Successful Completion of LA Metro Regional Connector Transit Project

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ABSTRACT

The Regional Connector Transit Project is a 1.9-mile-long underground light rail system that will connect LA Metro's A (Blue), E (Expo), and L (Gold) Lines in downtown Los Angeles. This $1.75-billion design-build project is scheduled for revenue service in Spring 2023. The project consists of 21-foot diameter twin-bored tunnels, a 300-foot-long crossover SEM cavern, three new underground stations (at 1st Street/Central Avenue, 2nd Street/ Broadway Avenue, and 2nd/Hope Streets), and cut-and-cover tunnels along South Flower, Alameda, and 1st Streets. This paper, which is the continuation of our previous paper presented in RETC 2019—LA Metro Regional Connector Transit Project: Successful Halfway-Through Completion, will provide insight regarding the construction of major components, and the system integration and testing work undertaken for this complex transit project.

INTRODUCTION

The Regional Connector Project (Project) is a complex subway light rail project designed and constructed by Regional Connector Constructors (RCC), a joint venture between Skanska USA Civil West California District, Inc. and Traylor Brothers Inc., with Hatch Mott McDonald (HMM) as the Engineer of Record (EOR). Please refer to the RETC 2019 paper—LA Metro Regional Connector Transit Project: Successful Halfway-Through Completion, for details regarding the initial design and construction phases of the project. This paper mainly focuses on the remaining construction, system integration, and testing parts of this project.

Tunnels

The twin bored tunnels were completed in January 2018. After completion of the tunnel invert slab, RCC started work on the emergency walkways inside bored tunnels in August 2018. Prefabricated steel forms were used to accelerate the construction. Each segment of prefab form was 10 feet long to be able to fit the tunnel design curves. The form segments utilized wheels running on tracks installed along the tunnel invert. Once positioned, additional dowels were installed to resist lateral load from concrete pour. The top of frame was anchored to the tunnel lining to prevent lateral movement. The prefabricated forms proved to be efficient in expediting the emergency walkway construction and being reusable for other projects. Figure 1 and Figure 2 show the emergency walkway under construction and at completion.

The Regional Connector tunnels were designed as a watertight system with double gaskets installed at the segment joints as well as at the ring joints. At the interfaces between the tunnels and cast-in-place (CIP) structures—such as the cut-and-cover (C&C) tunnels, stations, and SEM cavern—an Omega seal system was installed to seal the gap between the separate structures. The seal assembly utilized a continuous reinforced rubber sheet tightly clamped into galvanized steel plates. These

Figure 1. Emergency walkway prefabricated forms

Figure 2. Completed emergency walkway

galvanized plates were attached to the structures by embedding them into the CIP concrete along one side of a joint, and by bolting them to the tunnel rings on the other side. The seal assembly was designed to withstand the anticipated groundwater pressures while also allowing for the Omega seal sheets to be shaped to accommodate seismic ground movements and differential settlement. Figure 3 shows a mockup of the Omega seal assembly. Figure 4 shows the installation of an Omega seal assembly in the field.

Figure 3. Omega seal mockup assembly

Figure 4. Omega seal installation

Tunnel Cross Passages

The typical construction sequence for the cast-in-place concrete cross passages consisted of installing 60-mil thick High Density Polyethylene (HDPE) waterproofing membranes and geotextiles atop temporary shotcrete linings, and then placing reinforcing steel and formwork to accommodate CIP concrete placements. The waterproofing membranes were compartmentalized utilizing closed rings of HDPE water barriers (with re-injectable grout hoses, or Fuko hoses, installed at the mid-length), remedial grout hoses within each compartment, and mechanical connections to the precast concrete tunnel lining via anchor bolts, steel straps, and hydrophilic strips.

