Observational Design Approach:
Foundation Construction beneath the Philadelphia Museum of Art

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ABSTRACT

The Philadelphia Museum of Art is a major landmark in Philadelphia, Pennsylvania. In 2000, the Museum of Art Board of Trustees' Facilities Master Plan outlined a number of improvements, including the "Core Project", that were initiated in 2012 and broke ground in 2017. The scope of work included a variety of complex geotechnical challenges. Many of these challenges could not be fully defined prior to construction, due to access constraints within the existing museum building. As a result, an observational design approach for both temporary and permanent earth support and foundation modifications was developed during design and implemented during construction. This paper discusses various geotechnical issues, construction related challenges, proposed solutions, and lessons learned upon completion of the project. Key takeaways included the importance of having proper coordination and protocols in place to address changes in the field, utilizing an observational design approach when working below this historic structure, and completing below-grade work while not impacting daily operations of the Museum.

INTRODUCTION

Renovations within and below this historic structure posed a unique set of engineering challenges. Available records for the Museum structure were found to be an inaccurate representation of what was constructed. Historic construction details and material types including past construction means and methods may not be fully understood until new construction is underway. Addressing these design and construction challenges requires creative solutions and construction approaches that preserve the integrity of the structure while allowing new construction to proceed in a safe and effective manner.

The Philadelphia Museum of Art (herein referred to as "the Museum") is a historic structure and an architectural landmark in the City of Philadelphia. It houses over 240,000 famous works of art and priceless artifacts, and saw approximately 793,000 visitors in 2017 alone (Philadelphia Museum of Art, 2017). This paper will discuss various geotechnical design and construction related challenges encountered during the renovation of the main building.

Part of renowned architect Frank Gehry's vision for transforming the Museum while respecting its original architecture, the Core Project includes improvements to the circulation at the heart of the Museum and a new gallery space. A key part of the circulation improvements includes a central space known as the Forum; to be located below the Museum's Great Hall and below the existing foundation system. The project also includes installation of numerous new utility systems as part of an upgraded infrastructure system. Geotechnical challenges included developing flexible design criteria for varying bedrock conditions, identifying appropriate construction sequencing, and establishing over-arching project performance criteria to preserve the integrity of the historic Museum structure, prevent damage to the priceless collections, and maintain uninterrupted public access during construction.

Historic site development

The Museum site is geographically located on a topographic high point within the City of Philadelphia. In the early 1800's, the site was developed for the former Fairmount Water Works and Fairmount Reservoir to provide clean water to the City of Philadelphia and remained in operation until 1909. Between 1909 and 1919, the site remained relatively inactive and unoccupied. In 1919, construction began for the Museum within the limits of the former Fairmount Reservoir (Gibson 1988). The location of the construction for the Museum is shown on Figures 1 and 2.

