

Construction of the Gemini Escalator Tunnel as Part of the Prague Metro Line D Project

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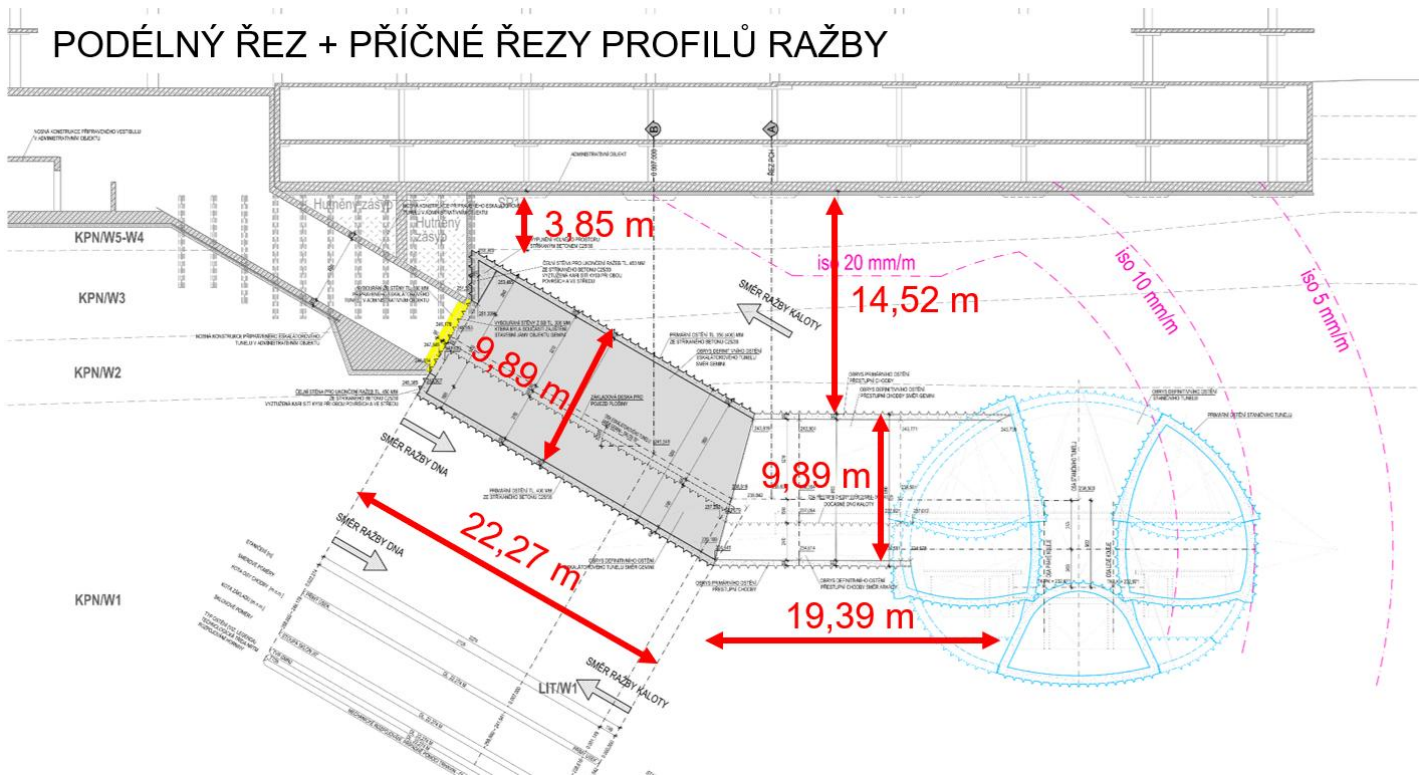
ABSTRACT: This paper seeks to present the construction process of the Gemini escalator tunnel, which forms part of the construction of Line D of the Prague Metro and is one of three escalator tunnels providing access from the Pankrác D station. The paper describes the complete realization of the structure, from tunneling works through the installation of the waterproofing system to the concreting of the final lining of both the lower and upper vaults.

