Shotcrete constructed cut and cover tunnel portal

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ABSTRACT: The reconstruction of the Weehawken Tunnel for the New Jersey Transit Hudson-Bergen Light Rail System is about to be completed. The more than \$145M contract encompasses the enlargement of running tunnels, the construction of an access shaft for the new underground station and new portals. A series of innovative construction techniques have been applied to meet the challenging project requirements and aggressive schedule. The contract design called for a permanent portal structure with a trumpet-shaped roof geometry, while the sidewalls funnel out towards the tunnel entrance. The structure started in the mined section and lead to the portal. The curved sidewalls for the portal structure were converted to vertical concrete walls complying with the contract's geometric requirements. For the roof portion, reinforced, high-quality shotcrete was used to form the complex contour. The membrane tunnel waterproofing was extended to the portal face wall. Construction of the new portal was timely completed while meeting the quality requirements stipulated in the Contract Documents.

1 INTRODUCTION

A Value Engineering Change Proposal (VECP) was developed and accepted which proposed to substitute the planned cast-in-place concrete lining at the east portal mined section, transition section to the cutand-cover section and the east portal cut-and-cover with a shotcrete lining. The proposed shotcrete lining provides an equal product to the contract's cast-inplace concrete. While providing an equal product, the concrete spray-on process provides for greater flexibility in its application mainly due to the geometrical configuration. In contrast to the contract design, the spray-on process allows for a 'smooth' geometric arrangement of the bifurcation between the tunnel and the trumpet-shaped east portal.

The shotcrete final lining design entailed structural computations, design drawings that depict the lining geometry, design details and application procedures along with a method statements.

Frontier Kemper Constructors, Inc., J.F. Shea, Beton und Monierbau Joint Venture (FKSB) was the contractor with Gall Zeidler Consultants, LLC (GZ) as their design consultants. The Owner was New Jersey Transit and their prime contractor was Washington Group International. The owner's project designer was Parsons Brinckeroff, New York.

2 THE CONCEPT

The contract drawings showed a rounded tunnel portal with a complex geometrical form resulting in three, dimensionally curved sidewalls and roof as well as



Figure 1. Portal structure shotcrete application.



Figure 2. Waterproofing membrane in mined section.

a trumpet-shaped enlargement for the portal area. For the mined section, the Contract Design specified straight, cast-in-place concrete sidewalls monolithic with the roof arch.

To optimize flexibility and facilitate tunnel access. the construction method was redesigned in a value engineering effort. The crews were familiar with the A-frame forms used for the sidewalls in the mined station sections. Hence, the curved sidewalls for the portal structure were converted to straight walls complying with the contract's geometrical dynamic envelope requirements. For the roof portion, reinforced, highquality shotcrete was used to form the complex contour optimized to the existing rock profile. The shotcrete reinforcement comprised lattice girders, steel wire mesh for the mined section and rebar reinforcement for the open cut section. The membrane tunnel waterproofing was extended to the portal face wall to protect the permanent portal structure against water infiltration. The portal canopy was backfilled with structural backfill.

3 VECP PROCESS

The Value Engineering Change Proposal (VECP) process requires the Contractor to delineate and provide the following specific aspects of their VECP.

- Description of the existing Contract requirements which are involved in the proposed change.
- Description of Proposed Changes.
- Difference between existing requirements and the proposed changes, together with advantages and disadvantages of each.
- Itemization of the Contract requirements which must be changed if the VECP is approved.
- Justification for changes in function or characteristics of each item and effect of the performance of the end item, as well as on the meeting of requirements contained in the Mandatory Documents.

- Date or time by which a Change Order adopting the VECP must be issued in order to obtain the maximum cost reduction including any effects on the Project Schedule.
- Cost estimate for existing Contract requirements compared to Contractor's cost estimate of the proposed changes.
- Cost of development and implementation by Contractor.

4 SHOTCRETE LINING PERFORMANCE REQUIREMENTS

The shotcrete permanent lining generally has to meet the same criteria in terms of durability, reflectivity and smoothness as specified in the Contract Design for the cast-in-place concrete lining.