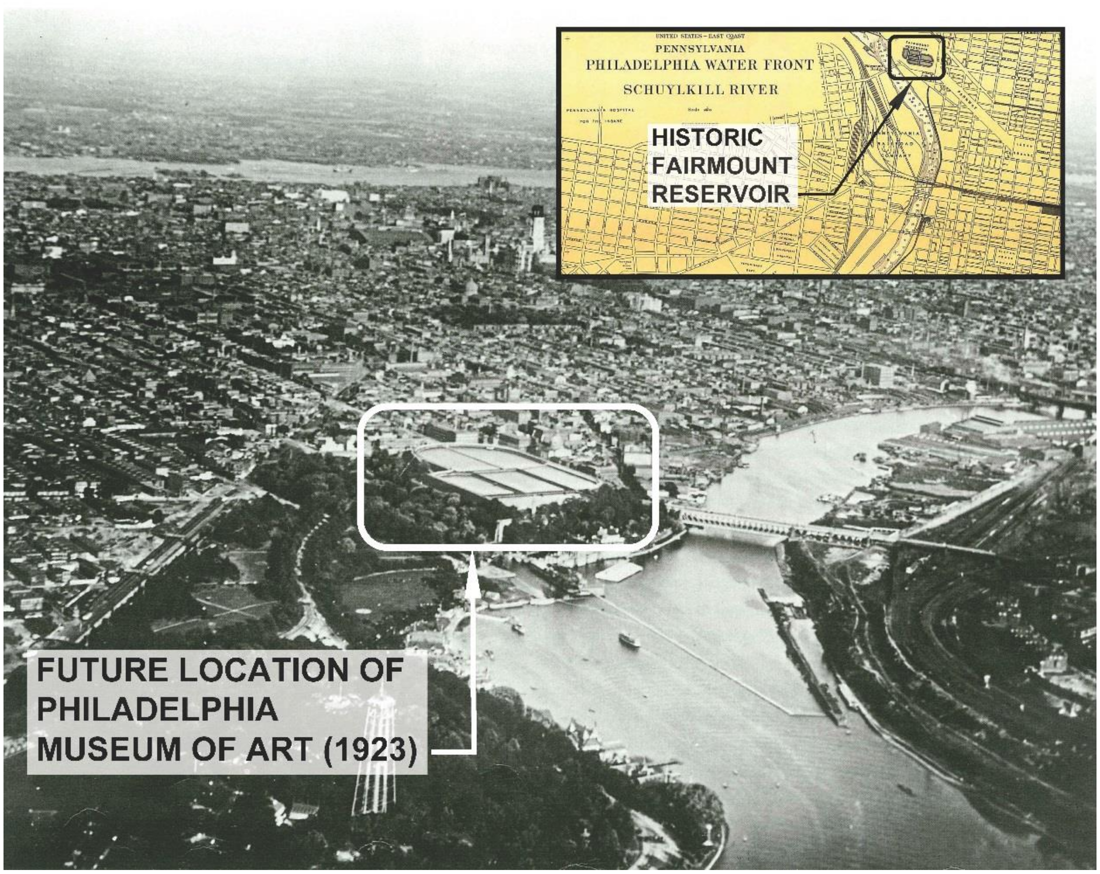


Figure 1. Historic Fairmount Waterworks and Reservoir, Early 1900's (image from NOAA 1923; main) (image from Brownlee 1997; inset upper right).

Planning and design of a museum within the limits of Fairmount Reservoir was first conceived in the late 1800's by numerous architects, engineers, and influential members of the community contributing to the project. The final design concept for the new museum was determined by a committee of collaborators and architects, specifically Clarence Zantzinger, Charles L. Borie Jr., Horace Trumbauer, and Peter A.B. Widener from the Fairmount Park Art Association. The group of Zantzinger and Borie, as well as Trumbauer submitted separate designs. Ultimately Trumbauer and his office, including lead architect Howell Lewis Shay, were awarded the project by the Fairmount Park Commission (Brownlee 1997).

Museum foundation construction began in 1919 (Figure 2) and was completed in 1922. The Museum opened to the public in 1928 (Brownlee 1997). During the 1950's, 1960's, and 1970's several phases of renovations to the Museum were completed including the Great Hall, a new cafeteria, and other refurbishments to modernize the Museum (Philadelphia Museum of Art 2018).

Figure 2. Museum foundation construction (image from Brownlee 1997).

Today, the Museum has two major below-grade levels across the footprint of the Museum and an additional third level below portions of the Museum. The lowest level in the Museum, Level C, is located at approximately El. 15.5 m (50.92 ft), City of Philadelphia Datum [which is 1.8 m (5.81 ft) below the National Geodetic Vertical Datum (NGVD), as referenced herein]; slightly above the grade at Eakins Oval level and the east entrance to the Museum. Level B is located at approximately El. 20.5 m (67.33 ft) and is lower than the Museum's west entrance. Level A, approximately El. 25.0 m (81.85 ft), is at the current grade of the Museum's west entrance.

Foundation records from Borie, Trumbauer, and Zantzinger Architects and the Philadelphia Museum of Art indicate foundation walls and interior columns were supported on unreinforced concrete footing foundations bearing on weathered and/or sound bedrock. Lowest level floor slabs were constructed as concrete slabs-on-grade bearing on weathered bedrock or soil fill (Philadelphia Museum of Art 1920).

Local area bedrock geology

Bedrock geology underlying the Museum site contains a defining geologic contact (Figure 3). The geologic contact generally trends east/west and is comprised of the Waterworks Gneiss to the west and the Wissahickon Formation to the east. Both bedrock formations were typically encountered at various locations throughout the Museum at bearing elevation for the existing foundations between approximately El. 22.0 m (72 ft) to El. 13.7 m (45 ft).