Waterproofing system installations were especially challenging due to the complicated shapes of the cross passage excavations and the stiffness of the HDPE membranes. Installation crews were unable to bend the membranes at tight corners and instead had to cut and weld the sheets using multiple smaller pieces. An example of a

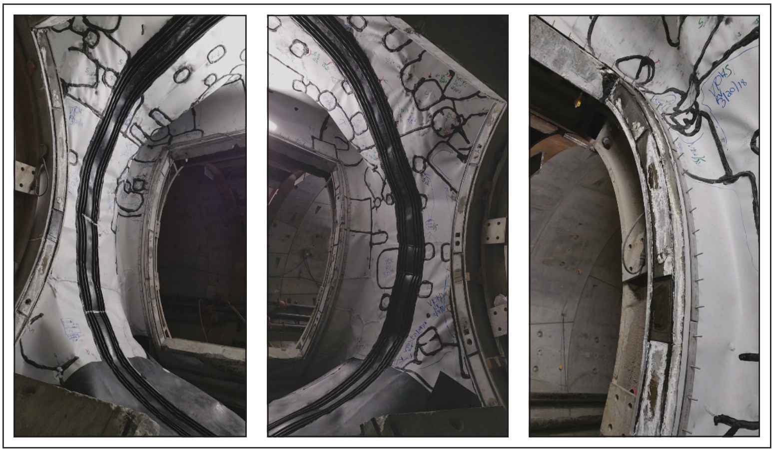

Figure 5. Crosspassage HDPE waterproofing system

completed membrane consisting of numerous small pieces and welds is presented in Figure 5. Not surprisingly, water intrusion at some of these completed cross passages has since been observed, possibly due to HDPE weld imperfections or the tearing of seams during concrete placement. Further discussion of the cross passage water intrusion challenges is presented below.

Placement of the CIP concrete for the final cross passage linings also proved to be difficult. Concrete placement for the first cross passage (CP3) was unsuccessful due to the incorrect use of a low slump concrete mix and the crew's ongoing learning curve. After curing and form removal at CP3, voids were found at the crown and along the surfaces of the CIP lining. To correct the defects, the Contractor had to pump large quantities of cement grout into the voids, and perform significant concrete surface repairs along final lining.

Construction of the two other cross passages (CP1 and CP2) did improve however, as lessons learned from the first cross passage were incorporated. The use of a higher-slump and smaller aggregate concrete mix for CP1 and CP2 resulted in fewer voids and surface defects.

SEM Cavern

The SEM cavern is located at the eastern end of the Historic Broadway Station and is an important structure of the project. It consists of 1'-6" thick CIP reinforced concrete final lining with a thickened invert slab of up to 5'-6" at the middle. Inside the cavern, a plenum slab was designed and constructed to separate the trainway from the ventilation plenum in the upper part of the cavern, which is connected to the emergency fan room located at the eastern end of the Broadway station.

The construction sequence of the SEM permanent structure consisted of constructing invert slab first, followed by the side walls, plenum slab, and cavern crown. The work started with the invert slab sections at the eastern end of the cavern and progressed toward the Broadway station. As soon as the first sections of invert slab were completed, the side wall work started. The same work pattern was repeated for the plenum slab and cavern crown.

The final lining was designed with a compartmentalized water proofing system consisting of a 60-mil thick HDPE membrane on the exterior face. This HDPE water barrier was installed with re-injectable Fuko hoses at each of the construction joints, and with remedial grout hoses inside each compartment.

Nonwoven geotextile was first installed on the face of initial shotcrete lining to smoothen out the substrate and provide a cushion for the HDPE membrane. Hanging the wall and crown HDPE membrane prior to concrete placement was a challenge. The contractor proposed to use Velcro strips adhering on the back of HDPE membrane to hang it to the nonwoven geotextile. It was accepted by Metro after the mockup sample showed it could be a good solution. It worked well in the field except some sagging of HDPE at localized locations. A bigger challenged came when it was recognized that the concrete pours at the lower portions of the invert slab and walls pulled down the HDPE membrane that has been installed on the upper parts. As the membrane does not have enough slack to accommodate the stretch, the crew had to cut the wall HDPE and add a new piece along the side to provide sufficient slack and avoid tearing during concrete pours for the walls and cavern crown. Figures 6 shows the HDPE installation in progress.

