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Federico Pinto
CONICET – Universidad Nacional de Córdoba, Argentina

Gary M. O'Neil
McPhail Associates LLC, Cambridge, MA

Amy D. Apfelbaum
McPhail Associates LLC, Cambridge, MA

Andrew J. Whittle
Massachusetts Institute of Technology, Cambridge, MA

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Federico Pinto
CONICET – Universidad Nacional de Córdoba
Córdoba, Argentina, 5016

Gary M. O'Neil
McPhail Associates LLC
Cambridge, MA 02140, USA

Amy D. Apfelbaum
McPhail Associates LLC
Cambridge, MA 02140, USA

Andrew J. Whittle
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

ABSTRACT

Renovations of the MBTA Copley Station in Boston included construction of a new elevator shaft to improve disabled access to the existing Green Line station. The site is immediately adjacent to the Eastern façade of the historic Old South Church. The construction work required excavation support including a perimeter secant pile wall and a jet-grouted base plug. Significant ground and structural movements were observed during jet grouting, mainly associated with soil displacements during grout injection. A three dimensional numerical model was developed, using the Plaxis 3D Foundation^{TM} program, in order to test the hypothesis that the observed movements of the structure could be associated with the installation of the jet grout piles. The amount of volume expansion associated with installation of jet grout piles is estimated based by calibrating the model to measured ground movements. The finite element model results give a consistent explanation for the observed pattern of movements, including the heave of the church wall and lateral displacements at inclinometers located within the vicinity of the structure, measured at the time when damage occurred. The model assumes there is a vertical line of weakness in the masonry, representative of a pre-existing structural crack, as observed by structural investigations; and hence, confirms the underlying mechanical hypothesis for the source of ground movements.

INTRODUCTION

The Copley Station of the MBTA Green Line abuts the Old South Church (OSC); a historic structure built in 1874. Renovations to the Station included an elevator for handicapped access to the outbound platform (Fig. 1). This project involved excavations for a vertical shaft to the existing underground station. The Contractor's system for Support of Excavation (SOE) included a perimeter secant pile wall along the Northern, Eastern, and Western limits of the excavation, with jet grout columns at perimeter locations. The Southern limit includes a flow-fill gravity wall cast above the existing station. The base of the shaft is also stabilized using a series of jet grout columns that cutoff groundwater seepage and provide foundation support. There was no provision for relocation of utility lines associated with the contract.

Work on the project was suspended in December 2008 due to observations of damage to the East façade of the Old South Church including the widening and extension of cracks that extended up from the foundation level, through the stone walls above the main stained glass windows up to the roof level (and height of more than 60ft), causing significant damage to the interior plaster wall. Fig. 2 shows vertical displacements measured at several displacement measuring points (DMP, Fig. 1). The ground and structural movements were attributed to jet grouting activities for the new elevator shaft that were on-going at the time. Subsequent investigations focused on possible mechanisms causing the movements including detailed inspections of the OSC foundations (involving load testing of several timber piles), an extensive geotechnical site investigation, and implementation of a sophisticated instrumentation program to monitor for any further ground or structural movements. After establishing that movements had stabilized, the below grade works resumed in November 2009 using a revised construction sequence. With careful planning and execution, the elevator shaft was completed in April 2010, with no further movement or damage to the Old South Church. This paper summarizes the development and validation of a 3-D model of the soil-structure interactions that was carried out to test the hypothesis that the observed movements of the OSC could be associated with the installation of the jet grout piles.

SITE CONDITIONS

Figure 3 shows the typical soil profile, together with a vertical section showing the excavation support system for the elevator shaft and pile foundations of the Old South Church.