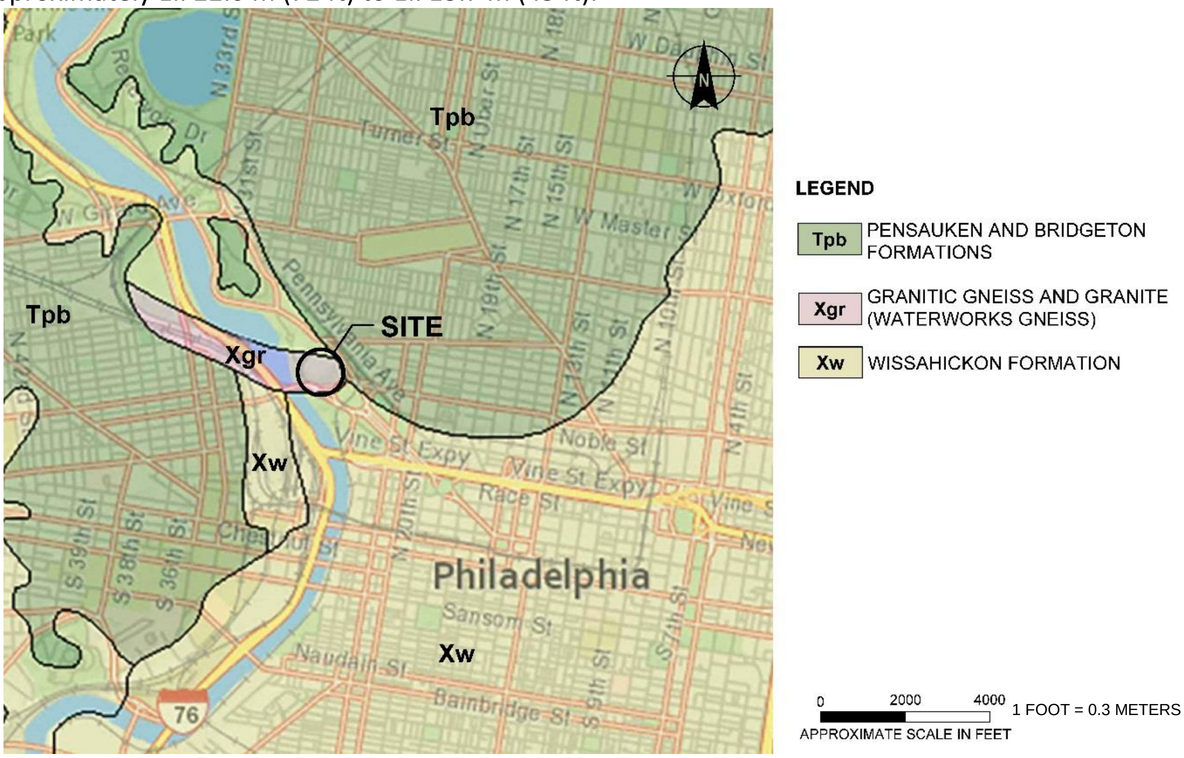


Figure 3. USGS Geologic Map of at Philadelphia Museum of Art Site (image from Pennsylvania Department of Conservation and Natural Resources 2018).

Waterworks Gneiss (USGS Classification Xgr). The Waterworks Gneiss is locally included in the Granitic Gneiss and Granite Formation associated with the overall Inner Piedmont Province of southeastern Pennsylvania. The formation consists of a fine-grained granitic gneiss and granite composed of hornblende granitic gneiss and some quartz, microcline, and biotite. United States Geologic Survey (USGS) documentation indicates bedding in this formation is generally poorly developed with massive bands and bedrock joints that exhibit an irregular pattern, are moderate in abundance, widely to moderately spaced, and steeply to vertically dipping (Geyer and Wilshusen 1982).

Waterworks Gneiss observed at the site was highly resistant to weathering but was often observed as slightly weathered to shallow depths. Site-specific unconfined compressive strength testing data (ASTM D7012 Method C) from sound Gneiss bedrock cores indicated strengths varying from approximately 92.4 MPa to 121.3 MPa (13,400 to 17,600 psi). Refer to Figure 4 for rock core samples.

Wissahickon Formation (USGS Classification Xw). The Wissahickon Formation includes albite-chlorite schist, Marburg schist, and oligoclase-mica schist. The most common bedrock type observed at the site is the albite–chlorite schist and was observed to be highly schistose and contain large muscovite flakes (approximately 1 cm diameter). The presence of numerous, highly micaceous foliations in this bedrock typically resulted in a negative effect to the strength properties of this material. Foliation orientation was variable due to the complex highly-folded nature of the bedrock, but in general the observed dip of the foliations in the bedrock ranged from 10 to 50 degrees (Geyer and Wilshusen 1982).

The Wissahickon Formation at the site was observed to be moderately resistant to weathering, but in select locations was observed to be highly weathered to a moderate depth below the top of geologic bedrock. Site-specific unconfined compressive strength testing data (ASTM D7012 Method C) from sound Schist rock cores indicateed strengths varying from approximately 49.6 MPa to 57.2 MPa (7,200 to 8,300 psi), an approximate 50% reduction in compressive strength compared to the Waterworks Gneiss. Refer to Figure 4 below for rock core samples.

Figure 4. Waterworks Gneiss (left) and Wissahickon Schist (right) bedrock cores (images by Becker).

Subsurface Soil and Bedrock Conditions at the Museum Foundation Level. Near surface subgrade conditions around the site generally consist of fill overlying weathered bedrock or sound bedrock. Weathered bedrock varied in degree of weathering from completely weathered to slightly weathered. Sound bedrock was typically encountered at shallow depth at the south and west portions of the site and sloped downward to the north and east portions of the site. Bedrock jointing was observed to dip at low angles and joint spacing was close to wide with slight oxidation staining observed. A limited number of vertical joints were observed in bedrock cores. Table 1 provides a summary of weathered and sound bedrock properties.

Table 1. Weathered and Sound Bedrock Properties.

	Thickness Encountered (m)	N-Values (blows/0.3 m)	Rock Core Recovery (%)	Rock Quality Designation (%)
Weathered Bedrock	0 – 7.6	27 to >100	0 - 75	0 - 20
Sound Bedrock	-	-	20 - 100	20 - 100 [(a)]

[a] Rock Quality Designation (RQD) values ranged from 20 to 100% and was qualified as "sound" only if a minimum of two consecutive runs were greater than 20%.