The side walls and SEM crown were constructed using prefabricated steel forms with rolling wheel on tracks installed at invert or plenum slab. The form has both wall mounted vibrators and ports for needle vibrators. Figures 7 and 8 show the prefabricated forms for the walls and cavern crown being installed and ready for concrete pours.

The final lining was designed using 4,000-psi concrete; however, the contractor elected to use a 5,000-psi concrete mix design to allow early form stripping time. The concrete mix also used superplasticizer and small aggregate to allow for better workability. The concrete work came out successfully without any major defects. The SEM permanent lining construction took 13 months to complete, started in April 2019 and completed in May 2020. Figure 9 shows the completed SEM cavern at track level.

Upon completion of the final lining, the contractor performed contact grouting through the grout tubes that were installed along the cavern crown to allow grouting both front and back of the HDPE simultaneously to avoid damage to the waterproofing membrane due to unbalanced grouting pressure. Thicker grout of 4:1 and 6:1 ratio (i.e., a ratio of 4 gallons of water to 1 bag of 94 lbs of Portland cement) was first used at the ends of the SEM cavern to create a barrier to prevent grout from filling the Omega seal or travel to the station structure. For the remaining middle section of the SEM cavern, a thinner grout of 8:1 ratio was used to allow grout to travel farther and fill all voids.

Figure 6. SEM cavern HDPE installation

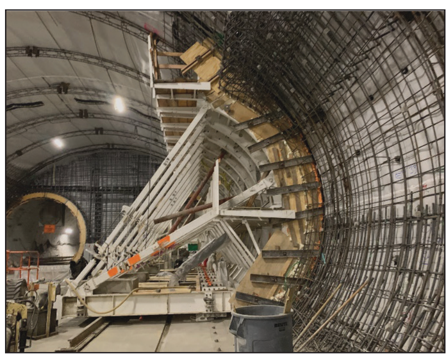

Figure 7. SEM cavern prefabricated wall form

Figure 8. SEM cavern crown form

Figure 9. Completed SEM cavern at track level

A total of 36.16 cubic yards of grout was injected for a 283 feet long cavern, of which 23.9 cy was injected inside the HDPE and 12.26 cy was injected outside the HDPE.

Cut and Cover Tunnel and Underground Stations

There are three C&C tunnel segments along 1st Street, Alameda Street, and Flower Street, and three underground stations which are the Little Tokyo/Arts District Station, Historic Broadway Station, and Grand Ave./Bunker Hill Station. The C&C tunnels are typical CIP reinforced concrete structures with a compartmentalized HDPE waterproofing membrane on the exterior face. The construction of C&C tunnels went smoothly without any major issues. The main challenge was to construct the roof of tunnel under extremely low headroom. Figure 10 show the C&C structure underneath the 1st and Alameda St. intersection where the top of concrete is only a couple inches below the support of excavation waler or existing utilities.

The construction of each underground station has unique challenges by its own. All three stations were designed with a fluted wall finish at the track level. The fluted finish was created by using a thermoformed plastic liner as shown in Figure 11 to attach to the interior face of a regular formwork system. The first couple of concrete wall pours at the Grand Ave./Bunker Hill Station were not very successful as there were a lot of honeycombs and voids on the fluted surface. This was caused due to a combination of factors, including the use of a low slump mix design by the contractor, congested wall rebar, and poor workmanship. The concrete pours were later improved with the use of a concrete mix having higher slump using superplasticizer and small aggregate to allow for better workability.

Figure 10. Construction of C&C tunnel roof

Figure 11. Thermoformed plastic formliner


Figure 12. Example of station wall rebar

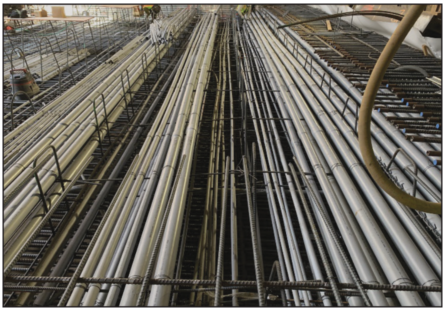
Figure 13. Example of embedded conduits in roof slab