In the introduction, it briefly outlines the necessary preparatory work in the area of design, in relation to tunneling methods verified by geological investigations in this area. The design work had a direct influence on the selected tunneling method and the machinery used. For the inclined top-down excavation of the escalator tunnel, a prototype working platform was developed.

The paper further describes the geology of the site as well as the tunneling procedure and technology of the escalator tunnel, which was affected by the possibility of access only from the lower end. During the tunneling works, contamination of the rock mass and groundwater by petroleum substances was identified within the area of this structure, resulting in additional complications to the excavation works and necessitating changes to the waterproofing system, including the system of precautionary and sealing grouting.

1. PREPARATORY AND DESIGN WORKS

The tender documentation for the construction of Prague Metro Line D was prepared in 2018. Prior to the commencement of construction works, an engineering-geological investigation of the area was carried out, during which methods for improving the rock mass were verified. In particular, advance chemical grouting proved effective, as it not only improved the quality of the rock environment for the excavation itself but also sealed the excavation area against excessive groundwater inflows. These findings were subsequently incorporated into the design documentation for construction, making it possible to change the tunnelling concept of the Gemini escalator tunnel.



“Fig. 1 – Longitudinal section of the escalator tunnel and transfer corridor”

In the original design documentation from 2018, the excavation was designed using the New Austrian Tunnelling Method (NATM), with horizontal subdivision of the excavation profile into the top heading, bench, and invert, and with vertical subdivision of the top heading into left and right partial excavations. The crown of the top heading was supported by double-row micropile umbrellas made of $\text{Ø}127$ mm pipes with a wall thickness of 12 mm, drilled to a length of 10 m into a progressively enlarging excavation, so-called “chapels.” A maximum of 8 excavation rounds with a maximum length of 0.8 m were carried out in each chapel. The overlap of the micropile umbrellas was approximately 3.5 m. The thickness of the sprayed concrete lining was designed as 350 mm, reinforced with two layers of welded wire mesh $8 \times 8 / 150 \times 150$ and a reinforcement lattice girder in each excavation step.

By incorporating the findings of the engineering-geological investigation, it was possible during construction to change the excavation subdivision to a horizontal division into the top heading with a temporary strutting concrete slab and the invert. Support of the crown and improvement of the rock mass were achieved by advance chemical grouting carried out through boreholes equipped with self-drilling anchors 8.0 m in length in every fourth excavation round (Fig. 1).

The contractor began developing a prototype platform for top-down excavation of the escalator tunnel 1.5 years before the start of tunnelling works. Thanks to the efforts of numerous experts from various disciplines, one of two alternative solutions was selected, enabling safe excavation of the top heading from a hydraulically operated platform on which all machinery required for excavation and support in each excavation step could be used. The platform was designed with a load capacity of 25 tonnes, including a static reserve for dynamic effects caused by potential rock falls onto the platform. The development required the coordination of many factors and disciplines, particularly the development of hydraulic movement, electrical installation of safety sensors, control programming aimed at eliminating human error during platform movement, design of safety features for safe personnel movement on the platform and transitions into unsupported excavation, and compliance with legislation governing mining-type construction activities. These requirements were often conflicting, necessitating prioritization among alternative solutions. The technical design itself took 12 months, followed by an additional 6 months for production and testing at the manufacturer.

2. GEOLOGICAL CONDITIONS

From a geological perspective, the excavated structures constructed from the PAD1b construction site towards Pankrác D station pass through the core of a syncline formed by Silurian rocks represented by the Kopanina and Liteň formations. Closer to Pankrác D station, the Liteň formation predominates. The excavation of the transfer corridor and the escalator tunnel was carried out entirely within the Liteň formation. The Liteň formation consists of dark grey to black clayey to silty shales, with frequent layers and lenses of very strong limestones in its upper part. Tuffitic layers are also common. The total thickness of the Liteň strata is approximately 30–80 m. The shales are thinly bedded with abundant graptolite fauna on bedding planes. Bedding is often indistinct, and joints represent the main predisposed planes of disintegration.