Core project

In 2000, the Museum's Board of Trustees commissioned architect Gehry Partners, LLP to develop a Facilities Master Plan detailing concepts for renovation and expansion of the Museum. The Core Project was created as part of the master plan and was initiated in 2012. One of the goals for the project was to open the "core" of the existing Museum and create a new central space, referred to as the Forum, to allow for vertical movement and facilitate improved visitor circulation. Construction of the Forum space included phased renovations and improvements requiring below grade expansion of the existing structure and numerous new underslab utilities and infrastructure within the soil and bedrock below the Museum.

As part of the design team, Haley & Aldrich provided geotechnical design for a variety of complex below-grade foundation conditions. These complex challenges included designing temporary and permanent earth/rock support and strengthening existing foundations for increased loads.

Historic foundation records from the original Museum construction and subsequent renovations were utilized in conjunction with more recent subsurface exploration programs for planning and design of the below-grade Core Project work (Philadelphia Museum of Art 1920). Available foundation information indicated interior foundation walls surrounding the Forum space were supported by an unreinforced concrete strip footing bearing on bedrock that stepped downward from between approximately El. 19.8 m (65 ft) and El. 12.5 m (41 ft).

As the Core Project construction work began, it became apparent the original Museum plans and records deviated considerably from the as-built conditions encountered; unexpected and undocumented existing foundation locations, dimensions, and bearing elevations were discovered across the Museum. These unexpected conditions required quick adaptation and engineering ingenuity to protect the Museum structure, its contents, and continued uninterputed use by patrons and staff, and to maintain the construction schedule.

The following sections of this paper will discuss some of the specific challenges confronted, proposed solutions, and a review of the foundation support system performance in the proposed Forum space. For reference, a plan showing the approximate location of the proposed Forum on the Museum footprint is shown in Figure 5.

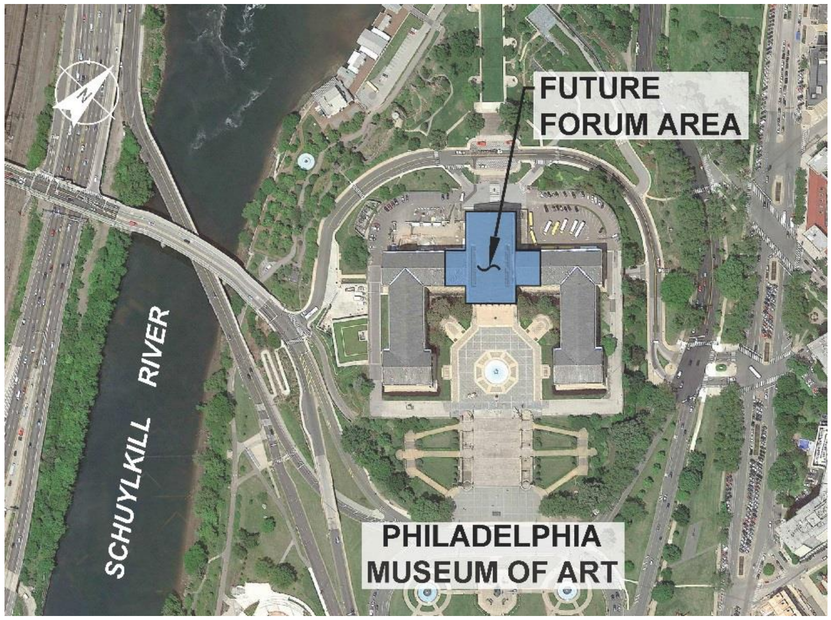


Figure 5. Location of Future Forum within Museum Building (image by authors; aerial imagery from Google Earth Pro, May 15, 2018)

FORUM WALL STRIP FOOTING challenges

Historic records indicate the existing foundation grades in the proposed Forum area were typically at B level to the west and at the C level to the east. The bearing elevation for the north and south foundation walls (Figure 6) stepped down west to east from El. 16.0 m (52.5 ft) to El. 13.4 m (44 ft). Existing loads on these walls and strip footings are approximately 0.178 kN per linear meter (12.2 kips per linear foot), as provided by the structural engineer (Magnusson Klemencic Associates), and in the future would need to support an increase load of approximately 0.194 kN per linear meter (13.6 kips per linear foot).