Figure 14. Threaded rods for future overbuild

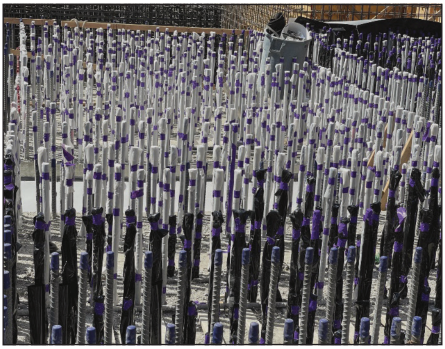
Figure 15. Protection of threaded rods prior slurry fill

At the Historic Broadway Station site, the challenges came from the extremely congested rebar of the entrance structure as it was designed to support a high-rise overbuild structure in the future. Figures 12 shows an example of wall rebar of the entrance structure. Another challenge is that there a great number of conduits that are embedded in the roof and invert slab for the MEP and communication system as shown in Figure 13. Despite the extreme congested rebar and embedded conduit conditions, most of the concrete pours came out satisfactorily. Some wall pours were less successful with a presence of voids and honeycombs on the surface. Coring of the full wall thickness was then required for quality verification purposes. The testing and visual inspection of the concrete cores determined that the structural walls were satisfactory and only surficial repairs were necessary.

The Historic Broadway entrance structure also accommodated a load transfer system (LTS) to allow for structural connection of the future overbuild structure. After multiple design alteration and evaluation, it was decided to extend the vertical threaded rods above the top of LTS that were then be protected with plastic wrap and slurry fill to avoid corrosion. Figures 14 and 15 show the extended threaded rods on top of LTS for future overbuild.

The architectural finish and artwork started at all three stations as soon as the major structure works were completed. Figures 16 show the 17 by 60 feet mosaic artwork piece and high-speed elevator head house installed at the Grand Ave./Bunker Hill Station.

Figure 16. Mosaic artwork and high-speed elevator headhouse at Grand Ave./ Bunker Hill Station

Trackwork

The Regional Connector project required special trackwork along some segments to mitigate the potential for ground borne noises and vibrations to impact certain sensitive adjacent properties. A floating slab track section was designed and installed at the Grand Ave./Bunker Hill Station and along 1,100 feet of each tunnel where the alignment crosses beneath The Broad Museum, Colburn School of Music, and the Walt Disney Concert Hall. Stared in November 2019, this floating slab system utilizes precast concrete segments supported by vertical and lateral elastomeric pads. The precast slab segments were delivered to the site where vertical support pads were then adhered to (i.e., glued) into 1-foot diameter recesses cast into the bottoms of the slabs. The precast segments were then lowered to the track level and installed atop a finished invert slab. Once the precast floating slab segments were installed, rails and direct fixation anchors were placed and grouted into place. Figures 17 and 18 show the floating slab and rail installation work.

In addition, a Low Vibration Track (LVT) system was also required for the tunnel section at the eastern end that goes under the Japanese Village Plaza and adjacent to the residential buildings in the area. For the rest of the alignment, traditional concrete

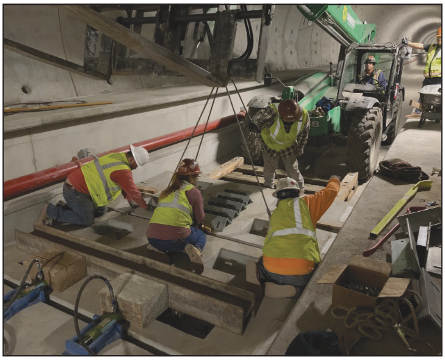

Figure 17. Floating slab track installation

Figure 18. Completed floating slab track

Figure 19. LVT rail system with strong back support

Figure 20. Infill concrete placement

plinth was required per the contract. However, for construction convenience and schedule benefits, the contractor elected to use the LVT system for the rest of the alignment except at the special trackwork locations. The rails and LVT blocks were first delivered and installed on the tunnel invert. The rail system was then set into the position and supported with the pour-in-place (PIP) strong back systems at every 4th resilient tie. "Cow pie" concrete was poured to lock the resilient ties next to strong back systems in place. Infill concrete was delivered by on-track buckets to the pour location to complete the LVT embedment. Figures 19 and 20 show the LVT ties and rail supported with the PIP strong back systems and the infill concrete placement in operation.