3. EXCAVATION OF THE ESCALATOR TUNNEL

The construction structure SO 11-24, consisting of the transfer corridor and the Gemini escalator tunnel, includes a short transfer corridor with a length of 19.39 m and an excavation profile area of 94.59 m². The transfer corridor is curved and connects perpendicularly to the excavation of the single-vault Pankrác D station. Longitudinally, the corridor rises from the station at a gradient of 0.5%. The excavation is horizontally divided into the top heading and the invert. Excavation was carried out using a standard mechanical set for large-profile tunnelling, including a Rocket Boomer E2C drilling rig, Liebherr 950 tunnel excavator, Volvo 120 wheel loader, Meyco Potenza shotcrete manipulator, and DC 16/HL aerial work platform. Due to surface structures above the excavation, the transfer corridor was classified into support class TT 5b. This class required excavation rounds with a maximum length of 1.0 m and sprayed concrete lining 350 mm thick, reinforced with two layers of welded wire mesh 8×8/150×150 mm, Ø16 mm reinforcement bars, and a lattice girder in each round. Improvement of the rock mass was carried out by advance grouting into the face using boreholes equipped with IBO R32 self-drilling anchors 8.0 m in length in every fourth excavation round. The boreholes were pressure-grouted with an organo-mineral resin. Grouting parameters were set to a consumption of 10 kg per borehole or attainment of a pressure of 60 bar. Grouting was terminated upon reaching either parameter. The crown of the excavation was supported by injected spiles made of IBO R32 self-drilling anchors 6 m in length in every second excavation round, also pressure-grouted with parameters of 15 kg per borehole or 60 bar. Excavation commenced on 15 March 2025 and was completed in both headings by 5 April 2025 (Fig. 2). Preparations then followed for excavation of the inclined section of the escalator tunnel, which is 22.27 m long with an excavation area of 105.13 m². The escalator tunnel was excavated top-down at a slope of 30°. The contractor made use of the option to excavate approximately 10 m of the top heading of the inclined section using the same mechanical equipment employed for the excavation of the transfer corridor. Subsequently, a temporary reinforced concrete strutting slab forming the invert of the top heading was cast. The slab had a thickness of 400 mm and was reinforced with two layers of welded wire mesh 8×8/150×150, with transverse Ø16 mm reinforcing bars and additional shear reinforcement in the area of anchorage of the two rack rails used for moving the platform for the inclined excavation of the escalator tunnel.



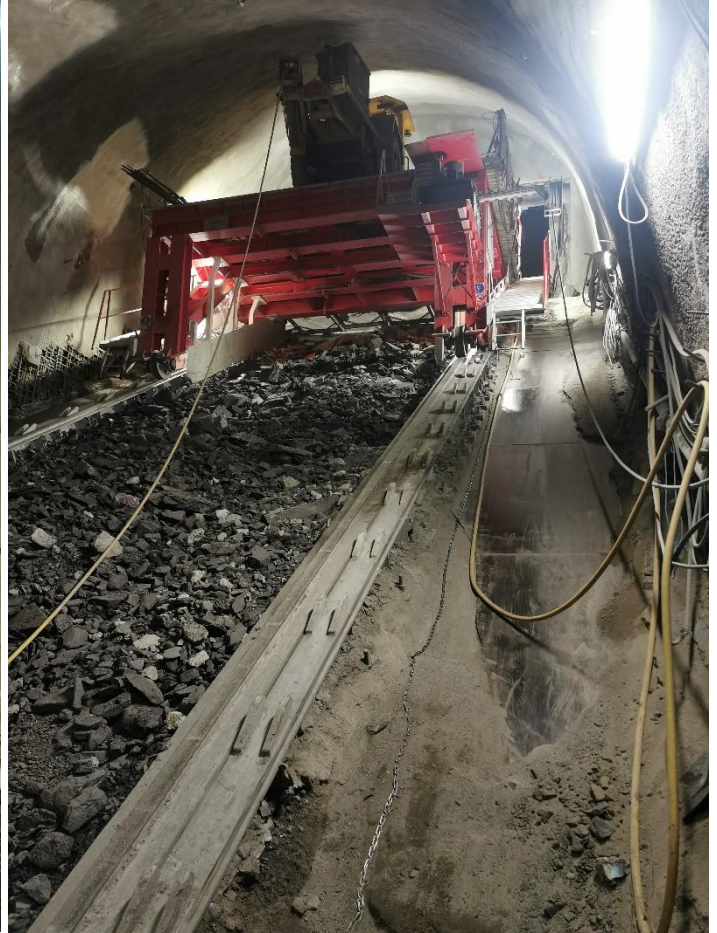
“Fig. 2 – Commencement of excavation of the transfer corridor top heading”