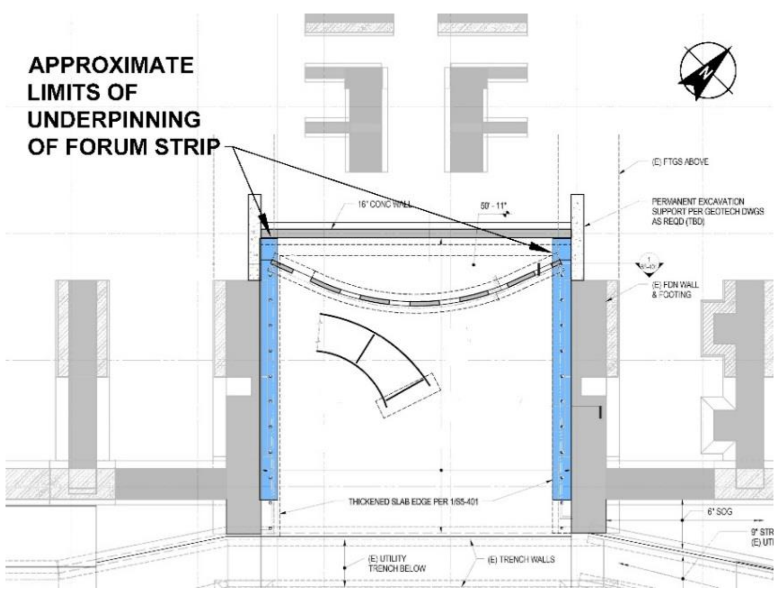


Figure 6. Section 4 Structural Plan (image adapted by authors; original courtesy of Gehry Partners, LLP and Magnusson Klemencic Associates)

The excavation for the new Forum space required removal of a portion of the existing strip footing and vertical excavation within the underlying bedrock to meet the dimensional requirements of the design (Figure 7). The excavation approach included underpinning a portion of the north and south walls of the proposed Forum and relocation/redesign of proposed utilities to reduce the magnitude of bedrock excavation and associated building underpinning. Construction protocols to control potential building movement, vibrations, noise and dust were critical to limit impacts to the Museum and its operations.

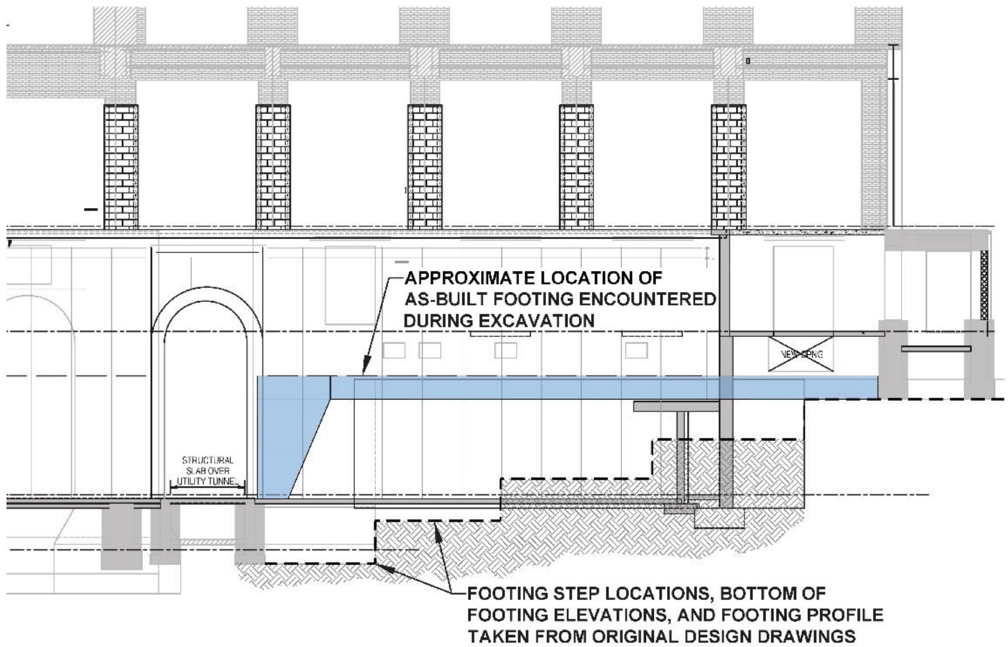


Figure 7. Cross-Section Through Wall Showing Record and As-Built Foundation Conditions (image adapted by authors; original courtesy of Magnusson Klemencic Associates)

Prior to the start of construction, geotechnical design criteria were established based on bedrock properties such as structural orientation to address bedrock failure modes in both the permanent and temporary conditions. The desired outcome was to have a design that (1) could be quickly adjusted in the field based on engineering observations to control the bedrock mass, and (2) could be applied to differing site conditions encountered below the Museum as the Core Project progressed through construction.

Permanent Support of Excavation System Design. Long-term stability of the bedrock excavations required that no active or passive pressures be exerted from the bedrock onto the new, interior foundation walls. Reinforcements were designed to prevent failure from sliding along horizontal bedrock surfaces, limit over-stressing of the bedrock (including structural footing loads) with a minimum safety factor of 2, and limit the potential for movement of the structure. Based on engineering observations where bedrock was to remain below the existing foundations, permanent reinforcement consisted of a system of steel rock dowels and a permanent reinforced shotcrete wall (Figure 8).