4.1 Reflectivity, maintenance, and ventilation

The shape and evenness of the shotcrete liner in both radial and longitudinal direction was achieved using lattice girders and indicator pins (tell tales). For further control, straight edges were utilized when completing the finishing shotcrete layer. The surface quality was typical of state-of-the-art spray-on shotcrete surfaces and current shotcrete lining standard practices.

The shotcrete surface applied in the arch, i.e. generally about 11 feet above the top of rail had little impact on the reflectivity and illumination characteristics of the transition sections. Its surface finish will allow for regular maintenance.

Although the surface finish is rougher than a castin-place concrete finish (mainly due to the aggregate size) a negative impact on ventilation performance of the tunnel structure was not anticipated, due to the size relationship between the tunnel openings and the very small increase in the surface roughness. The surface and shape qualities of the shotcrete final lining therefore met project requirements.

4.2 Fire resistance

The Institute for Concrete Technology in Innsbruck, Austria, had recently tested concrete panels with different concrete mix designs and under different conditions with regard to fire temperature, humidity of concrete and loading conditions. Those tests demonstrated that there is no significant difference between sprayed and poured concrete of the same strength class. Spalling of concrete may reach deep into the concrete cross section under severe test conditions. To prevent spalling polypropylene (PP) micro fibers were added to the mix. This observation corresponded with the findings of other international tests that have been reported in the literature reviewed in preparation for this project. Polypropylenes belonging to the polyolefin group, which are plastics that are extremely resistant to chemical and mechanical influences. As PP only consist of carbon and hydrogen atoms, no toxic substances are created when they are burned completely. Typical PP fibers melt at 150°C to 160°C. As a result, the permeability of the concrete with PP fibers is increased in the event of a fire. The additional pore volume created when the PP fibers melt enable moisture vapor produced to be better distributed and escape from the surface. This reduces the risk of explosive-like spalling substantially because the concrete's permeability is increased in the event of a fire.¹

The shotcrete lining design therefore incorporated the addition of PP fibers (2.0 lbs/yd^3) in the last (inner) four-inch thick layer.

4.3 Shotcrete durability in portal zone

A cement based and epoxy enhanced sealing coat, was finally applied in the portal vault section which is exposed to annual temperature fluctuations.

5 STRUCTURAL DESIGN

The basic premise for the structural design was to provide a structurally equal product to that depicted in the Contract. A set of loading conditions was developed from the computations generated by Parsons Brinckerhoff that formed the basis for the design. The loading assumption for the lining included the individual loads as listed below. No independent verification of these loading assumptions was performed. The structural computations provided in the VECP further detail the load combinations that dictated the case of greatest loading under the assumptions for the liner design.

- · Lining dead load,
- · Rock and rock wedge loads,
- · Hydrostatic loads,
- · Grout loads,
- Support loads for utilities,
- Intermediate construction loads, and
- · Impact load caused by rock fall.

These load cases and load combinations resulted in lining thicknesses ranging from 12 to 20 inches in the smallest and widest cross sections respectively. The structural reinforcement of the shotcrete liner consists of two layers of D18 × D18, 6 × 6 welded wire fabric with additional #3 @ 12" longitudinal rebar reinforcement in the mined section and 2 layers of #6 @ 6" longitudinal and #5 @ 6" radial, rebar reinforcement in the open cut section.

The shear capacity at the joint between the vertical cast-in-place concrete sidewalls and the shotcrete arch was enhanced by a roughened surface and continuous shear reinforcement for the outer and inner reinforcing layer.

6 QUALITY ASSURANCE

6.1 Shotcrete mix acceptance tests

Apart from the standard compatibility and strength test of the shotcrete mix prior to construction, the shotcrete mixes were tested as to their sprayability. A series of test panels were sprayed using the site equipment to assess the suitability for 100% encapsulation of all reinforcement elements as required for the permanent lining. Particular attention was paid to the ability to fully encapsulating the lattice girder in shotcrete without voids.