Emergency Ventilation, Traction Power, and Other Systems

A Fire Dynamics Simulation (FDS) and computational fluid dynamics (CFD) package was used to design the station and tunnel emergency ventilation systems. This package modeled the three-dimensional aspects of the smoke and heat movement from a medium-growth fire to simulate the impact that Emergency Ventilation Fans (EVF's) would have on air movement throughout the project corridor. The CFD analysis allowed the engineering team to determine the emergency ventilation system capacities (as per the LA Metro Design Criteria and NFPH 130) necessary to provide tenable environments for passengers during a fire evacuation event.

A key finding of the CFD analysis was that two fan plants—each plant having a nominal capacity of 500 kcfm—were needed at each of the three new stations. The analysis also showed that an additional fan plant was necessary at the Alameda Wye where the two track alignments diverged. To achieve these flow rates, 600-HP and 400-HP vane axial reversable fans were installed, in pairs, at each end of the new stations and at the Wye. Figure 21 shows a 600-hp EVF assembly being installed.

The systems were also designed to accommodates 60 separate Emergency Ventilation Evacuation Operations scenarios (EVOP's). In the unlikely event of a fire emergency, a Metro Controller or first responder can activate any one of the 60 EVOP's using a single-button command. These commands can be executed either locally at the station Emergency Management Panels (EMP's), or remotely from Metro's Rail Operations Center (ROC) in central Los Angles.

In addition to the emergency ventilation equipment, water suppression systems were installed to assist with the control of heat and smoke from a fire. The water suppression systems include a standpipe distribution network connected to two separate city mains, for redundancy, along with under-train deluge systems at each of the station platforms. Provisions for removing traction power are provided during a water discharge event to help protect passengers, first responders, and other personnel. Figure 22 shows the undercar deluge systems adjacent to the Historic Broadway station platform.

The Regional Connector Traction Power (TP) Supply System was designed and constructed to be compatible with the existing equipment utilized on the Metro A-Line and L-Line. Primary power to each of the substations, which are located in back-of-house areas of the new stations, is provided by the Los Angeles Department of Water and Power (LADWP) at 34.5kV. These substations then covert the 34.5kV AC power to 750-volt DC, which is then distributed to trains along an Overhead Contact System (OCS). A unique feature of the project is that instead of utilizing traditional wire-based centenary assemblies for the OCS, an Overhead Catenary Rail (OCR) system was used. The OCR technology is relatively new for Metro but was chosen due to its durability and reduced maintenance requirements compared to wire-based systems. Figures 23 and 24 shows the OCR at the Alameda-leg crossover, and a typical traction power distribution equipment installation, respectively.

A Communications System consisting of audio, video, and data circuits was constructed to connect the new stations and tunnel areas with Metro's existing ROC in central Los Angles. Construction of this new system was especially challenging as it had to remain compatible with the existing A-Line, L-Line, and L-Line Eastside Extensions systems, each of which were constructed at different times. Some of the existing communication equipment on the A-Line, for example, is analog-based and more than 30-years old. The existing Supervisory Control and Data Acquisition (SCADA) cable runs, conduits, and communications network equipment had to be extensively evaluated to determine design requirements that would provide reliable

