rail service, at the southeast corner. The headhouse is a five-story stone structure built in 1899 and supported by 7.6- to 12.2-meter (25- to 40-foot) long timber piles.
- MBTA Red Line Station at South Station, crossing the alignment beneath Summer Street with access kiosks at four corners and a number of below-grade pedestrian tunnels. The subway station at this intersection has now been underpinned, a major undertaking.

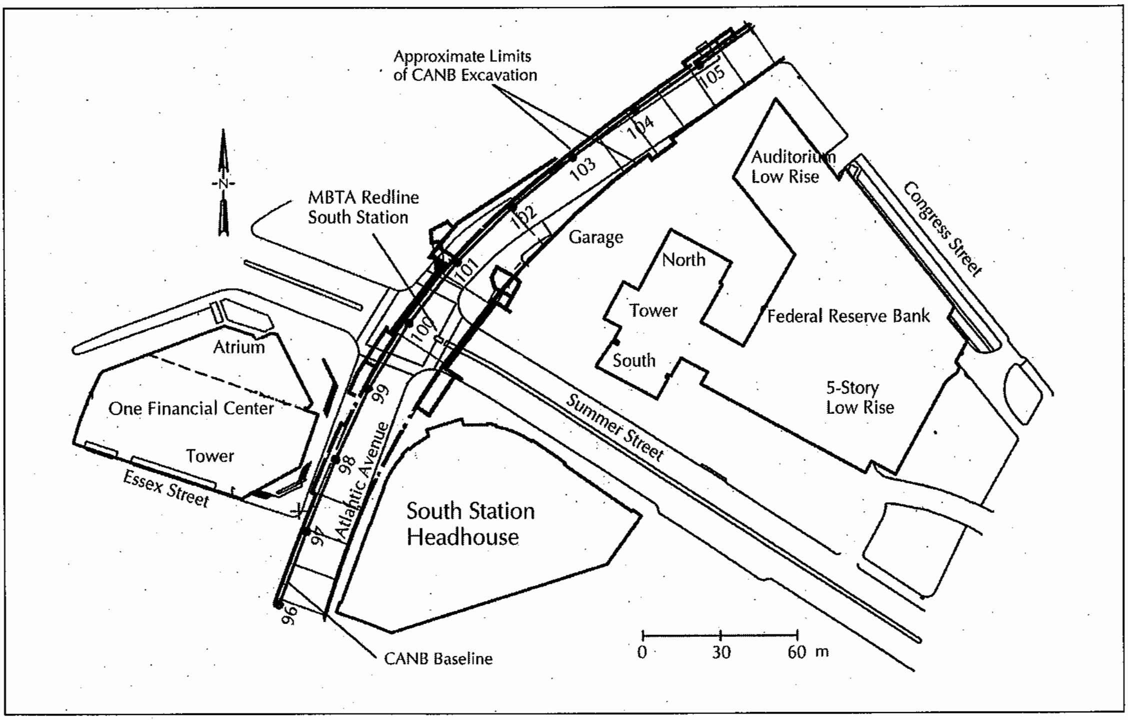

FIGURE 1. The location of the Federal Reserve Bank and One Financial Center.

- Federal Reserve Bank of Boston (FRB), a 33-story office tower at the northeast corner.
- One Financial Center (OFC), a 46-story office tower at the southwest corner.
- Dewey Square vehicular tunnel (not shown on Figure 1), located west of the CANB alignment.

Since excavation-induced ground movements, even if small, may have large effects on large office buildings, measures were developed to minimize the effects of excavations for the CA/T Project on the FRB and OFC.

Description of the FRB & OFC Building Complexes

Federal Reserve Bank (FRB). The FRB complex consists of a number of structures built from 1972 to 1976. The tower structure is supported by two reinforced concrete mats (north and south tower mats), bearing at elevation 22.27 meters (73 feet), CA/T Project datum. For reference, the ground surface elevation is about 34.47 meters (113 feet). The complex's four-story auditorium is a steel-framed structure, which is supported over a two-level common basement that extends beyond the buildings to the site limits bounded by Atlantic Avenue, Summer Street, Dorchester Avenue and Congress Street. The half of the basement near Atlantic Avenue has two levels and is supported by spread footings founded at elevations ranging from 23.73 to 23.27 meters (77.8 to 76.3 feet). The first basement slab is a two-way concrete flat slab supported on steel columns, while the second basement slab is a mesh-reinforced slab on grade. The rear half of the complex consists of a five-story low-rise office structure underlain by one basement and supported by reinforced concrete drilled piers. This low-rise structure in the rear half of the FRB complex is beyond the zone of influence of the CA/T Project excavation and will not be considered further. All the FRB foundation mats, spread footings and drilled piers bear on glacial till.

Figure 2 illustrates the subsurface conditions beneath the FRB complex near the CA/T Project alignment. The tower mats, as well as the garage and auditorium footing foundations, bear in the T2 cohesive till that consists of a very dense mix of gray silt and fine to coarse