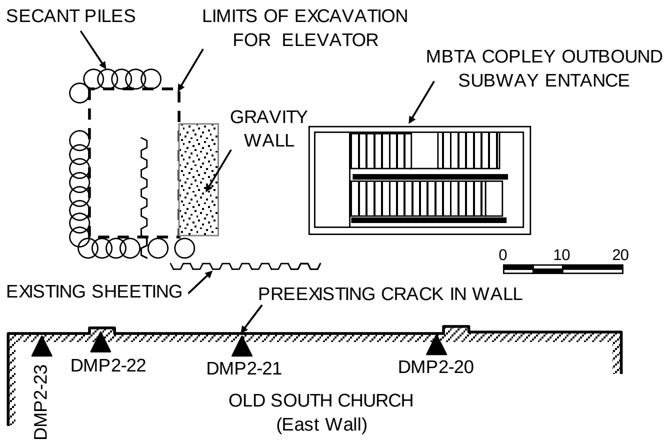


Fig. 1. Site plan

The ground surface is level at El. +117.5 ft. The average soil profile at the site is comprised of an 18-ft thick layer of dense sand and gravel fills (average N = 44 bpf), an organic silt unit of similar thickness (N = 6 bpf), and a 5-ft thick layer of very dense marine sand (N = 72 bpf), underlain by Boston Blue Clay (BBC). Groundwater conditions are assumed to be hydrostatic with a seasonally-averaged groundwater level located in the fill at El. +105ft. Laboratory tests conducted on samples from the forensic site investigation (September 2009) shows that the organic silts are lightly overconsolidated with an average OCR = 1.70, while the upper BBC is desiccated and more highly overconsolidated (OCR ≥ 5).

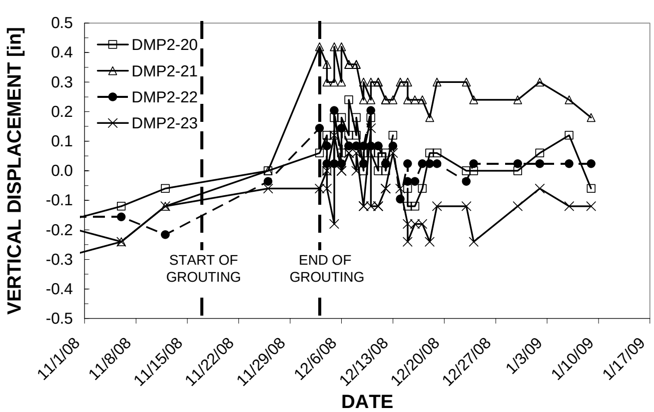


Fig. 2. Observed displacements at East Wall

The Old South Church is supported on timber piles end bearing on the very dense marine sand. The base of the new elevator shaft is located at El. +94ft (i.e., excavation is wholly within the fill and silt units), while the jet-grout pile plug and secant pile wall extend into the upper BBC.

The subsequent analyses use relatively simple, elastic and Mohr-Coulomb (i.e., elastic perfectly plastic) models to represent the stress-strain-strength properties of the soil units, Table 1. The Input parameters for the models were based on prior engineering correlations (e.g., Ladd et al., 1999) supplemented with data from the forensic site investigations.

STRUCTURAL MODEL

The structural model considers the complete East wall,of the Old South Church and its supporting wooden pile foundations together with a small section of the connecting North and South walls. The boundary conditions assume that the rest of the structure is not impacted by the construction of the elevator access shaft.

Figure 4 shows an elevation of the East Wall of the Old South Church, together with the observed cracking pattern. The observed cracks start at the fourth bottom window from the South (left in Fig. 4), coincident with the location of a pre-existing crack, and continue towards the top of the wall, initially following an almost vertical path.

Due to limitations in the capabilities of the FE program used in the current analyses (Plaxis 3D Foundation^{TM}, v2; Brinkgreve & Swolfs, 2007), only horizontal planes and lines are allowed in the model. Figure 5 shows a representative model of the East Wall, where a vertical crack is introduced at the observed location. The model approximates the crack pattern with a continuous vertical through-crack. This approximation captures the lack of continuity between the two wall "blocks", as well as the intersection of the discontinuity line at the ground corresponding to a point of rotation when deformations take place.

The East wall is represented by plate elements, using cutouts for the main windows, and a reduced thickness (lower stiffness) zone for the main rose window.

Figure 6 shows a 3D view of the FE model of the East wall and foundations, where the vertical crack is shown as a vertical discontinuity. Piles are modeled by means of embedded beam elements, connected to a granite pile cap that supports the church wall. Additional connection elements are included in order to provide a smooth transition of forces between these elements, without significantly altering the overall behavior of the foundation-wall system.