Temporary Support of Excavation System Design. In addition to adequate support of the structure, short-term conditions (e.g. during construction) required a safe working environment. This included restricting horizontal and vertical limits of bedrock cuts to no more than 1.5 m (5 ft) vertically and 7.6 m (25 ft) horizontally in weathered rock, locally applying flashcrete or poured-in-place concrete to stabilize weathered or highly fractured bedrock surfaces, and optical survey monitoring to evaluate performance of the existing structure during construction.

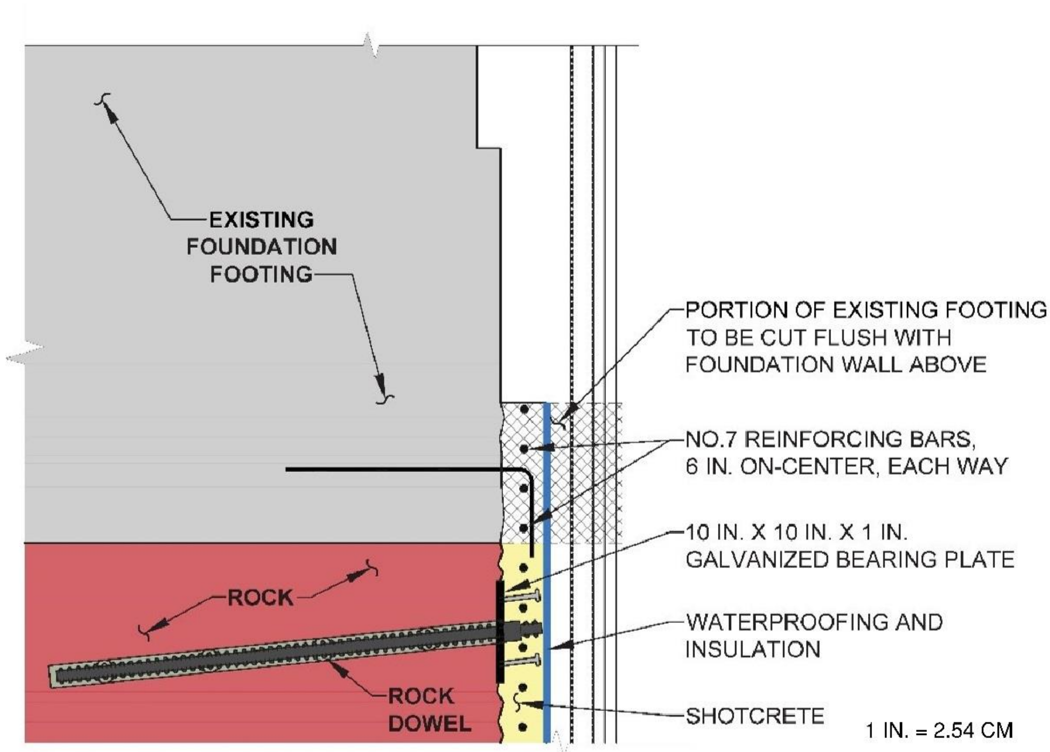


Figure 8. Rock Dowel and Shotcrete Underpinning Solution (image by authors)

Temporary and Permanent Support of Excavation During Construction. Following the start of excavation in the Forum, located directly beneath and supporting the Museum's Great Hall, the foundation bearing conditions were observed to be different than the existing design drawings. Foundations were encountered at approximately El. 18.4 m (60.5 ft), 2.4 m (8 ft) higher than anticipated below the north and south foundation walls. Finished grades in the Forum required excavations to about 3.6 m (12 ft) below observed foundation level, to approximately El. 14.8 m to El. 15.1 m (48.5 to 49.5 ft) with some locally deeper utility excavations beyond the zone of influence for the footings. This depth of excavation below the existing footings required modification of the original design to account for the different foundation geometry, bearing level and variable bedrock conditions. Start of construction shown in Figure 9.