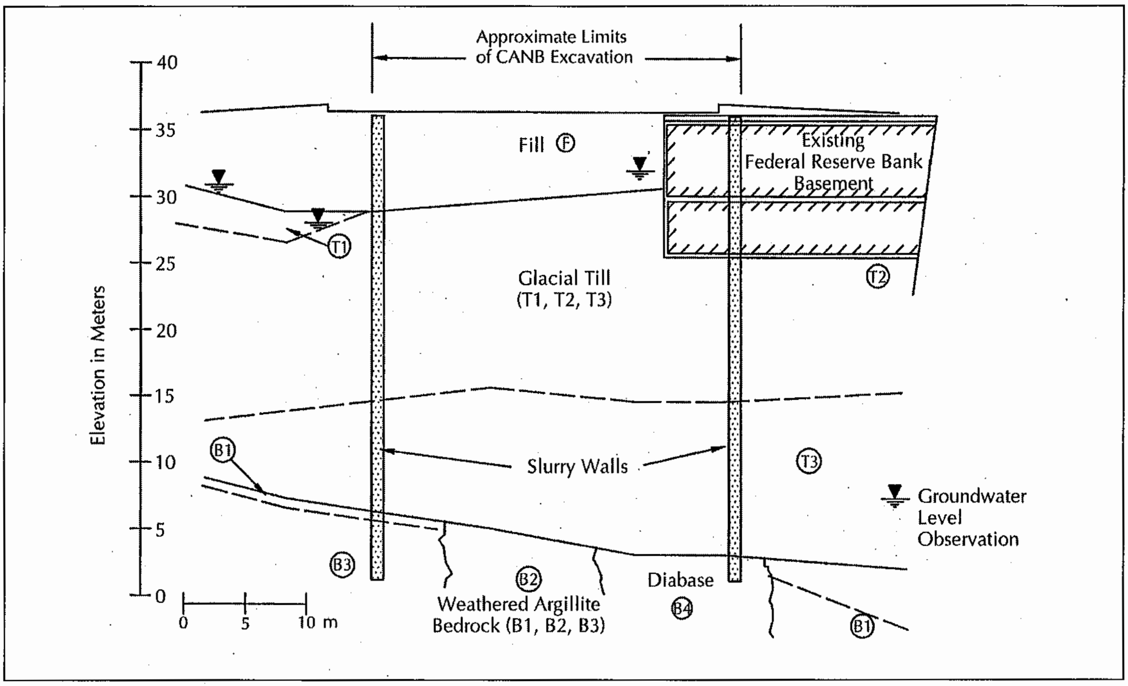

FIGURE 2. Subsurface conditions at the FRB (station 101+40 CANB).

sand, little fine gravel, little clay and occasional cobbles and boulders. The T2 till is underlain by a very dense granular till (T3) and bedrock. The bedrock ranges from completely weathered, very soft argillite (B1) to slightly to moderately weathered hard argillite (B3) and a moderately hard to soft, slightly to severely weathered diabase (B4).

One Financial Center (OFC). Built in 1981, the OFC building consists of a 46-story high-rise structure with an adjoining atrium. Both structures are underlain by a two-story basement that is used as a garage and that also contains maintenance and utility areas. The tower structural system is a steel tube frame constructed of heavy rolled steel columns and beams. The columns are socketed into a nominal 1.83-meter (6-foot) thick reinforced concrete mat that is locally thickened at the interior columns to 2.6 meters (8.5 feet). The mat bears approximately at elevation 23.79 meters (78 feet). For reference, the ground surface elevation is about 34.47 meters (113 feet). The atrium structure is on the northern side of the site adjacent to Summer Street. It is a glass-enclosed space truss, approximately 26.8 meters (88 feet) high, and it is supported by individual spread footings and a continuous perimeter wall footing. A 15-centimeter (6-inch) slab on grade serves as the basement floor, which is contiguous with the mat surface beneath the tower structure.

Figure 3 illustrates the subsurface conditions beneath the OFC building near the CA/T Project alignment. The tower mat and atrium footings bear in the T2 cohesive till, similar to the till beneath the FRB. The T2 till is underlain mostly by the slightly to moderately weathered hard argillite (B3), with only a thin layer of the completely weathered very soft argillite (B1).

Design of the CA/T Project Adjacent to the FRB & OFC

Work on the CA/T Project adjacent to the FRB and OFC buildings extends from approximately CANB station 97 (near Essex Street) to approximately CANB station 106+70 (near Congress Street). Most of this work (up to station 104+87) is being completed as part of CA/T Project Contract C11A1. The remainder of the work up to Congress Street will be built as part of contract C17A1 (but was designed as part of the C11A1 effort). The MBTA bus transitway (located above and generally within the CANB alignment) will be con-

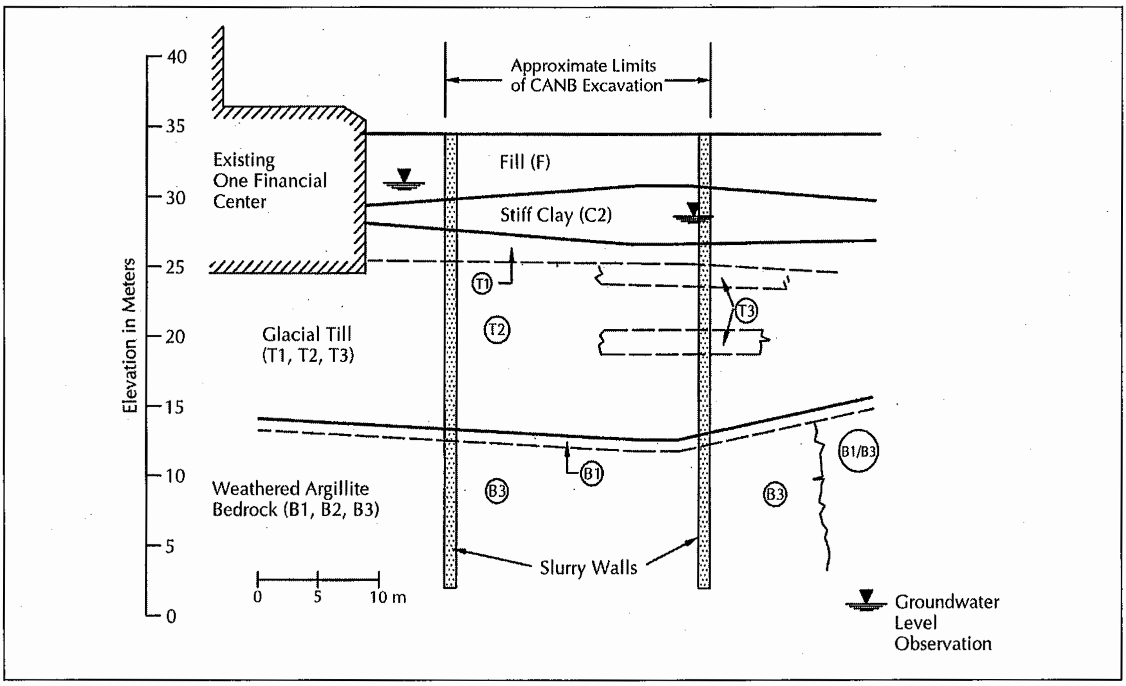

FIGURE 3. Subsurface conditions at OFC (station 97+00 CANB).

structed as the CANB tunnel is being backfilled and supported above its roof slab.