6.2 Pre-construction field trial

Following the successful test series of the shotcrete mix, field trials were carried out on standard test panels 3 feet by 3 feet and 8 inches thick with reinforcement that simulated field conditions. Vertical and overhead panels were established. Cores were retrieved and tested in accordance with ASTM. Compressive strength tests were carried out in accordance with the specified strength and strength gain requirements. The test panels were also saw cut for visual inspection of complete reinforcement encapsulation.

6.3 Nozzlemen qualification

With regard to the shotcrete application, the shotcrete nozzlemen experience is a key factor in assuring quality of the shotcrete product. FKSB took the following measures to assure a quality shotcrete application.

Nozzlemen for the project were certified in accordance with the guidelines set forth in ACI 506.3R. Two examiners, approved by ACI, qualified nozzlemen for installation of shotcrete at the project.

Additionally, a procedure was submitted and approved by the Owner by which a nozzleman may be qualified by performing field test panels that demonstrate his/her ability in performing the work.

In addition to the pre-construction field trials with standard test panels, a mock-up was constructed that replicated the conditions to be encountered in the tunnel. The entire work cycle from spraying the shotcrete through the first layer of welded wire fabric against the PVC membrane to the application of the finishing layer with the addition of PP fibers had to be simulated by this field trial. The test included spraying through and encapsulating a lattice girder.

Each candidate had to spray a vertical and an overhead panel to demonstrate their skill in shotcreting. Each panel measured at least 30 by 30 inches and 8 inches deep and contained reinforcement that simulated anticipated field conditions.



Figure 3. Installation of second layer reinforcement.

Subsequently, the panels were saw cut and observed by the Project Engineer (PB) and two ACI examiners who provide their observations on quality of the test panels and recommendations regarding the use of the nozzlemen on the project. Visual inspection examined reinforcement encapsulation, lack of segregation and proper consolidation.

The examiners consisted of Consultant Mr. George Yoggi and one representative of GZ.

6.4 Testing during construction

Quality control panels were sprayed concurrently with the shotcrete final lining installation for each 200cubic yards of material used in the shotcrete lining. Three, core test specimens from three panels were retrieved and tested in accordance with ASTM C 42.

7 LOCATIONS OF APPLICATION

The VECP was intended to be installed in two areas of the structure:

- the "mined tunnel section"
- the "open cut section".

Approximately 130 feet of mined tunnel was equipped with lattice girders and a final shotcrete lining. The open cut section extends approximately 30 feet outside the rock portal. Widening of the tunnel cross section commenced within the mined section. The overall tunnel height and width was increased in a smooth transition from the running tunnel size to the maximum height of approximately 23 feet and 55 feet width.

The thickness, reinforcement and height of the vertical cast-in-place concrete sidewalls in the mined section remained as per the Contract Design. In the open cut section, the concave sidewalls, as specified in the Contract Design, were replaced by vertical, cast-inplace concrete walls. The construction of the shotcrete permanent lining within the mined section was completed prior to construction of the portal structure in the open cut.

8 PREPARATIONS PRIOR TO SHOTCRETE LINING INSTALLATION

8.1 Mined section

Upon completion of the excavation and initial rock support installation, a smoothening layer of shotcrete was installed to prepare the substrate for waterproofing system installation. As defined in the Contract Design, the waterproofing system consisted of a geotextile layer and a PVC waterproof membrane. The sidewall drainage, footings and cast-in-place concrete walls were constructed as specified in the Contract Design.

In order to enhance the shear capacity in the interface between the cast-in-place concrete wall and the shotcrete lined arch structure, the concrete surface was roughened by power wash facilities (green cut) and reinforcement spanning the interface was provided.

In accordance with the Contract Design, the waterproofing system was installed against the shotcrete smoothing layer around the tunnel arch. BA-Anchors were used to secure in place the reinforcement for the shotcrete permanent lining. Grout hoses were installed in the longitudinal tunnel direction to serve as grouting ports for the contact grouting after completion of the shotcrete lining installation.

8.2 Open cut section

In order to avoid unnecessary excavation and demolishing work, the existing stone walls in the portal area were left in place to the extent they did not infringe on the clearance required to construct the new structure. Up to the crown elevation of the vertical sidewalls cast, drainage concrete was installed to provide enhanced capacities for draining any run-off surface water and fissure water from the rock face at the portal. Duct banks, drain lines and walkways remained as defined in the Contract Design.