The timber piles are assumed to extend 2ft into the very dense marine sand layer. Assumed pile properties are summarized in Table 2. The pile tops are modeled fully in contact with the overlying pile cap, this was confirmed by test pits performed during the forensic site investigations. These investigations also revealed a remnant sheet pile wall located around the existing subway entrance structure, Figs.1 and 7. This sheeting (section PZ-27) is assumed to extend to El. +72 ft, with an upper cutoff at El. +110 ft. The sheet pile wall is assumed to have elastic properties.

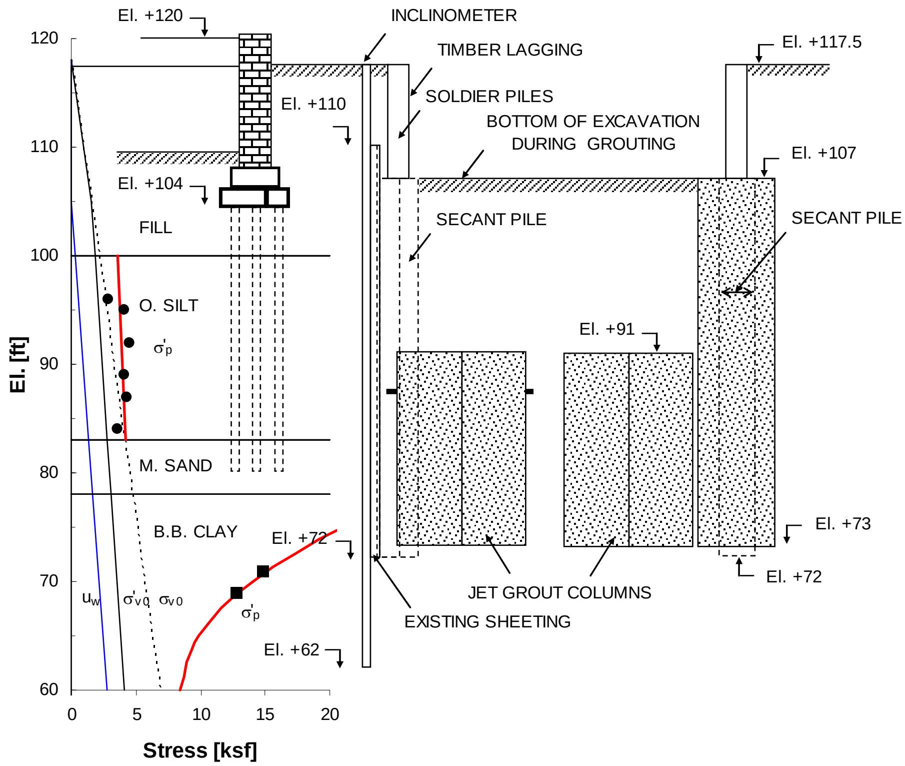


Fig. 3. Typical soil profile, OSC foundations and excavation support for elevator shaft

Table 1. Mechanical properties and models for soil layers
(MC – Mohr-Coulomb; LE – Linear, Elastic)

	Model	Effective Stress Strength γ [pcf]	c [psf]	$\Delta c/\Delta z$ [pcf]	ϕ [º]	ψ [º]	Basic stiffness - Standard formulation k_0	ν	E' [ksf]	$\Delta E'/\Delta z$ [kcf]
Fill	MC	115	0	0	34	2.0	0.50	0.25	150	20.0
O. Silt	MC	110	440	12.3	0	0.0	0.55	0.33	350	9.5
M. Sand	MC	125	0	0	40	5.0	0.45	0.25	900	11.2
Clay Crust	LE	120	-	-	-	-	0.77	0.30	660	9.3
Clay NC	LE	120	-	-	-	-	0.60	0.33	270	4.5