The CANB C11A1 tunnel alignment reaches its maximum excavation depth of about 33.55 meters (110 feet) below ground surface as it crosses beneath the Red Line at Summer Street, and the depth gradually decreases to about 30.5 meters (100 feet) near Congress Street. The alignment stays generally within the Atlantic Avenue right of way except for an approximately 46-meter (150-foot) length between stations 101 and 102+50 that intersects the corner of the FRB garage. This portion of the FRB garage has been demolished, resupported by temporary columns to support adjacent sections of the garage and will be reconstructed after the CANB tunnel has been completed. The alignment passes within about 6 meters (20 feet) of OFC.

The design cross sections of Figures 2 and 3 show the support walls and CANB tunnel limits in relation to the FRB and OFC buildings, respectively. The excavations extend more than 21.4 meters (70 feet) below the foundation levels of both buildings. The support walls are soldier pile tremie concrete (SPTC), nominally 1.07 meters (3.5 feet) thick, excavated using slurry techniques. The SPTC walls extend into till or bedrock and will become part of the permanent structure. They are supported during excavation by wales and cross-lot struts, with strut spacings varying from about 3.05 to 3.66 meters (10 to 12 feet) vertically and 4.88 to 6.1 meters (16 to 20 feet) horizontally. It is the contractor's responsibility to design the internal bracing system for the excavation support walls. The contract documents have provided excavation support system design criteria (including lateral earth pressure diagrams) and have suggested construction sequences for cut-and-cover tunnel construction that is intended to restrain lateral wall movement to the maximum extent possible.

The initial studies of the site conducted by the CA/T Project's area geotechnical consultant (AGC) for this contract included preliminary estimates of excavation-induced ground movement along the C11A1 alignment.[1] Calculations were made using the semi-empirical approach developed by Clough and O'Rourke[2] and by the finite element computer program SOILSTRUCT for a generalized glacial till profile. The semi-empirical approach consisted of first estimating the maximum horizontal wall movement (about 0.15 percent of

TABLE 1.
Summary of Preliminary Estimated Displacements of the FRB and OFC Resulting from Cut-and-Cover Tunnel Construction

Structure	FRB Low Rise	FRB High Rise	OFC
Distance From Excavated Support Wall			
Front of Structure (m)	0	25.6	7
Back of Structure (m)	39	58.6	68
Excavation Depth (m)	28.4-32.6	31.4	32.7-33.2
Estimated Excavation-Induced Movement			
Empirical Methods			
Maximum Lateral Wall Movement (cm)	3.8-6.4	3.8-6.4	3.8-6.4
Settlement at Front of Structure (cm)	2.8-4.6	1.0-1.8	2.5-4.1
Settlement at Back of Structure (cm)	0.3	0.0	0.0
Lateral Movement at Front of Structure (cm)	2.8-4.6	1.0-1.8	2.5-4.1
Lateral Movement at Back of Structure (cm)	0.3	0.0	0.0
Maximum Horizontal Strain (×0.001)	0.7-1.1	0.7-1.2	0.6-1.0
Finite Element Method			
Maximum Lateral Wall Movement (cm)	2.3-3.3	2.3-3.3	2.5-3.6
Settlement at Front of Structure (cm)	0.5-0.8	0.5-0.8	1.0-2.0
Settlement at Back of Structure (cm)	0.3-0.5	0.3-0.5	0.3
Lateral Movement at Front of Structure (cm)	2.0-2.8	1.3-1.8	1.5-2.3
Lateral Movement at Back of Structure (cm)	0.8-1.0	0.3-0.5	0.3
Maximum Horizontal Strain (×0.001)	1.7-2.4	0.6-0.8	0.2-0.3
Estimated Maximum Angular Distortion			
Empirical Methods (×0.001)	0.7-1.1	0.7-1.2	0.6-1.0
Finite Element Method (×0.001)	0.2-0.3	0.2-0.3	0.3-0.4
Allowable Angular Distortion (×0.001)	2.0	2.0	2.0
Building Damage Potential	Slight	Very Slight	Slight

From Ref. 3.

the excavation depth for these predominantly glacial till profiles) and then estimating the magnitude and distribution of horizontal and vertical (assumed equal to horizontal) ground movements away from the excavation. Both methods assumed that building displacements will be equal to free-field ground movement at the foundation bearing levels.

Table 1 summarizes the preliminary estimates by the section designers of the cut-and-cover excavation-induced ground movements of OFC and FRB using the two methods described above.[3] These estimates did not include consolidation settlement due to groundwater lowering.

Table 1 also compares the corresponding excavation-induced angular distortion compared with the allowable angular distortion of 0.002, based on CA/T Project design criteria. Finally, Table 1 presents the building damage potential resulting from the estimated angular distortions and horizontal strains. These potentials are estimated from the well known relationships established by Boscardin and Cording.[4] The damage potential was estimated to be slight (for the FRB auditorium low rise and OFC) to very slight (the FRB high rise), which suggests that the effects of the CANB excavation on the FRB and OFC may be small.

Communication Between the Abutters & the CA/T Project

The management of the FRB and OFC complexes assembled their own teams of consultants to work with the CA/T Project management consultant to develop measures to minimize the effects of the C11A1 excavation on their buildings. Formed during the early stages of the C11A1 design in 1992 and 1993, these teams developed a number of tactics that have been employed in this effort. The CA/T Project management consultant has regularly transmitted for FRB and OFC consultant review key documents such as:

- Draft contract plans and specifications as the bid documents were developed over a number of years;
- CA/T Project section design consultant reports;
- CA/T Project contract addenda;
- Contractor submittals such as support-of-excavation design and value engineering proposals; and,
- All relevant instrumentation data.

Some specialized work within the buildings (such as the required structural modifications in the FRB garage) has been contracted directly by the building owners, with reimbursement by the project. A most important tactic has been the establishment of regular meetings attended by the FRB and OFC consultants, the CA/T Project management consultant and section design consultant (SDC), as well as contractor representatives whenever appropriate. These working group meetings occur every one or two months (more frequently if needed), and, depending on the commonality of the agenda, the FRB and OFC meetings have been held either separately or combined. At various times, project representation has included design, instrumentation, construction and management personnel.