Prior to the installation of the platform for excavation of the inclined section, it was necessary to install a suspended rail system beneath the ceiling of the transfer corridor. The suspended system consisted of two steel beams and enabled the movement of heavy platform components toward the excavation face. Mechanical equipment had access to the installation area exclusively via the transfer corridor. The load capacity of each suspended rail was up to 10.5 tonnes. This was followed by the installation of the initial 8 m long rack rails for platform travel (Fig. 3). Anchoring to the strutting slab required core drilling for each anchorage point. The anchorage consisted of M30 threaded rods with a minimum embedment length of 250 mm. Each rail was anchored by two studs on each side at intervals of 1 m along its length. The installation of the platform itself, including connection of the hydraulic system and electrical controls, took 21 days. After completion of the installation, it was necessary to construct a granular access ramp to the platform, which was shored on the platform side with concrete panels. This created not only the required platform run-out area for machinery replacement but also a retention space for muck, which during excavation fell beneath the platform into this area. After completion of all these preparatory works, excavation of the remaining 12.2 m of the escalator tunnel could commence. Although this remaining length may appear short, without the installation of the platform for inclined movement even such a short excavation distance would have been impracticable. The remaining excavation works were carried out in support class TT 5b with the same excavation support as used for the transfer corridor, including advance pressure grouting. After completion of every two top-heading excavation rounds, a lamella of the reinforced concrete strutting slab was cast, including the rack rails with anchorage studs already installed within the reinforcement. This eliminated the time-consuming core drilling required for anchoring individual rail segments into the strutting slab. The rails could thus be extended in 1.0 m sections. Excavation of the top heading up to the interface between the escalator tunnel and the Gemini structure was carried out between 8 June and 7 July 2025. The excavation was performed using a mechanical set consisting of an Avesco TB 20 excavator (machine weight 20 tonnes), a Boomer S2 drilling rig, a Meyco Oruga shotcrete manipulator, and a Meyco Suprema concrete pumping unit. A notable feature of the excavation was the automatic movement of the platform in individual steps of 1.0 m, with the option to reduce the step length to 0.5 m (Fig. 4a). Platform movement was provided by three pairs of hydraulic cylinders: two pairs ensured anchoring of the platform during upward or downward movement, while one pair provided the actual longitudinal movement. The platform was secured to the rails via the individual rack teeth. A 1 m platform advance required approximately one minute, during which all hydraulic cylinders were activated sequentially.

After the start of excavation, it was also necessary to modify the surface of the reinforced concrete strutting slab, as it became evident that the muck accumulated on the slab near the face and did not move spontaneously toward the toe of the slab. The entire surface of the strutting slab was therefore lined with 1 mm thick steel sheet. Following this measure, the muck slid by gravity into the platform run-out area, where it was excavated by a tracked excavator and transported to the surface.