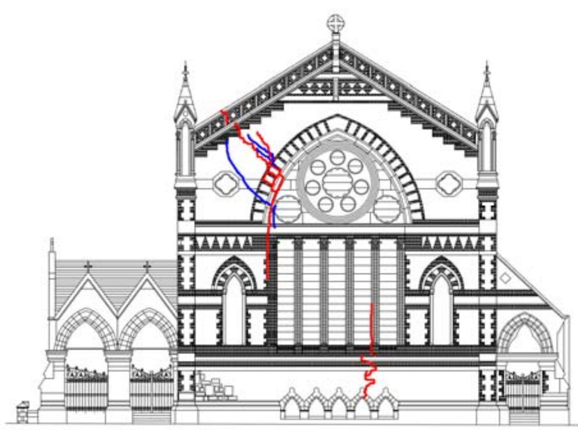


Fig. 4. East Wall – Observed cracks

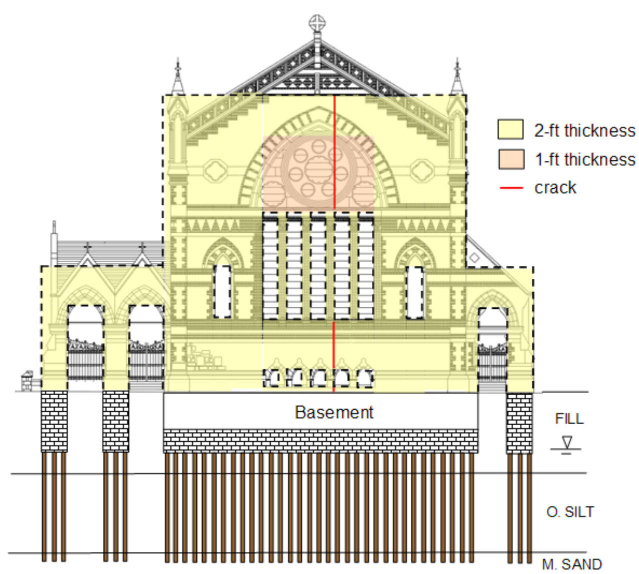


Fig. 5. FE representation of East Wall

Table 2. Timber pile properties

Property		Value	Units
Diameter, D		9	in
Young's modulus, E		1500	ksi
Length, L		20	ft
Skin friction	Fill	-	
	O. Silt	520	psf
	Sand	-	psf
End bearing	Sand	24	kips

The excavation support system of the access shaft consists of the installation of the following components:

- A flowable fill wall directly above the existing station and adjacent to the proposed excavation.
- Soldier pile and timber lagging from the ground surface to El. 107ft.
- A reinforced concrete secant pile wall between El. 107ft and El 72ft.
- The installation of jet grout columns to support utilities and a partially completed jet grout plug between El. 95ft and 75ft.

Thus, the list of structures involved in the analyses are: church walls, wood piles with granite caps, existing steel sheeting at the site, the flow fill wall adjacent to the excavation, soilcrete due to jet grouting, and concrete of secant shafts encasing the excavation. The structural properties considered in the analyses are summarized in Tables 3 and 4.

Table 3. Structural properties

	Model	γ [pcf]	ν	E [ksf]
Soilcrete	LE	90	0.20	2,160
Concrete*	LE	150	0.17	440,000
Flow Fill	LE	130	0.20	100,000
Wood	LE	33	-	220,000
Granite	LE	168	0.20	1,000,000
Wall	LE	160	0.15	500,000

* Concrete modulus is reduced by 30% due to potential cracking

Table 4. Properties of sheet pile wall

Property		Value	Units
Moment of Inertia	I1	184.2	in^4/ft
Virtual thickness	d	1	ft
Young's moduli (orthotropic)	E_1	3194	ksi
	E_2	160	ksi
Shear moduli (orthotropic)	G_{12}	160	ksi
	G_{13}	275	ksi
	G_{23}	83	ksi
Poisson ratio	ν_{12}	0	-
Unit weight	γ	27	pcf