These meetings have led to a number of measures to minimize the effects of the CA/T Project excavation on the FRB and OFC buildings. These measures include:

- Additional ground movement and structural analyses of the FRB and OFC.
- Additions to the CA/T Project instrumentation program.
- Special C11A1 contract provisions such as strict limits on the longitudinal extent and time duration of unsupported excavation between bracing levels and a contingency plan that includes additional bracing levels and tieback support that may be implemented if instrument response values are reached. (The instrumentation specification includes threshold and limiting values for all FRB and OFC instruments that may trigger responses ranging from more frequent readings to modifications of construction procedures and, in the extreme, to the implementation of the specified contingency plan.)

Additional Ground Movement & Structural Analyses

The CA/T Project management consultant and the SDC decided to perform site-specific analyses of the FRB and OFC because of the approximate and generalized nature of the preliminary analyses, the lack of consideration of soil-structure interaction effects, and the size and importance of the FRB and OFC buildings. The building damage potential relationships established by Boscardin and Cording do not apply to large modern buildings.[4] Because they are highly indeterminate, some large modern buildings are sensitive to even small differential foundation movements. On the other hand, the benefits of structural creep and relaxation on building response are unknown. There are virtually no data available on the response of large structures like the FRB and OFC to excavation-induced ground movements.

FRB Analyses. The site-specific FRB analyses evaluated the structural response to excavation-induced ground movements at three cross sections as follows:[5,6]

- CANB station 102+00 — through the south tower of the high rise to the slurry wall.
- CANB station 103+55 — through the north tower of the high rise to the slurry wall.
- CANB station 105+50 — through the auditorium and basement electrical area to the slurry wall.

The SDC first computed the free-field soil movements using SOILSTRUCT and the soil properties recommended in the AGC report, assuming that the groundwater would be maintained at preconstruction levels.[1] The finite element program ANSYS was then used to evaluate soil/structure interaction effects. ANSYS includes a non-linear gap interface element with friction along the interface. Figure 4 shows typical foundation displacements computed by these soil-structure interaction analyses. A comparison of the soil-only and soil/structure analyses indicates that the foundation footings and tower mat have minimal impact on vertical displacements but that the tower mat greatly smooths out the horizontal displacements. A number of structural models were then developed to evaluate the effects of these foundation movements on the FRB structures. These included a two-dimensional plane strain model with lumped column and beam properties as well as a comprehensive three-dimensional model for the north tower. These analyses concluded that:[5,6]

- The foundation movements will not compromise the safety of either the foundation or the superstructure.
- The two-story below-grade garage structure may experience some degree of structural distress when subjected to the estimated ground movements. This distress may consist of cracking, which may develop in the first and second basement slabs; additional cracking may appear in the foundation walls at abutting corners. There is marginal strength in the connection between the steel column and the two-way flat concrete slab at the first basement level to develop the bending-type loads imposed by the laterally displaced foundation and column base.
- The high-rise structure may experience some minor problems due to the displacement of the north tower mat. Cracking of the first basement and ground level slabs may occur.
- The deflection of the upper stories of the tower due to the base movements is within acceptable limits.
- The auditorium structure can sustain the movements; however, there is the possibility of localized distress developing in certain regions that may cause cracking of slab, wall and architectural elements.

As a result of these studies, a number of the connections between the steel column and concrete slab at the first basement level have been reinforced. These studies have also served as a basis for the FRB instrumentation program, with particular emphasis on the possible structural distress of the two-story below-grade garage when subjected to the estimated horizontal ground movements.

OFC Analyses. The site-specific OFC analyses evaluated the structural response to excavation-induced ground movements at three cross sections as follows:[7]

- CANB station 97+25 — through the south side of the high rise adjacent to Essex Street.
- CANB station 98+50 — through the north side of the high rise.
- CANB station 98+60 — through the atrium area.

As in the FRB analyses, the SDC first computed the free-field soil movements using SOILSTRUCT and the soil properties recommended in the ACG report, assuming that the groundwater would be maintained at preconstruction levels.[1] The SDC then used the finite element program ANSYS to evaluate soil/structure interaction effects. As noted in the FRB analyses, the OFC tower mat foundation also significantly smooths out the excavation-induced horizontal displacements; however, it has little effect on the vertical displacements. In the atrium, the computed vertical and horizontal displacements of the individual spread footings parallel the soil movement, indicating that the atrium structure (with its spread footings and simple framing) exerts a minimum restraining influence on the soil medium.

The SDC then used the GTSRUDL structural engineering software to evaluate the response of the OFC mat, tower superstructure and atrium to the computed excavation-induced movements. These analyses concluded that:[7]

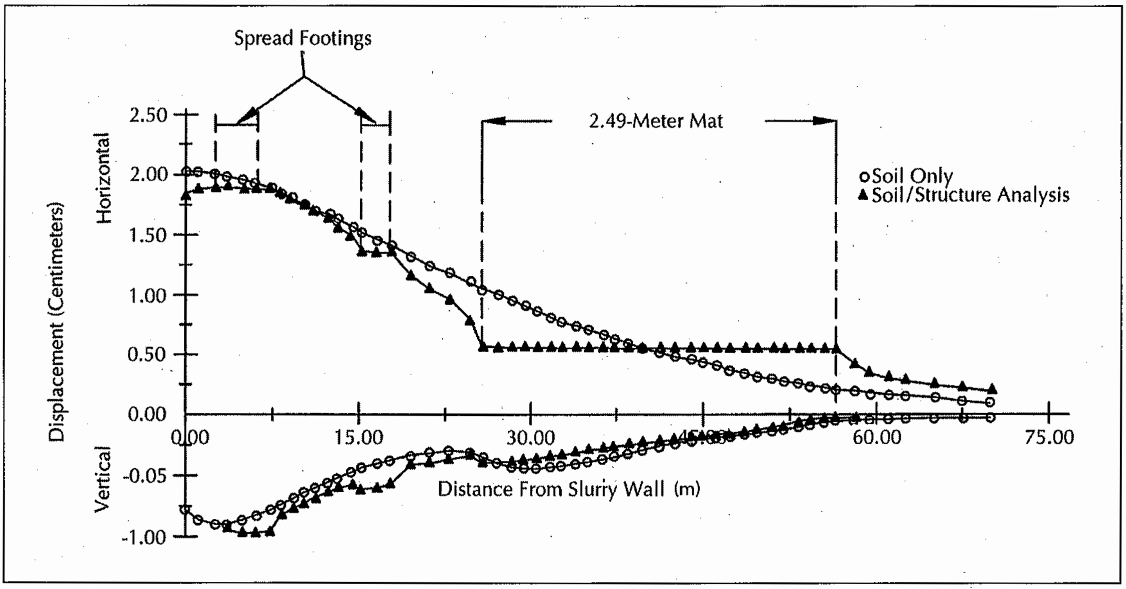

FIGURE 4. Foundation soil interaction for the FRB.