Figure 21. Emergency ventilation fan installation

Figure 22. Under-car deluge systems

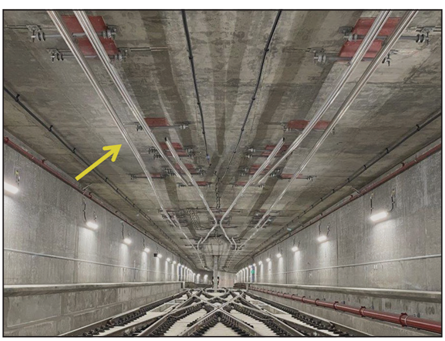

Figure 23. Overhead catenary rails at crossover

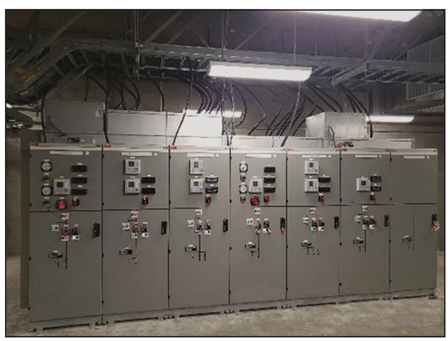

Figure 24. Traction power substations room

SCADA communications for the new train control, seismic detection, radio, CCTV, and other systems interfaces.

An Automatic Train Control (ATC) System and related components were installed to provide for fully integrated operations of the new system with the existing Metro system, so that train operations would be seamless. This new system provides continuous ATC operation from the existing lines into the Regional Connector corridor without train operators having to intervene. Also included is an Automatic Train Protection (ATP) system that provides for vital train detection, automatic protection, and interlocking control. All train control and related system elements interface with the existing SCADA system to allow for control requests from and to the ROC.

LEAK SEALING

One of the major challenges that the project team had to face was the water leakage that mainly occurred at the tunnel interfaces, cross passages, SEM cavern, and underground stations.

At the tunnel interfaces with SEM cavern or C&C structures, water leaks were observed soon after completion of the Omega seal installation as the groundwater pressure started building up behind the tunnel lining. Water intrusion was observed at the gaps between the steel ring plate and precast segmental lining. Leakage was also observed at the lining segment and ring joints near the interfaces where relaxation of ground confinement pressure occurred due to the station excavation. Water was also observed dripping from the bolt holes at the tunnel interfaces as well as along the tunnel reaches. To seal these leaks, the contractor had to drilled through the lining and inject two-component polyurethane grout to limit the water infiltration. Additional packers were also used to target the leaked segment joints and ring joints. The leaked bolt holes were cleaned and filled with leak master sealant before the bolts were reinstalled and tightened. After a significant sealing leak grouting operation, the contractor successfully sealed off all the leaks around the tunnel interfaces. Figure 25 shows water leakage at the Omega seal at the western end of the Grand Ave./Bunker Hill Station before and after the leak repairs.

All CIP structures of the project used the same waterproofing system that consisted of compartmentalized HDPE waterproofing membrane with water barrier and re-injectable grout hose installed at the construction joints and remedial grout hoses within the compartments. This compartmentalized system was design to allow for isolating the leak areas and injecting grout into the back of structures to seal the leaks.

Figure 25. Water leaks at 2nd/Hope tunnel interfaces before and after leak repair

Figure 26. Cross passage CP3 water leaks before and after leak repairs

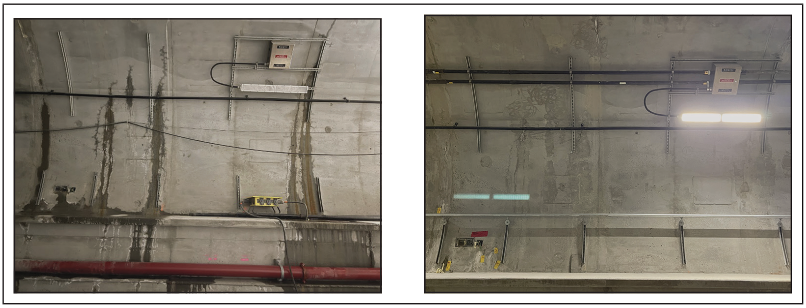

Figure 27. SEM cavern water leaks before and after repairs

Although the waterproofing system was installed with care and strict QA/QC procedure, some significant water leaks were observed at the cross passages, SEM cavern, and station structures after some rain falls in 2020 to 2022. The contractor had to inject two-component polyurethane grout into the Fuko hoses and remedial grout hoses to seal the leaks. Additional holes were also drilled to target the individual cracks. After multiple grouting passes, the water leaks in all cross passages, SEM cavern, and stations were successfully sealed. Figures 26 and 27 show the cross passage CP3 and the SEM cavern, prior to and after completion of the water intrusion repairs.