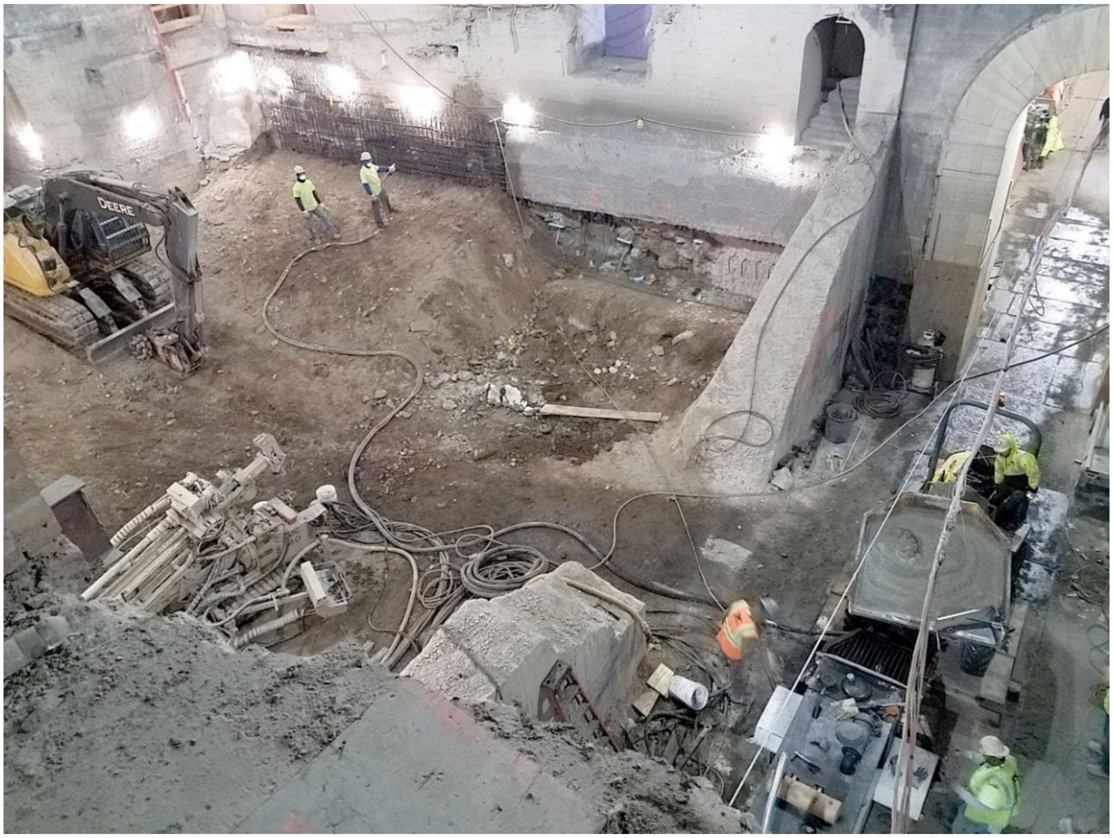
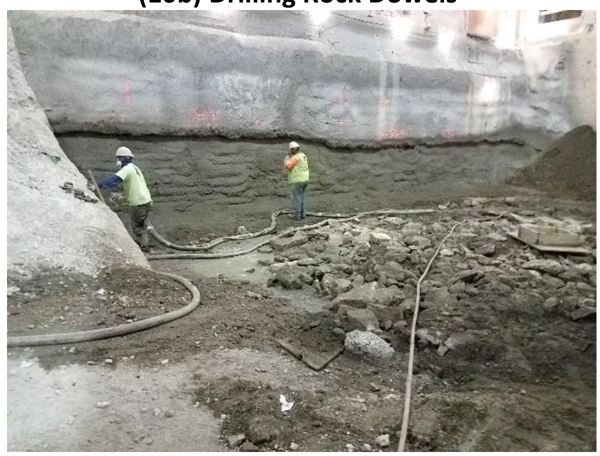


Figure 9. View of Support of Excavation Solution during Construction (image by Becker)

The as-designed support of the excavation system was modified during construction in accordance with geotechnical design requirements. Key modifications included adjusting the sequencing of the excavation to maintain safety and stability of the rock face and adjusting the rock dowel spacing based on the bedrock conditions encountered. Figure 10 shows the modified rock dowel and reinforced shotcrete wall underpinning solution, which consisted of:

- Assessing the quality of bedrock exposed during vertical cuts by a licensed professional geotechnical engineer or engineering geologist to evaluate bedrock conditions exposed versus the design criteria established.
- Excavating in approximately 1.2 to 1.5-m (4 to 5-ft) maximum depth "lifts";
- Applying a flashcoat shotcrete protection layer as required, which was dependent on the quality of exposed face of bedrock after excavation of each "lift" and before installation of rock dowels.
- Installing approximately 10.2-cm (4-in) diameter rock support dowels. Permanent rock support dowels consisted of 2.5-cm (1-in.) diameter and 4.4-cm (1-3/4 in.) diameter galvanized, high strength, upset threaded or deformed rebar (ASTM A-722 Grade 1034 MPA series), galvanized mechanical couplers, a galvanized bearing plate, and galvanized washer and nut.
- Torqueing to 150 ft-lbs to lock-off each rock dowel for passive resistance.
- Installing a reinforced shotcrete wall, minimum 0.23-m (9-in.) thickness and consisting of minimum 27.6 MPa (4000 psi) concrete, and a 15-cm (6-in.) on center vertical and horizontal no. 7 bar reinforcement matrix, fully encapsulating the rock dowel system.

(10a) Bedrock Lift Excavation **(10b) Drilling Rock Dowels**



(10c) Installing Reinforcement Grid **(10d) Shotcrete Wall**

Figure 10. Progression of Work (images “a” through “d” by Becker)

This bedrock support procedure was incorporated for rock dowels and installed at approximately 1.8 m (6 ft) on center spacing laterally, and 0.9 m (3 ft) on center vertically.