- The computed soil movements under the OFC building will not compromise the safety of either the foundation or the superstructure.
- The mat has sufficient capacity to carry the moments induced by the vertical displacements. However, some flexural cracking may occur.
- Some tower floor girders may experience additional excavation-induced stresses up to 27,580 kN/m^2 (4 ksi). However, these additional stresses will not pose any threat to the structural integrity of the structure.
- A bolt failure or concrete bearing seat failure may occur where the steel framing of the atrium connects to the foundation wall.
- The excavation-induced stresses in the atrium superstructure are acceptable.
- Some distress of the building's architectural components may occur, resulting in the cracking of wall and floor finishes. This cracking will most likely occur at the interface of the atrium and high-rise tower.

These studies have served as a basis for the OFC instrumentation program, with particular emphasis on the effects of vertical ground movements on the OFC structure.

Instrumentation Programs

CA/T Project designers established comprehensive instrumentation programs to monitor the performance of the excavation support system and the detailed response of the FRB and OFC buildings and their foundations to the CA/T Project construction. The instrumentation programs also includes a management plan for collecting, reducing, processing, plotting, reporting and interpreting the monitoring data.

Figure 5 presents the locations of instrumentation installed in the FRB building. These instruments include:

- deformation monitoring points (DMPs) in the lower garage for the precision survey of horizontal (29 points) and vertical (65 points) movements;
- thirty-three convergence gage anchorage points (CGAPs) to measure relative horizontal movements of select garage columns, the exterior garage wall and main tower mats;
- three inclinometers (INC) to measure horizontal garage and ground movements;
- four seismographs (SM) to measure vibrations in representative and/or critical locations;
- two hundred and eighty vibrating wire strain gages (VWSG) backed up by 280

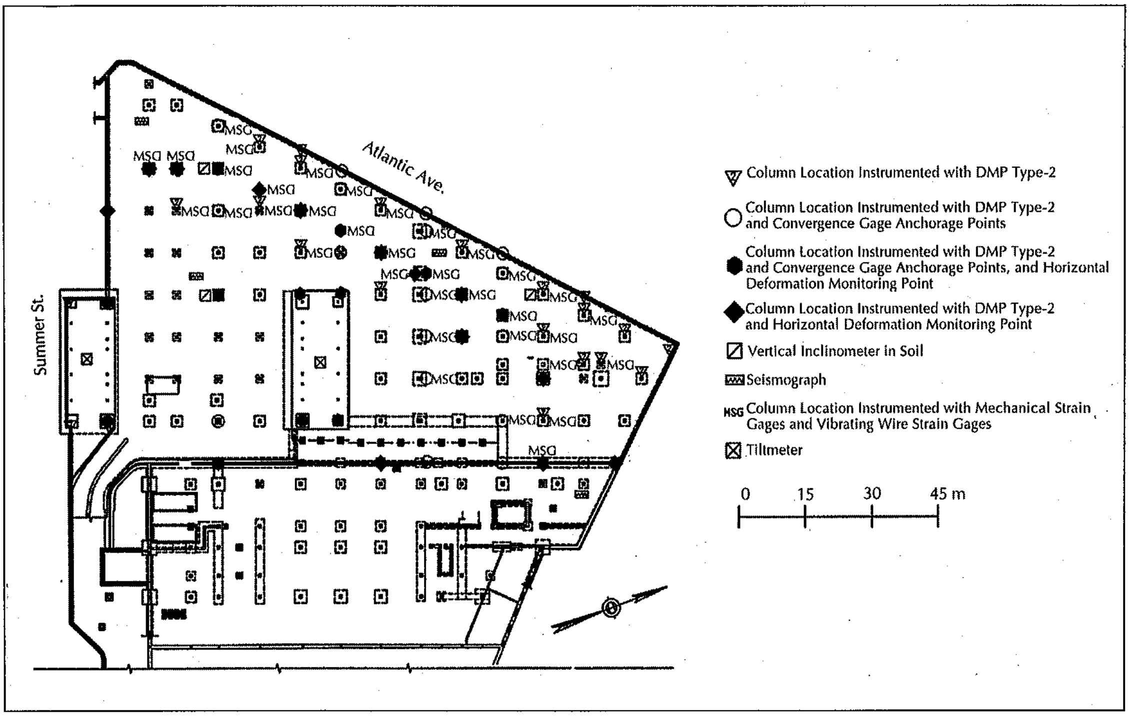

FIGURE 5. Instrument locations for the FRB.

pairs of mechanical strain gages (MSG) to measure bending strains at select column locations in the basement levels just above and below the B1 floor slab; and,
- two tiltmeters to measure bidirectional tilt of the tower mat foundations.

Figure 6 presents the locations of instruments installed at OFC. These instruments include:

- seven DMPs in the lower garage for precision survey of vertical movements;
- six CGAPs to measure relative horizontal movements of select garage columns;
- six shear displacement gages (SDGs) to measure the relative horizontal movement between the foundation mat and the atrium slab on grade;
- five single-position borehole extensometers (SPBXs) to measure the settlement of the foundation mat;
- one dial gage (DG) to measure the relative horizontal movement between the beam and exterior wall at column grid location J-1 in the lower garage; and,
- twenty-one tiltmeters (TMs) to measure bidirectional tilts of the foundation mat.

Also, 72 VWSGs (backed up by 72 pairs of MSGs) were installed to measure strains at select beams and columns throughout the structure.

After the FRB and OFC instruments were installed, significant construction activities included:

- utility relocations;
- Red Line stairway and escalator excavations;
- the demolition of part of the FRB garage that intersects the CA/T Project alignment; and,
- slurry wall construction.