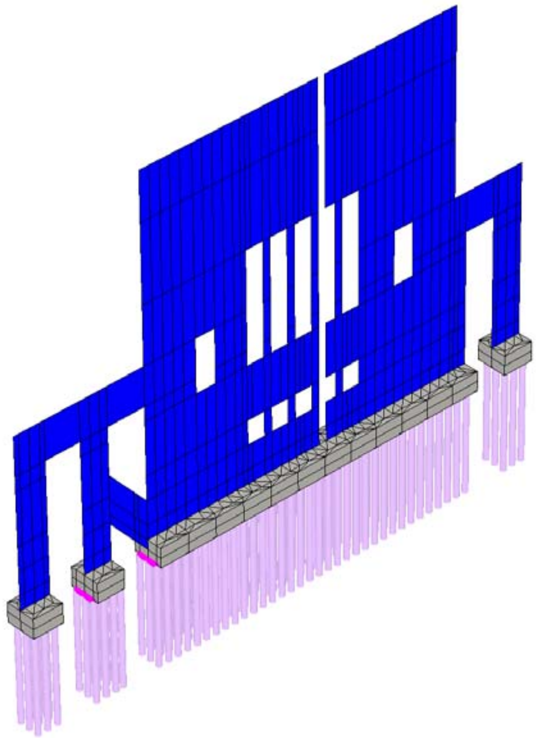


Fig. 6. East wall and foundations – FE Model

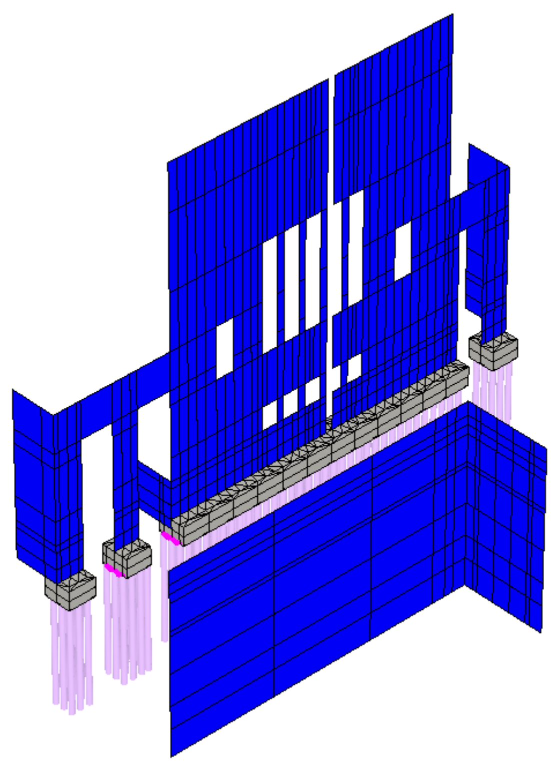


Fig. 7. FE Model showing OSC structural model and existing sheet pile wall (from MBTA Copley Station construction)

All structures are assumed to remain elastic within the range of displacements observed at the site. Regarding the church wall, cracks are introduced where yielding has been observed, but the rest of the wall is assumed to remain elastic.

MODELING OF JET GROUTING

Jet grouting is a well-established ground improvement technology that has been successfully implemented in a number of large scale engineering projects (e.g., Wen, 2005). However, since it involves the injection of fluids at high pressure within the ground, lateral ground displacements and heave are often a concern, particularly in clayey soils (e.g., Wong and Poh, 2000, Wang et al., 1999). The contractor used a double tube jet grouting system for the elevator access shaft. This system simultaneously injects high velocity grout and air, the latter improves the cutting efficiency and lifts the soil cuttings up to the ground surface.

Installation of the jet grout columns produced uplift of the structures as well as outward lateral movements in the adjacent subsurface soil units. Hence, volume expansion of the grout columns is considered to be a primary cause of the observed structural deformations during jet grouting. The numerical model attempts to represent this volume expansion phenomenon as described in the subsequent paragraphs.

The goal of the numerical model is to represent the ground response to the installation of jet grout columns adjacent to the church structure in order to assess the resulting deformation pattern and compare with observed movements in the inclinometer and settlement points monitored during the jet grout column installation.

The main question to be answered by the numerical model is whether the observed ground displacements can be explained by the combined effects of volume expansion of the jet grout columns.

The model considers the response of the different soil and structural elements to an imposed volumetric strain in the jet grout columns. However, as the behavior is assumed nonlinear, the actual calculation process proceeds from an initial reference state corresponding to a greenfield site (i.e., prior to the construction of the Old South Church itself). The construction stages can be summarized as follows:

- Initial drained equilibrium with horizontal soil layers under K0-stress conditions (with parameters listed in Table 1).

- Stresses caused by construction of the Old South Church are represented in several stages including pile installation, cap construction, basement excavation, and church wall construction. These events took place more than 100 years ago and are solved assuming drained equilibrium at all stages. Similarly, the perimeter sheet pile wall was part of the prior MBTA Copley Station construction (dating to 1914) and hence, the perimeter sheet pile wall (Fig. 6) is activated using assumptions of drained equilibrium.