"Fig. 3 – Suspended rail system for platform installation"



"Fig. 4a – Excavation of the escalator tunnel top heading"

After reaching the interface with the Gemini structure, the soldier pile shoring of the Gemini construction pit was first removed as part of the excavation works, followed by cutting a rectangular opening into the reinforced concrete underground wall of the structure using a wall saw. Excavation of the lower vault was carried out by gradually retreating the platform from top to bottom. In individual steps of 2.0 m, the strutting slab was demolished, the rack rails for platform travel were dismantled, and the primary lining of the lower vault was constructed (Fig. 4b). After the platform had retreated back to the beginning of the rail track, the granular access ramp to the platform was first removed, and the platform was then dismantled and transported to the surface using the suspended rail system. The remaining 8 m of the invert were excavated from the transfer corridor using the large-profile tunnelling equipment once again.



„Fig. 4b – Excavation of the lower vault of the escalator tunnel“

4. WATERPROOFING SYSTEM

The waterproofing system in the escalator tunnel structure is designed in the same way as in all other underground structures of the newly constructed metro line, i.e., a “submarine” type system. Around the entire perimeter, the final lining is protected against the effects of groundwater pressure by a closed intermediate waterproofing layer applied between the primary shotcrete lining and the final monolithic reinforced concrete lining. The closed waterproofing system also serves as a passive secondary protection against stray currents. The choice of waterproofing material was influenced by the fact that approximately between 1955 and 1985, a surface fuel pumping station with underground storage tanks operated at Pankrác. Due to long-term leakage of the tanks, contamination of the rock and groundwater with petroleum substances was encountered during excavation. This fact was not known during the preparation of the design documentation and was only discovered during the excavation of the Pankrác D station. This made it impossible to use a 3 mm thick PVC waterproofing membrane, which is used in other construction structures. Instead, the tunneling designer selected a material resistant to petroleum substances. The newly designed waterproofing system consists of a 2 mm thick LDPE membrane installed in two layers. A protective layer of geotextile (800 g/m^2) is placed in contact with the primary lining. At construction and expansion joints, reinforcing strips of LDPE waterproofing membrane are installed. The construction works also include connecting the newly built system to the existing PVC waterproofing system of the Gemini administrative building by clamping both membranes in stainless-steel flanges. At the floor level, the waterproofing membrane is protected from above by geotextile (500 g/m^2) and a protective layer of concrete screed, 100 mm thick in the horizontal part of the transfer corridor and 280 mm in the inclined part of the escalator tunnel. The designer also proposed a double safeguard injection system – a systematic surface injection and a secondary safeguard. The first injection system, which is intended to prevent the flow of groundwater potentially containing petroleum substances along the escalator tunnel, is placed between the

waterproofing membrane and the primary lining. The safeguard system considers chemical injection into the space between the two waterproofing membranes, which is intended to be applied only if the executed waterproofing proves to be leaky.

5. FINAL LINING

The escalator tunnel and transfer corridor structure is divided into a single expansion segment with a length of 31.937 m. Additionally, the structure is separated by expansion joints from the adjacent structures of the Pankrác D station and the existing Gemini office building. The concreting of the lining is divided by horizontal construction joints into the floor and the arch concreting. The final lining is designed from reinforced concrete C30/37. The invert is reinforced with conventional tied reinforcement, while the reinforcement framework of the upper vault consists of lattice girders supplemented on both the intrados and extrados by welded mesh and reinforcing bars.

6. CONSTRUCTION PROCEDURE FOR THE FINAL LINING

After the excavation works were completed, significant water inflows mixed with gasoline were observed in the invert area of the sloped part of the escalator tunnel. For this reason, a systematic area-wide grouting of the floor was designed and carried out using short boreholes approximately 600 mm deep and 14 mm in diameter, arranged in a 1 × 1 m grid. A total of 190 boreholes were executed. Each borehole was injected through a packer with a two-component organic-mineral resin at a maximum allowable pressure of 20 bar.

In chronological order, the waterproofing system, including grouting tubes, was first installed across the floor of the horizontal section. This was followed by tying of the reinforcement, including its protrusion into the sloped structural part of the floor, installation of formwork from both sides, and subsequent concreting.

