Shotcrete Placement for Initial Support: CLIMATE PLEDGE ARENA TUNNEL PROJECT

By Mark Pinske, Elizabeth Lenker, and Paul Mockus

The Washington State Coliseum was an arena built for the 1962 Seattle World's Fair. More than half a century later, in 2019, a $1B construction program began to redevelop and expand the arena. The redeveloped building, with a new name — Climate Pledge Arena — retains the historical roof, but below the surface is another story. Underground, the arena continues 30 ft (9 m) below the original floor to expand the arena's capacity. As part of the project, a tunnel was constructed under Thomas Street and the Bressi Garage, a 100-year-old unreinforced masonry landmarked building, so trucks could directly access the arena without disrupting traffic in the surrounding area (Fig. 1). This tunnel is approximately 180 ft (55 m) long, with a finished width of 25 ft (7.6 m) and a vaulted roof 20 ft (6 m) high. The project design was led by the architectural firm Populous. Construction was awarded to Mortenson Construction, who selected Delve Underground and J.W. Fowler in a design-build subcontract for the tunnel construction.

The design phase was performed under an accelerated schedule to meet the arena's fixed opening date. The tunnel excavation was completed within 2 months, and the tunnel and portal construction were completed in 14 months. Given the limited cover and proximity to the Bressi Garage, a pipe arch canopy was installed as a pre-support system to enhance ground stability and safety during excavation. The canopy consisted of 24 in. (600 mm) diameter pipe canopy tubes, which were set around the tunnel perimeter, as shown in Fig. 2. The tunnel was constructed using the sequential excavation method (SEM), with each advance stabilized with 14 in. (350 mm) deep steel sets and steel fiber-reinforced shotcrete (SFRS) lagging. Note that the south tunnel headwall is within 6 ft (1.8 m) of the Bressi Garage, and the tunnel passes within 3 ft (0.9 m) of the building's foundations. The ground between the pipe canopy and the existing footings was improved using permeation grouting prior to the excavation.

Soil conditions along the tunnel alignment consisted of less than 15 ft (4.6 m) of fill over very dense, glacially overridden granular soils, with interbedded layers of over-consolidated fine-grained soils. Static groundwater was approximately 20 ft below the ground's surface. A system of eductor wells and wellpoints was installed to lower the groundwater below the tunnel, allowing successful shotcrete placement without the