- The flow fill gravity wall is the first element of the elevator access shaft that is installed (activated within the FE model). For this and subsequent excavation and support stages, the organic silt and clay layers are assumed to be sheared under undrained conditions.

- Installation of the perimeter concrete secant pile wall (solid elements) and the upper soldier pile wall (plate elements).

- The jet grout pit excavation: is simulated by activating the timber lagging and removing soil elements to a depth of 10-ft below the ground surface.

- The original design planned to use 37 jet grout columns of different diameters and lengths to form a base plug. At the time when construction was halted, 27 of these columns were installed as shown in Fig. 8. Each grout column is represented using rectangular elements in the FE model with stiffness properties corresponding to soilcrete (Table 3).

Soil deformations arise during jet grouting due to the fact that injected volumes are generally greater than the collected spoils, leading to a net increase in volume within the grouted mass. Generally, the ground movements and pressures are limited by measuring and controlling the proper return of spoils during field operations. Nevertheless, the spoil volumes are normally only a fraction of the injected volumes, thus leading to some (generally unknown) degree of volume expansion within the grouted mass.

The analyses herein described assume a uniform volumetric deformation associated with the theoretical volume occupied by the jet grout columns. The imposed volumetric deformations at the jet grout columns produce deformations throughout the soil mass as a consequence of displacement field compatibility.

The volume expansion of the grout column is implemented using the 'volumetric strain' option for solid elements within the PLAXIS 3D Foundation™ program. This function sets a uniform "target" strain distribution with depth. However, it should be noted that the final equilibrium volumetric strain in the model generally differs from the target value and is dependent on the stiffness of the material elements surrounding the grout column.

Figure 9 shows a plan view of the FE model of support elements for the elevator access shaft.

Figure 10 shows an isometric view of the complete structural model, highlighting the relative positions of the elevator access shaft, the pile foundations and eastern façade of the Old South Church.

MODEL RESULTS

The volumetric strain to be imposed in the grout columns is determined empirically in order to match the observed ground movements. There are no direct data on the volumes of cut soil flowing to the surface. However, Wong and Poh (2000) report a case study of jet grouting in clay where 80-90% of the soil within the grouted zone was displaced. Hence, the analyses assume a volumetric strain of 15% as a first estimate.

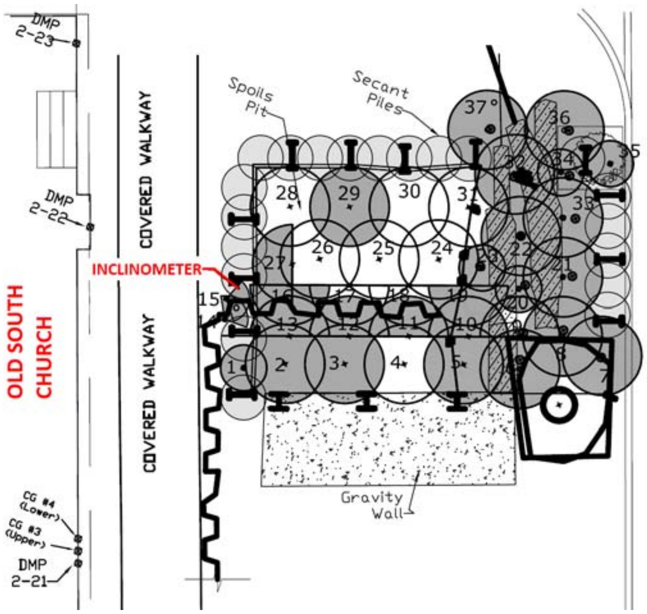


Fig. 8. Partially completed jet grout piles as of Dec. 3, 2008

A single inclinometer (located adjacent to jet grout pile #27, Fig. 8 with toe at El. +64ft in the upper BBC) was used to monitor ground movements during the initial construction phases for the elevator access shaft. Figure 11 compares the predicted and measured ground movements (direction A is orthogonal to the eastern walls of the access shaft and OSC) caused by access shaft construction at the time when damaged was observed (Dec. 3, 2008). The results show a maximum lateral deformation of 1.75 in towards the OSC (at El. +92ft).