Following the footing and drainage concrete installation, the vertical cast-in-place concrete walls were constructed. Between the drainage (popcorn) concrete and the vertical concrete wall, the waterproofing system as described above was installed. Similar interface details between the concrete walls and the shotcrete arch were installed as described for the mined section.

8.3 Reinforcement installation

8.3.1 Mined section

Following the erection of the vertical cast-in-place concrete sidewalls, the first (outer) layer of the D18 \times D18, 6 \times 6 welded wire fabric and rebar reinforcement



Figure 4. Reinforcement installation in the open cut section.

was installed. Lattice girders on 5-feet centers were erected founded on adjustable footplates mounted on top of the concrete sidewalls. Tie-bolts and steel spiders were attached to the BA-Anchors to secure the wire mesh and lattice girders in place during shotcreting. Tie wires were mounted at the first layer of mesh reinforcement in preparation for fixing the second mesh layer at a later stage.

8.3.2 Open cut section

Upon completion of the sidewall construction, the outer layer of the bar reinforcement and the lattice girders were erected on 5-foot centers. Temporary support to the steel reinforcement was provided by tie-back rock dowels installed in the rock portal face wall and auxiliary rebars installed in longitudinal and radial direction. To facilitate shotcrete installation, expanded metal sheets were installed on the extrados side of the portal structure. The expanded metal sheets were covered with a shotcrete smoothening layer at a later stage to prepare for the installation of the waterproofing system on the outside of the portal structure.

An expansion joint element was previously installed and anchored in the shotcrete lining for the mined section to form the interface to the open cut section.

9 SHOTCRETE APPLICATION PROCEDURES

The application of shotcrete was carried out utilizing robotic spraying equipment operated by trained personnel. Experienced, skilled supervision ensured uniform application that resulted in the shotcrete lining quality in accordance with the project requirements. High quality wet-mix shotcrete was employed.

Shotcrete was applied in a series of stages where the reinforcement members were progressively encased, thus preventing the spraying through multiple layers of reinforcement and avoiding shadowing. The first shotcrete layer was applied against the waterproofing membrane and the outer reinforcing layer of welded wire fabric. The welded wire fabric facilitated the application of the shotcrete against the membrane and provided a supporting mechanism for the wet shotcrete. The subsequent shotcrete application to the full design thickness was carried out in subsequent steps that were executed within a time frame not exceeding seventy-two (72) hours. This sequence resulted in an overall continuous shotcrete application.

Preparations for and the shotcrete application were carried out in accordance to a procedure defined during the VECP design phase. The procedure entailed among others the following check steps:

- Spray area, check if additional deck-chairs are required to avoid sagging of the waterproofing membrane
- · Availability of lifting devices
- Availability and working condition of robotic spraying equipment and pumps
- · Availability and condition of accelerator
- Illumination of work area
- Adequate protection of concrete sidewalls
- Shotcrete order and delivery, time, temperatures
- · Slump test of each delivery
- Retardation of shotcrete, if necessary.

9.1 Shotcrete application in the mined section

9.1.1 Application of first shotcrete layer (plain shotcrete)

The constant shotcrete spray was applied from the bottom of the haunch proceeding to a maximum of 5 lattice girder bays and repeated on the opposite side. Following that, shotcrete was placed along the lattice girders in an alternating sequence on both sides of the tunnel until the lattice girder was encased in shotcrete over the entire arch length. Excess shotcrete was then removed from the intrados bar of the lattice girders.

If required, additional deck chairs were mounted behind the exposed mesh reinforcement to strap back any sagging part of the waterproofing membrane. Following that, the bays between the girders were filled



Figure 5. Installation of second layer reinforcement in the open cut section.

with shotcrete, starting from haunch up to the top of tunnel in alternating sequences from both sides of the tunnel.

9.1.2 Installation of the second layer of reinforcement

The second layer of mesh was fixed on to the tie wires previously placed and protruding from the shotcrete surface. Thickness indication pins were installed in the first shotcrete layer to ensure the required thickness of the second shotcrete layer to be installed following the wire mesh installation.