These activities have provided baseline data and an opportunity to evaluate the performance of the instrumentation system.

CA/T Project excavation adjacent to the FRB and OFC, as well as the building instrumentation systems, were designed under the assumption that there would be only a small amount of groundwater lowering in the area

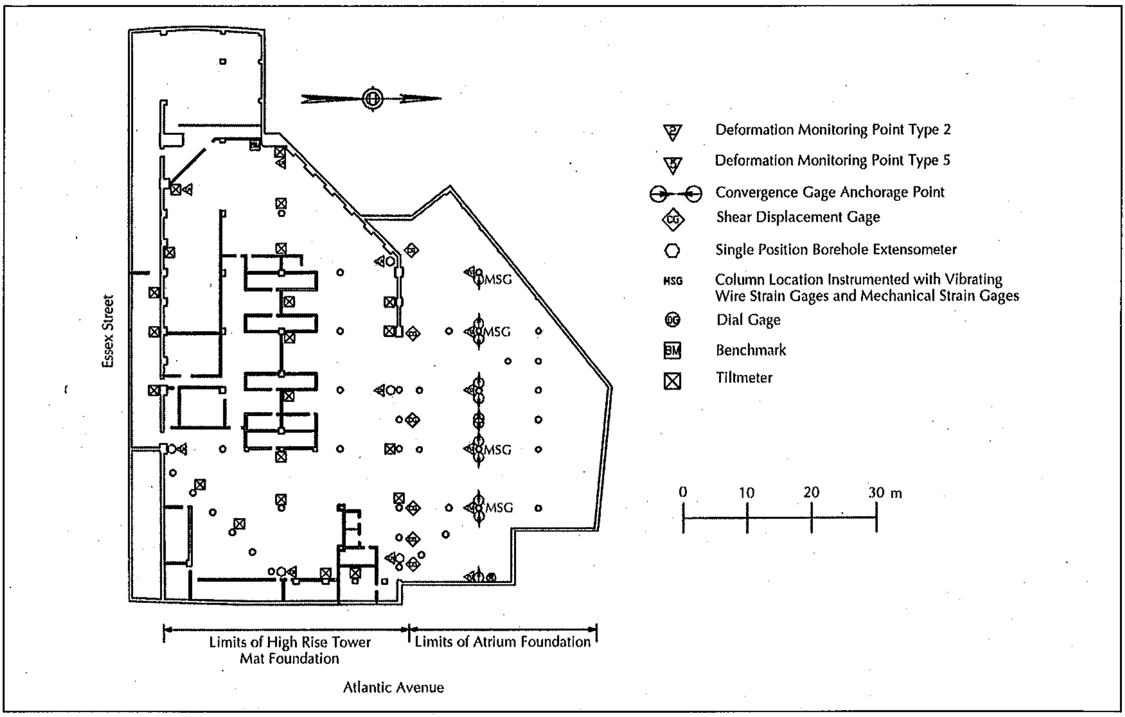

FIGURE 6. Instrument locations at OFC.

during construction. However, the underpinning of the MBTA Red Line South Station subway station required substantial construction dewatering, lowering the piezometric surface to below elevation 6 meters (20 feet) within the CA/T Project alignment. The initial baseline measurements — especially when the groundwater was lowered for the Red Line underpinning — suggested that there was a need for additional instruments. At the FRB, these instruments have included DMPs for vertical survey, additional CGAPs in the garage and piezometers installed below the garage. At OFC, additional SPBXs and one multiple position borehole extensometer (MPBX) have been installed to measure the settlement of the foundation mat and to serve as deep benchmarks for the vertical survey. Also, an extensive array of vertical DMPs has been added to replace the TMs that performed poorly because of moisture from the OFC garage floor wash water.

Representative data are presented in Figures 7 through 10. The representative FRB inclinometer data presented in Figure 7 reveals a four-year record of excellent repeatability and very small horizontal movements accumulated to date. Representative FRB tiltmeter data in Figure 8 shows mostly the effects of seasonal variations with little effect caused by the adjacent construction activities. Figure 9, an OFC DMP settlement profile, illustrates the precision achieved by these high-order DMP surveys. Representative OFC strain gage data in Figure 10 depicts the strain gage response of the structure to both construction activities and seasonal effects. Computer-controlled systems continuously monitor the strain gages at both buildings and will trigger an electronic 24-hour alarm that notifies a list of key individuals if readings exceed contract-specified response values. These data selections illustrate the quality of data that the instrumentation has provided during the main CA/T Project excavation.

Discussion

The groundwater lowering in Dewey Square for the Red Line underpinning has significantly affected the building and instrument response to the CA/T Project construction. The FRB and OFC have settled, as illustrated by Figure 9, mostly due to the compression of the underlying soils caused by groundwater