Prior to excavation, the original design included a total of four vertical rows with between seven and nine rock dowels per row. However, as excavations progressed, observations of bedrock competency improved considerably with depth. At approximately El. 17.1 m (56 ft), the quality of the bedrock transitioned to more competent, massive gneiss bedrock. As a result, the design was re-evaluated, and the frequency of rock dowels was reduced to one final row of rock dowels centered at approximately El. 16.0 m (52.5 ft) rather than the two vertical rows originally anticipated.

Figure 11 indicates the as-built layout of dowels, with the shaded zone indicating the installed limits of the shotcrete wall.

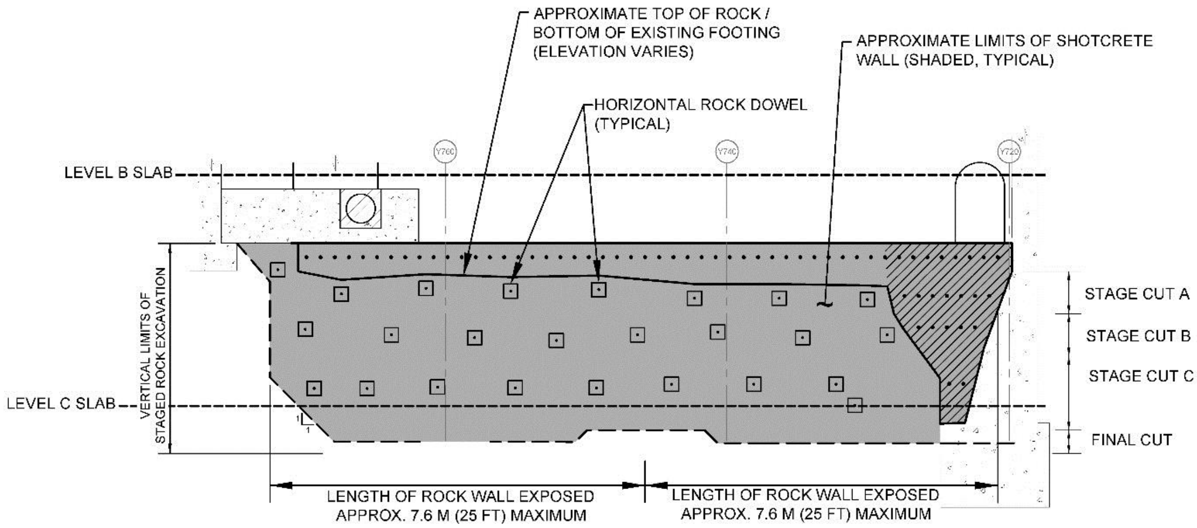


Figure 11. Final As-Built Rock Dowel and Shotcrete Underpinning Solution (image by authors)

Measured Performance. Through the use of the temporary and permanent bedrock support system, vertical excavations within bedrock ranging in quality from weathered to massive resulted in little to no vertical movements and little to no surficial disturbance to the Museum structure. Open bedrock cuts up to 2.4 m (8 ft) vertically and in-plane with the edge of existing footings resulted in no visual movement or propagation of cracks within the Museum structure when allowed to remain open for periods of up to two weeks.

Baseline survey points were established along the north and south walls and interior column locations prior to the start of bedrock excavation. Measured data indicated less than 3.2 mm (1/8 in.) of total movement. Visual observations conducted throughout the Museum after completion of the work have shown no signs of foundation movement.

Based on the success of the observational design approach, underpinning system performance, and the unimpeded operation of the Museum during the work, this method was used throughout the Museum for subsequent excavations and bedrock support of foundations as required.

Summary

Construction of the Forum space required excavation below the existing Museum structure while it remained operational. This work required close observations of bedrock conditions and the performance of bedrock cuts and underpinned foundations during construction. The below-grade work was conducted to successfully control construction-related noise, vibrations and dust, and in turn allowed the unimpeded operation of the Museum. The observed bedrock and existing foundation conditions required the use of an observational design approach using bedrock mapping and observations of bedrock quality as work progressed. This observational method was critical to the success of the project, controlled risk to the owner, and allowed the temporary and permanent bedrock support system to be modified quickly to facilitate construction.

Underpinning techniques for foundations bearing on bedrock do not always require lowering the bearing elevation. The underpinning method utilized at the Museum incorporated a rock dowel and shotcrete wall system to provide both temporary excavation support and permanent foundation support. This was a creative approach that was adaptable across the Museum and allowed for a quick and effective solution when differing foundation bearing conditions were discovered below the Museum.

Close coordination and a clear protocol system was required between the design and construction team when working beneath this historic structure. The ability to adapt and adjust was critical to allowing work to proceed in an economic, timely, and safe manner. Collaboration between the design and construction teams at the Museum allowed for the Level C Forum work to be undertaken successfully.

Finally, when working below existing structures, expect the unexpected and be ready to adapt and adjust designs to unforeseen conditions.

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- Architect – Gehry Partners, LLP
- Structural Engineer – Magnusson Klemencic Associates
- General Contractor – L.F. Driscoll
- Excavation Contractor – JPC Group, Inc.
- Project Surveyor – Copeland Surveying, Inc.

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