Surveying was used to process data and mark out the neat line. A #3 bar, radially installed on the indicator pins was used to set out the required shape and profile for the second shotcrete layer.

9.1.3 Intermediate shotcrete layers

The shotcrete surface forming the substrate for the subsequent shotcrete application was cleaned using power wash facilities. Second shotcrete layer.

Shotcrete was applied along the previously installed profile indicator bars. Upon completion, the pins and indicator bars were cut and removed. Using power wash facilities, the substrate for the shotcrete application in the bays between the previously installed shotcrete stripes was prepared. The panels were then filled with shotcrete using the previously installed shotcrete strips for thickness guidance.

9.1.4 Final shotcrete layer

To ensure adequate tunnel profile of the final product, studs mounted on the lattice girders were used for thickness and shape guidance.

PP fibers were added to the mix for the final layer of shotcrete to enhance the fire resistance and spalling behavior of the shotcrete. The final layer is approximately 4 inches thick.

9.1.5 Contact grouting

After the shotcrete reached the design strength of 4,000 psi, contact grouting using cementitious grout was carried out to establish a near voidless contact between the shotcrete final lining, the waterproofing system and the initial shotcrete tunnel support. To facilitate the contact grouting, and ensure the filling of voids, grout hoses were attached to the waterproofing membrane prior to the initial mesh and shotcrete installation.

9.2 Shotcrete application in the open cut section

The checking and application procedures implemented prior to and during the installation of the shotcrete in the open cut were generally similar to those employed for the mined section.

Upon completion of the first shotcrete layer, thickness indicators, cleaning measures and the second layer of rebar reinforcement was applied in a procedure similar as described for the mined section.

After completion of the final shotcrete layer, a thin cement based sealant layer was applied to enhance concrete durability under variable climate conditions.

On top of the shotcrete canopy, a smoothening shotcrete layer was installed covering the expanded metal sheets to prepare for the waterproofing system installation.

Upon completion of the construction of the shotcrete canopy, the portal head wall was constructed and connected with reinforcement to the shotcrete canopy.

The waterproofing system previously installed in the sidewall areas was continued over the roof of the shotcrete canopy. A protection layer was installed to protect the waterproofing system from damage during subsequent backfilling of the portal.

10 ATTACHMENTS TO THE SHOTCRETE FINAL LINING

Generally, the attachments to the shotcrete final lining for utilities were carried out as per the Contract Design as far as minor loads are concerned. Typically, expansion anchors were used for this purpose. In cases where higher loads had to be supported such as the catenary system, attachments and local reinforcing elements (inserts or "spiders") were provided and installed as part of the reinforcement of the shotcrete and were sprayed in along with the build-up of the shotcrete lining section.

11 SUMMARY

Table 1 summarizes the basic dimensions, lining thicknesses, reinforcement as applicable to the VECP sections of the Weehawken Tunnels.



Figure 6. Shotcrete application.

Table 1. Summary of basic dimensions.

Section Length	Width	Height	Thickness	Reinforcement
Mined 2 57'-10"	28'-0"	17'-4″	12″	2 layers WWF D18 × D18, 6 × 6, #3 rebars @ 12" Lattice Girders @ 5
Mined 1 71'-2"	28'-0" to 37'-9"	17'-4" to 23'-5"	12" to 16"	2 layers WWF D18 \times D18, 6 \times 6 Lattice Girders @ 5
Open Cut 27'-9"	to 55'-4"	23'-5"	20"	#6 @ 6" longitudinal #5 @ 6" radial, 2 layers

12 CONCLUSIONS

The use of the cast-in-place concrete sidewalls in combination with high quality shotcrete to form the complex transition geometry proved to be successful at the Weehawken Tunnels Project.

The timely completion in accordance with the Contract quality requirements demonstrate that a combination of traditional and modern construction techniques can provide state-state-of-the-art solutions to challenging project requirements.



Figure 7. Completed portal structure.

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New Jersey Transit has not endorsed this paper. The contents are for informational and educational purposes only.

REFERENCE

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