Field and Systems Integration Testing

Testing of all systems-related project elements was performed utilizing Local Field Acceptance Testing (LFAT) procedures and a 2-phase Systems Integration Testing (SIT) approach. Local testing, or LFAT's, were performed directly by the Contractor and their subcontractors, and the results documented and submitted to Metro for approval. Upon successful completion of an LFAT, the first phase of systems integration testing (i.e., SIT-1) of that component could commence. The purpose of this SIT-1 work was for the Contractor—with Metro witnessing—to verify that specific components were performing as designed while operating in a local-mode configuration. Upon a successful

SIT-1 test, Metro staff would then perform the second phase of integration testing (i.e., SIT-2), where proper remote communication and control through the SCADA system was confirmed. During the 14-month testing period more than 600 systems data points and commands (i.e., SCADA points) were tested between the project corridor and the ROC.

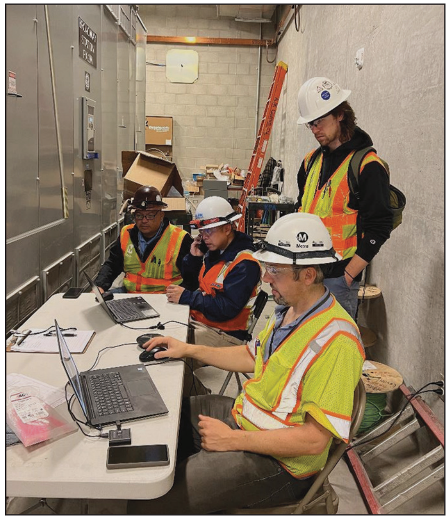

Figure 28. SIT-2 testing of power systems

In addition to the LFAT and integration testing, extensive train testing through the Regional Connector corridor was performed. These series of tests included Minimum Headway Verifications, Signal Sightings Confirmations, and Operational Stress Tests, among others. The purpose of this train testing was to confirm that Metro could successfully operate its trains in compliance with the project operational specifications and per the predictive models. Figures 28 and 29 show systems integration testing at an electrical substation, and a Light Rail Vehicle (LRV) traveling though the SEM cavern crossover during headway verifications, respectively.

CONCLUSION AND LESSONS LEARNED

The overall construction of Metro's Regional Connector Project was highly successfully; however, valuable lessons were still learned regarding the underground construction techniques and design details employed. These lessons learned are being

Figure 29. SIT-2 headway verification testing

shared throughout the transit agency and will be considered as Metro's advances its multi-decade construction program. Examples of lessons learned include:

1. The tunnel cross passage geometry was too complex. As discussed previously, field crews had much difficulty getting the simi-ridged HDPE liner to conform to and fit into the tight corners and bends, resulting in voids and weld tears when the CIP final liner was placed. Utilization of a simplified cross passage geometry, with fewer and sweeping bends, would allow the HDPE installation to be performed more smoothly and improve the overall quality of completed work.
2. The design of the interfaces between the bored tunnels and the cut-and-cover structures must be improved. Compression of the tunnel lining joints near the interfaces with the cut-and-cover structures tend to become relaxed, primarily due to a reduction of ground confining pressures from the adjacent excavations. Additional compression in the circumferential and longitudinal directions of the bored tunnel lining, in the form of pre-tensioned cables or rods, should be considered to ensure proper compression and the effective control the water leakage through the joints.
3. Do not wait until the end of construction to address water infiltration issues. Water leak sealing work should start as soon as possible, as the outcome of leak repairs is not readily predictable. Leak repairing is a time-consuming process and the work may require several passes before the leaks can be sealed successfully. It also requires great care to protect the other completed works in the vicinity of the leak sealing, as grout may expand into or spill over adjacent systems elements or architectural finish works.