The computed results are in reasonable agreement between with the measured ground deformations in the A axis (and in excellent agreement in the B-axis, parallel to the eastern façade), for a target volumetric strain of 15% in the jet grout piles.

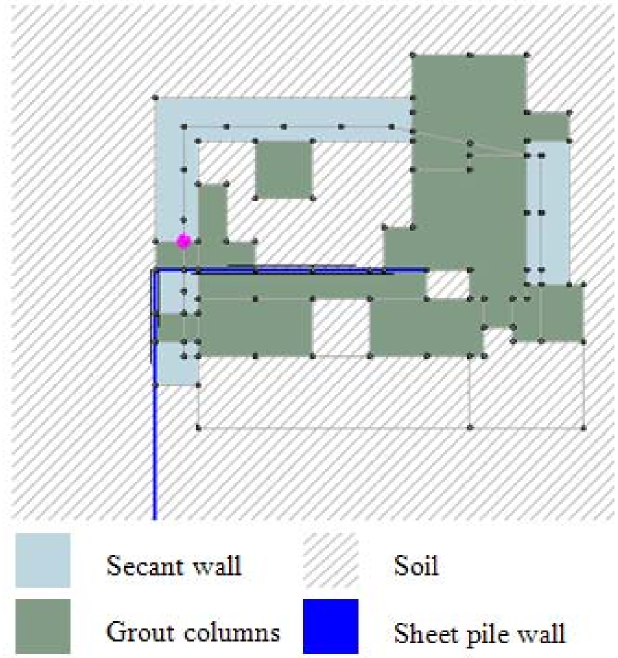


Fig. 9. Plan view of FE representation of jet grout piles installed through Dec. 2008

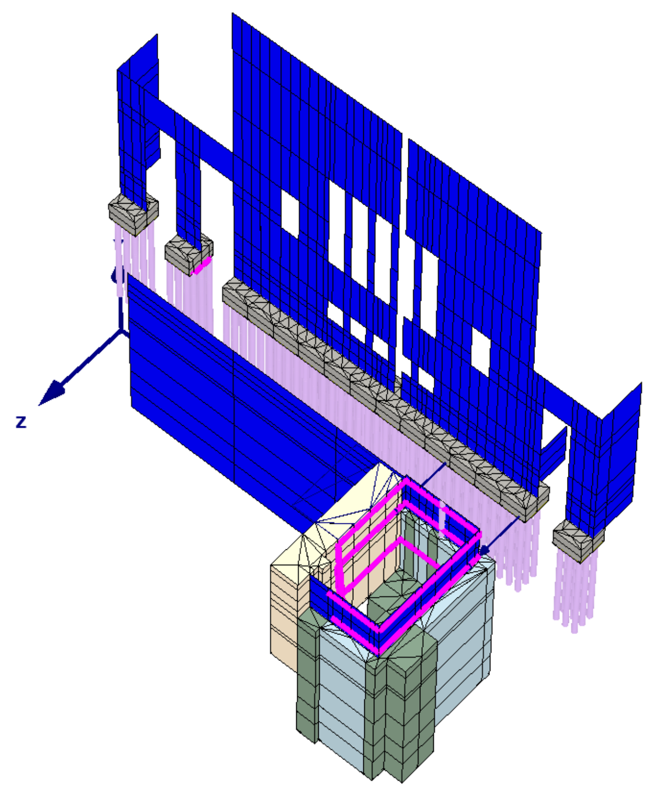


Fig. 10. FE model showing all structural elements for support of the elevator access shaft and Old South Church façade