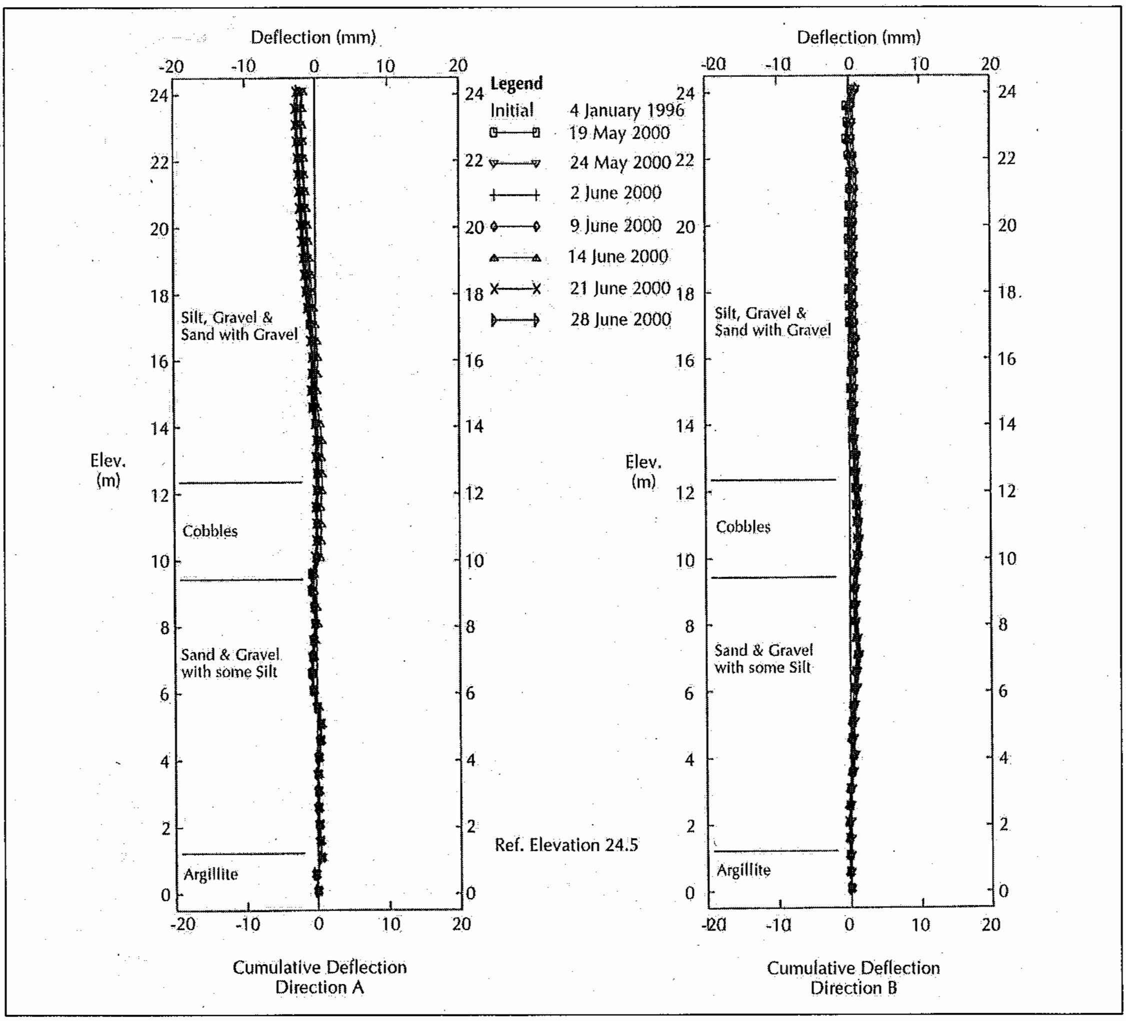

FIGURE 7. FRB inclinometer data (from inclinometer 85705).

lowering. Measured horizontal movements have been small — much less than predicted — due to the reduced hydrostatic pressures on the very stiff CA/T Project bracing system. For example, the FRB inclinometer data (see Figure 7) show very small horizontal movements. These movements are as small as the repeatability of the inclinometer measuring system. Although not depicted, the CGAP data also show very small horizontal movements. Seasonal variations can be a large portion of the instrument response values, as illustrated by the FRB tiltmeter data presented in Figure 8. These variations must be accounted for when interpreting all data for the effects of the CA/T Project excavation. A more detailed discussion of the instrumentation data, including comparisons with the predicted movements, is beyond the scope of this article.

The abutter/project communication process during the design period led to the valuable development of analysis methods, monitoring methods and contract provisions. This process has been extremely important during construction as instrument data are gathered, contractor issues develop and construction procedures are modified based on conditions in the field. For example, abutter/project communication facilitated the project response to the Dewey Square groundwater lowering. This response included adding instruments to the monitoring program and developing follow-up analyses that have shown that the combined effects

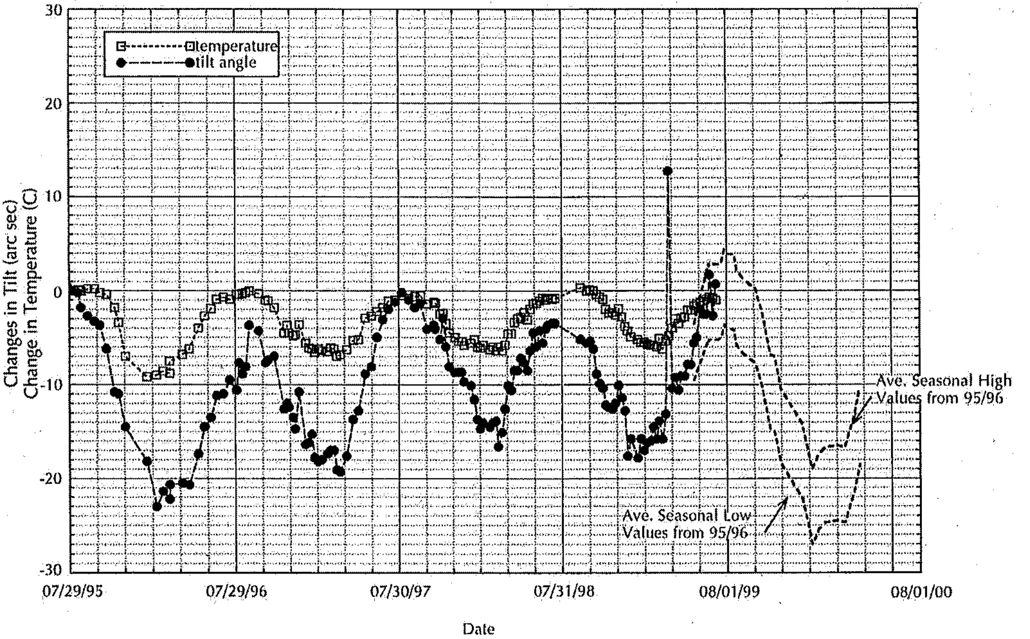

FIGURE 8. FRB tiltmeter data (from tiltmeter 51859, y-axis).

of ground movements caused by the excavation and groundwater lowering would likely cause comparable or less impact on the FRB and OFC buildings than what was anticipated for the assumed design condition of CA/T Project tunnel excavation without dewatering.