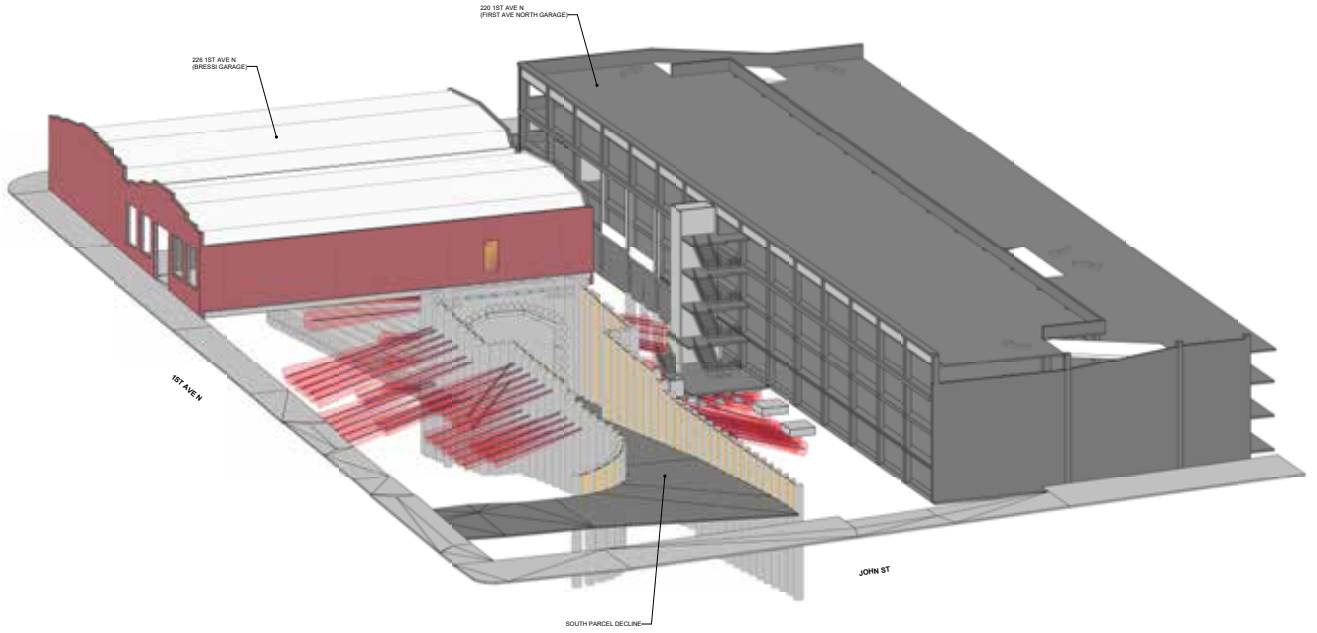

Fig. 1: Partial site plan showing decline, tunnel, and proximity to adjacent structures

Fig. 2: Pipe arch canopy being installed prior to tunnel excavation; note the proximity of the future tunnel and existing Bressi Garage

presence of groundwater.

The initial structural support for the tunnel consisted of steel sets every 4 ft (1.2 m) on center, with steel-fiber reinforced concrete utilized as lagging by shotcrete placement. The steel sets were chosen as the temporary tunnel support because of how quickly they could be assembled and erected. This also minimized the amount of field corrections to fit each steel set. This temporary tunnel lining was designed for full overburden pressures, as it was assumed that soil arching could not be considered because of the shallow cover over the tunnel. This assumption resulted in larger steel sets, and thus a thicker shotcreted layer to bring the concrete lagging flush with the steel sets.

Concrete was shotcreted robotically and by hand. The robotically applied concrete was a wet-mix concrete, delivered to the site by concrete trucks that backed into the tunnel and end-dumped into the hopper for the shotcrete robot. The easy access for concrete trucks to reach the shotcrete robot meant that no pump truck was needed, minimizing the congestion in the tunnel during shotcreting operations with the robot. The shotcrete robot used was a Normet Spraymec 8100 VC (Fig. 3), which was able to reach between the steel sets and apply the concrete. The wet-mix concrete was applied once a day and was in tandem with the excavation sequence of one 4 ft round of excavation per day. The concrete was placed in multiple lifts to reach the design thickness. One placement concern was that the shotcreted concrete might not adhere properly to the steel pipe canopy tubes that made up the roof of the tunnel as the tunnel was being excavated. Wire mesh was on site and ready to be placed on the canopy tubes to help the concrete adhere to them. However, this ultimately was not needed as the shotcreted concrete adhered to the canopy tubes without issue, and no fallout was observed during or after shotcrete placement.

During excavation of the tunnel, dry-mix concrete was hand nozzled and used as flashcrete. Flashcrete was applied as a 2 to 3 in. (50 to 75 mm) layer of unreinforced or fiber-reinforced shotcrete to the face and sidewalls of the excavation as a way to retain soil moisture and limit premature ground relaxation in advance of the temporary shotcreted steel set support installation. Face maps were completed at the end of each shift or round of excavation to detail the ground conditions at that time. The face maps included details of the type and location of soils encountered, groundwater seepage, and any other notes relevant to the excavation. An example of the face map used during construction is shown in Fig. 4.

Shotcrete placement was completed by ACI-certified shotcreters who were certified for both dry-and wet-mix vertical and overhead positions. Preconstruction trials were used to prequalify the shotcreters for the project and allowed the design team to evaluate overall quality, such as workmanship, uniformity, and strength of the concrete mixture. Test panels were shot in both vertical and overhead positions for both dry- and wet-mixes. Early preconstruction test panels did not meet the performance requirements, therefore alternative mixtures and trials were performed to meet the design requirements.

During construction, shotcrete placement testing included shooting daily test panels. These were a combination of dry-mix shotcreted test panels shot by hand and wet-mix shotcreted test panels shot by the robot. A penetrometer was used to test the 1-hour early strength. These panels were then cored and tested for compressive strength at 1-day, 7-day, and 28-day intervals. The purpose of early concrete strength testing was to inform the contractor and design team that the shotcreted concrete had gained enough strength to provide sufficient ground stability under the excavated face prior to the next advance. Flexural concrete panel testing per ASTM C1550 was originally specified to calculate the residual flexural strength of the steel-fiber reinforced concrete. Due to challenges with obtaining reliable test data and additional correlation testing required to verify the residual flexural strength values using round panels, the ASTM 1609 test was ultimately used to directly evaluate the flexural performance of fiber-reinforced concrete.