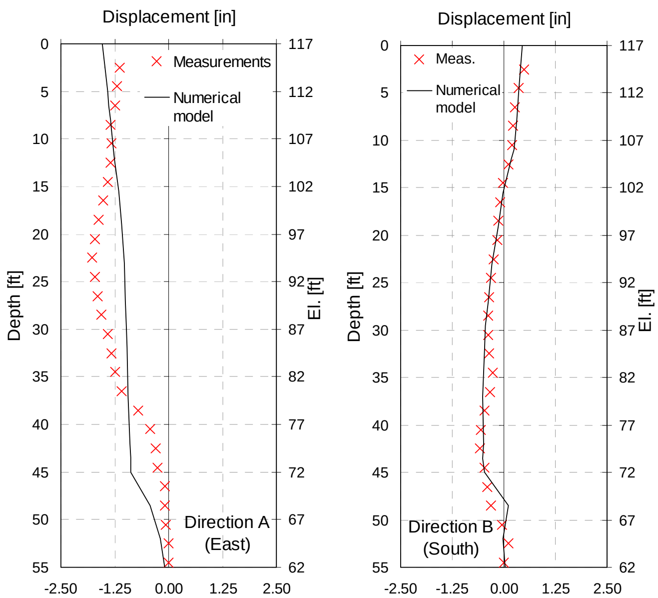


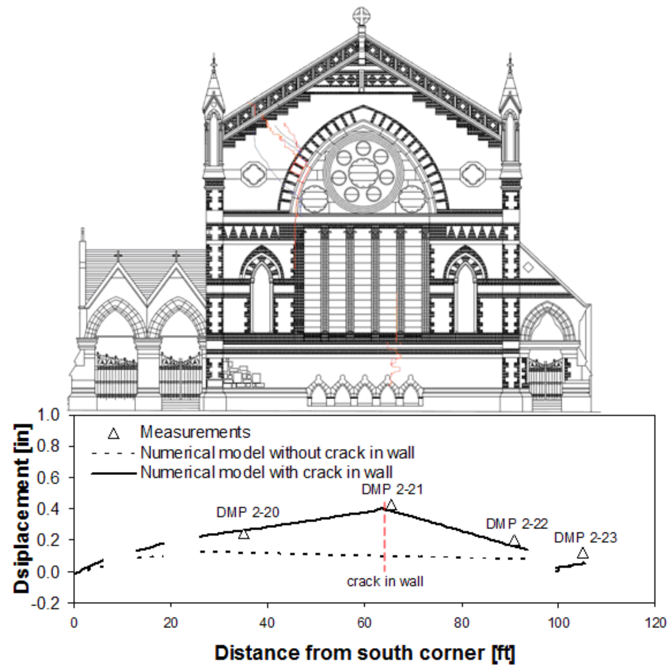
Fig. 11. Comparison of computed and measured lateral ground displacements due to elevator access shaft construction (measurements on 3-Dec-08)

Figure 12 shows further comparisons of the computations with vertical displacements measured at a series of Displacement Measuring Points (DMP) along the Eastern Wall of the OSC in early December 2008. The figure shows results of two finite element models, one case assumes that the Eastern façade of the Old South Church is intact (no cracks) and the second assumes the full height vertical through-crack described above (Figs. 4 and 5). The results for the intact wall show relative uniform vertical deformations along the wall with a maximum heave on the order of 0.1 in. In contrast, the vertical through-crack model predicts much larger deformations (0.4 in) hinging at the assumed crack location. These results are in very good agreement with the magnitude and distribution of DMP measurements (with maximum 0.43 in). Hence, the FE model appears to confirm that volume strains associated with jet grout pile installation are the source of damage to the Old South Church.

CONCLUSIONS

Significant ground and structural movements occurred at the historic Old South Church during construction of the access shaft for the MBTA Green Line Copley Station outbound elevator #2. Lateral movement in the direction perpendicular to the East Wall of the Old South Church was 1.75in towards the structure, whereas maximum heave observed at the wall was 0.43in. The observed movements are associated with soil displacements during installation of the jet grout piles, possibly due to a lack of proper return and/or the development of large injection pressures.

A 3D non-linear finite element model was developed to represent the soil-structure interactions using the Plaxis 3D Foundation™ v.2. The model represents the eastern façade and foundations for the Old South Church, together with an excavation support system and structural supports for the construction of the elevator access shaft. The soil conditions and properties are based on a detailed forensic site investigation and pre-exisitng correlations.



Fig, 12. Vertical displacements along East Wall predicted by numerical model

The computed results, assuming a target volumetric strain of 15% in the jet grout piles, provide good agreement with measured ground deformations, while deformations of the Old South Church are consistently described by introducing a vertical through-crack in the wall. The analyses support the hypothesis that jet grouting was the cause of damage to the historic OSC structure

ACKNOWLEDGMENTS

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