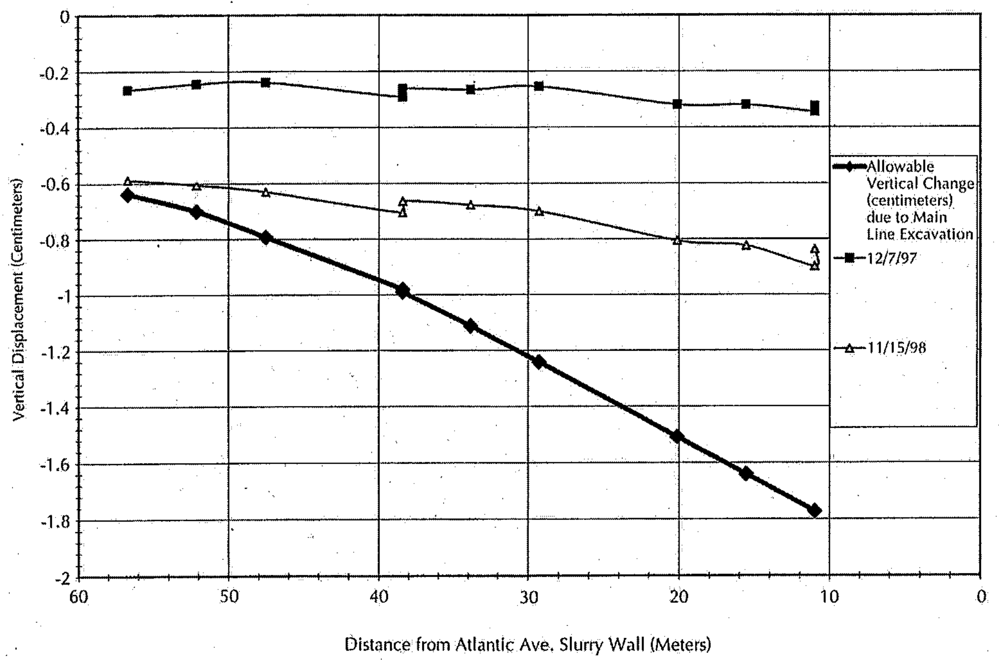

FIGURE 9. OFC DMP settlement profile (column line E).

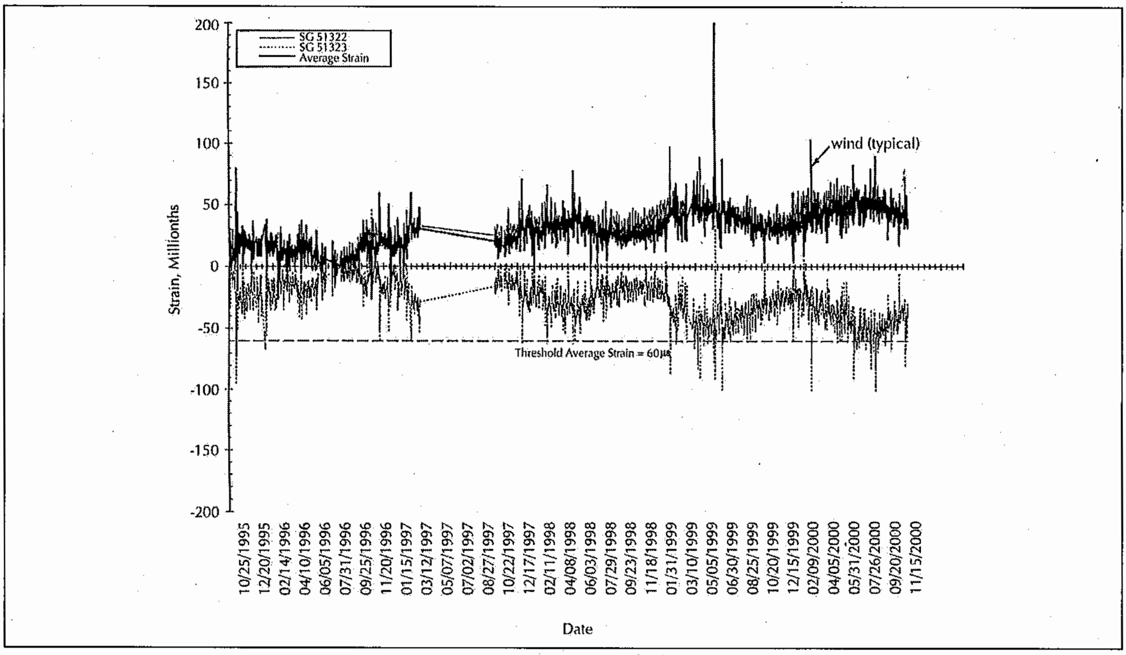

FIGURE 10. OFC strain gage data (plate girder along the E-line).

This benefit is due to the reduced hydrostatic pressures on the excavation support system.

Summary & Conclusions

Measures were developed to minimize the effects of an excavation for the CA/T Project on the FRB and OFC. Protective measures included:

- abutter review of excavation support design, contract documents, contingency plans and contractor submittals;
- extensive ground movement and structural response analyses;
- geotechnical and structural instrumentation systems (hardware, data processing, management, etc.); and,
- structural modifications.

These measures were developed by a cooperative effort between the abutter consultants and the CA/T Project management consultant. In a project of this complexity, size and duration, clear communication between the interested parties is essential. Regular working group meetings have been particularly important for establishing procedures for transmitting information, for abutter review of design and construction, and for maintaining continuity of effort. The process can benefit other large and complex projects with significant potential abutter impact. It requires that the abutter and project have appropriate technical expertise, and that they cooperate and communicate clearly.

NOTES — *The Bechtel/Parsons-Brinckerhof (B/PB) joint venture serves as management consultant for the Massachusetts Turnpike Authority (MTA) in the CA/T Project work. Geotechnical Engineers, Inc. (GEI), served as the area geotechnical consultant and a joint venture of Seelye Stevenson/Deleuw Cather, in association with Haley & Aldrich, Inc., (SS/DC/H&A) served as designers of the CA/T Project work adjacent to the FRB and OFC buildings. This description of the CA/T Project is based on the final geotechnical engineering report, the final design summary report and the contract drawings and specifications for contract section C11A1. Consultant teams for the RFB and OFC consisted of Lewis Edgers (geotechnical), Thomas L. Weinmann of CTL, Inc. (instrumentation), and Kenneth B. Wiesner of LeMessurier Consultants (structural) for the FRB; and Lewis Edgers (geotechnical), Thomas L. Weinmann of CTL, Inc. (instrumentation), and Richard Henige of LeMessurier Consultants (structural) for OFC.*

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