Monitoring of the Bressi Garage was performed continuously with approximately 60 optical prisms monitored by an automated motorized total station (AMTS), supplemented with manual survey monitoring of convergence points inside the tunnel. Delve Underground's structural engineers performed pre- and mid-construction walkthroughs to assess the structural condition of the nearly 100-year-old building, including its original wood beams and concrete foundation. An independent third-party building condition

Fig. 3: Shotcrete robot (Normet Spraymec 8100 VC) applying flashcrete to the advanced top heading

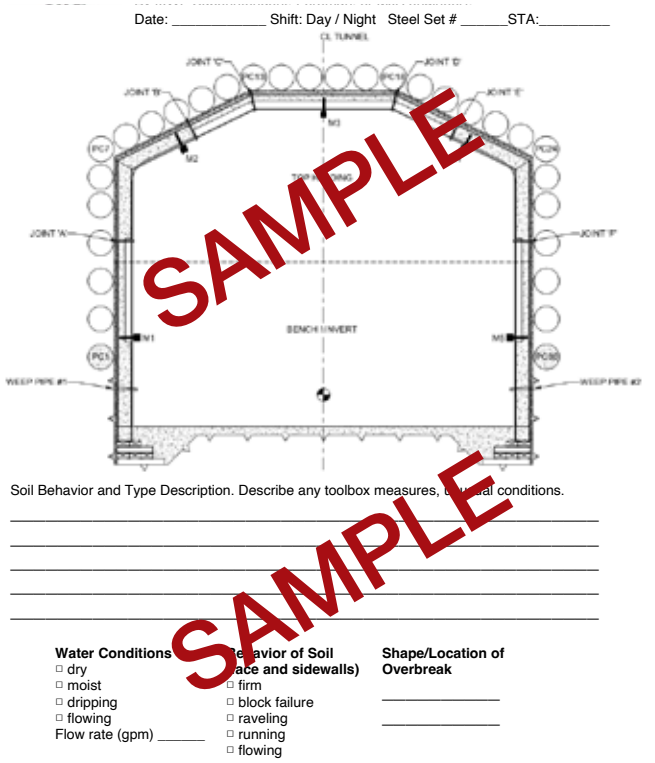

Fig. 4: Example of a face map data sheet

survey was also performed. Twenty-three crack gauges were installed on existing cracks in the concrete and masonry walls and were monitored weekly during tunnel excavation. Manual surveys were performed within the tunnel to measure convergence on survey points installed on the steel sets and within the concrete lagging. Up to about 0.3 in. (8 mm) of vertical displacement in the tunnel crown was observed, as shown in Fig. 5, with minimal horizontal inward movements measured on the vertical sidewalls. Similar magnitudes of movement were observed in the steel sets as observed on survey points installed on the concrete lagging between the steel sets. These movements were generally below the 0.3 in. trigger level criteria and stabilized within about 2 weeks or less after the steel set was installed. Even with such little cover between the top of the tunnel and the bottom of the historic building foundations, total recorded settlement of the building monitoring points was less than 0.75 in. (29 mm), and no significant widening or cracks were observed.

In conclusion, shotcrete placement played a crucial role in the successful completion of the Climate Pledge Arena access tunnel. It was utilized as lagging, foundation support, and a means of initial ground stabilization, while additionally providing the necessary structural support and allowing for safe and efficient excavation. The project used both wet-mix and dry-mix concrete and included shotcrete placement both robotically and by hand, demonstrating its versatility. The success of the tunnel construction validates shotcrete placement as an indispensable tool in modern underground construction, particularly in projects with sensitive surroundings.

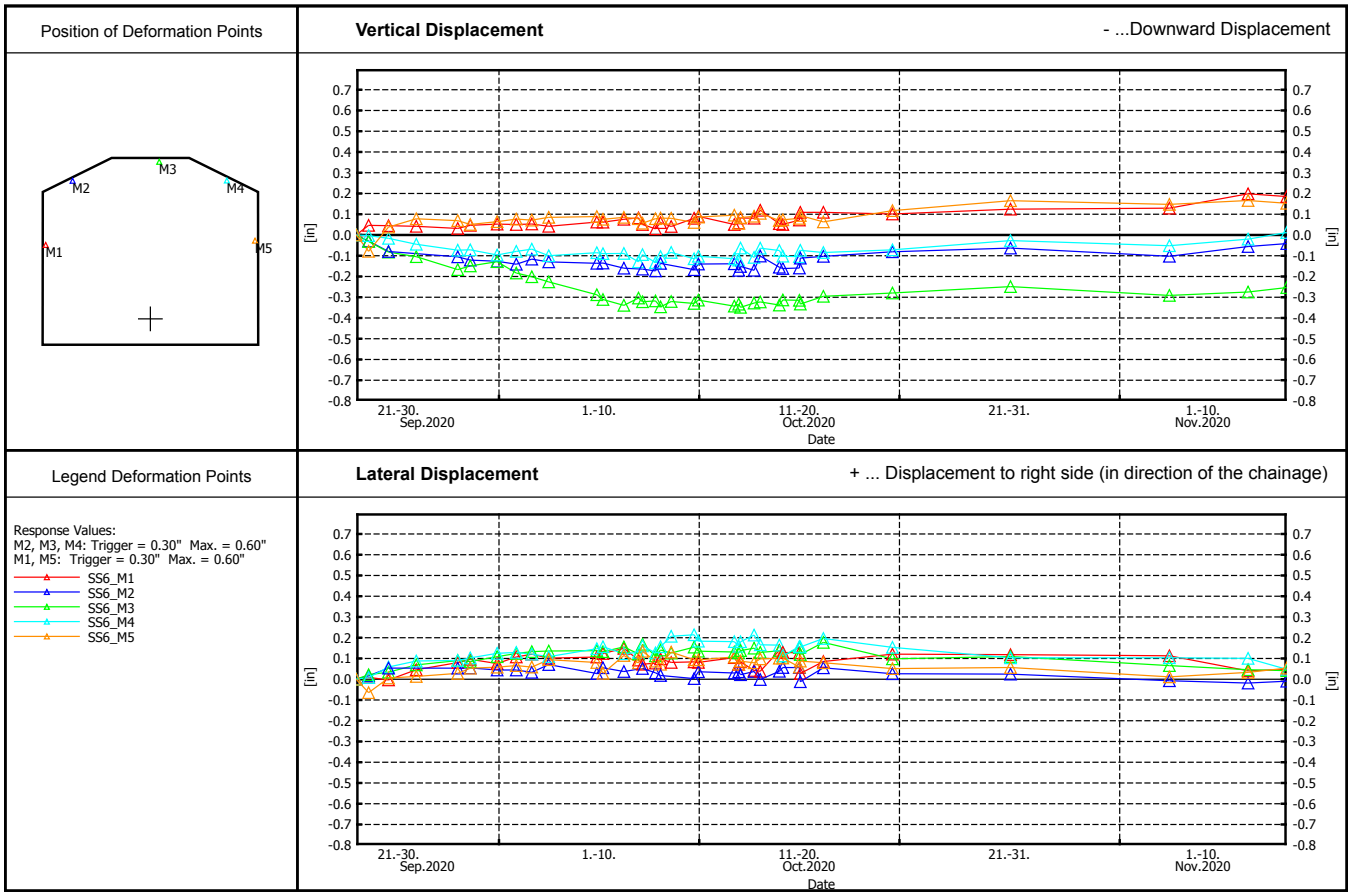

Fig. 5: Displacement observed during tunnel excavation

Elizabeth Lenker *is a Senior Project Engineer at Delve Underground. She has over 13 years of experience with a focus in geotechnical engineering, tunnel lining design, SEM tunneling, and construction management. Elizabeth earned her B.S. in Civil Engineering from Seattle University, and she is a licensed Professional Engineer in Washington State.*

Mark Pinske *is an Associate Engineer at Delve Underground. He received his B.S. and M.S. in Civil Engineering from the University of California, Davis. Mark has over 14 years of geotechnical engineering experience on a variety of underground construction projects including tunnels, shafts, and excavation support. He is a licensed Professional Engineer in Washington State, California, and Idaho.*

Paul Mockus *is a Lead Associate Engineer at Delve Underground. He has over 14 years of structural design experience for underground structures and works primarily on projects associated with rail and highway transit and water/wastewater storage/ conveyance. Paul has a B.S. in Civil Engineering and a M.S. in structural engineering, both from Purdue University. He is a licensed Professional Engineer in Washington State, California, and the District of Columbia.*