In the next step, scaffolding was erected in the sloped section to enable the waterproofing of the floor and the installation of metalwork for the transition of the waterproofing into the Gemini building. The insulation was carried out from top to bottom with progressive dismantling of the scaffolding.

The protective screed of the sloped section served multiple purposes: it prevented damage to the waterproofing membrane, allowed installation of anchors for the floor reinforcement, and provided a safer walking surface on the otherwise slippery membrane. In this section, a special C30/37 concrete mix with melamine additive supplied by TBG Metrostav was tested on the 30° slope; this mix was also used in the invert of the final lining of the sloped section. It was necessary to verify the effect of concrete transport on its consistency, as the only transport route was via a vertical pipe with 25 m of angled segments to the bottom of the PAD 1b excavation pit, where the concrete was transferred to a truck mixer and then pumped to the placement location. Melamine helps maintain concrete consistency, but it spreads during vibration. Unfortunately, prolonged transport and handling can reduce the effect of melamine.

Subsequently, reinforcement tying for the floor was carried out in the same manner as in the horizontal section. For concreting, a method commonly used for dam spillway chutes was adopted: a cylindrical rotary finisher was used to shape the final surface. The finisher moved along guide rails anchored to the sides of the primary lining, and its movement was powered by two winches using steel cables anchored to the front wall of the Gemini building. Again, concrete with a melamine additive was used. The fresh concrete thus maintained the required slope while remaining workable, compactable, and suitable for finishing the top surface. Thanks to the finisher (Fig. 5), the entire sloped section was concreted in a single operation over 30 hours. During this period, a total of 260 m³ of concrete mix was placed. To create the waterproofing system for the upper arch, including completion of the metalwork for securing the waterproofing at the Gemini building, full-space scaffolding was erected. From this scaffolding, the reinforcement for the upper arch of the sloped section was tied after minor adjustments. Due to the steep slope, the reinforcement had to be anchored with drilled anchors in the horizontal section (not yet waterproofed), which was not feasible in the double-layer waterproofing of the sloped section.



„Fig. 5 – Finisher for concreting the invert (bottom arch) “

A separate chapter was dedicated to the formwork of the upper arch. A system was sought that, after partial modification, could cover both the sloped straight section and the horizontal section, which is partly curved and partly straight. The same formwork was also intended to be used for the junction between the horizontal and sloped sections.

For concreting the blocks, a steel formwork carriage with an automatic hydraulic slide was chosen, which moved along the sloped surface on saw/gear rails. Due to limited space for mechanization and the need for various modifications of the formwork carriage, the steel shell was divided into individual welded segments, which were attached to lightweight aluminum elements of the modular formwork system.

The concreting of the sloped section of the escalator tunnel was carried out progressively from the bottom upward to the interface with the Gemini administrative building. The sloped section consisted of five blocks in total. Only two blocks had a standard length of 4.9 m. The first block at the slope change had to be formed using the hydraulic formwork carriage with an added triangular formwork for the slope transition (Fig. 6). After the first concreting, the triangular formwork was detached from the carriage, which then continued upward over the next two standard blocks to the fourth block, which was 3.8 m long. The fourth block connected to the front section, including a rectangular transition to the initial part of the escalator tunnel within the Gemini building. The front wall formwork was supported by the hydraulic formwork system.

After completing the sloped section of the escalator tunnel, the formwork descended along the gear rails into the horizontal section. The horizontal section consisted of three concrete blocks. First, a spatial scaffolding was erected to install the waterproofing system, including a stainless steel fixture to ensure

the transition of the tunnel's waterproofing system to the Pankrác D station's waterproofing, which is expected to be, according to the project documentation, 3 mm thick PVC foil.

After installing the waterproofing, the reinforcement for the upper arch along the entire length of the horizontal section was installed. The first block of the secondary lining, adjoining the sloped section, was straight and 4.397 m long. This length included the triangular formwork for the slope-to-horizontal junction. Before concreting the remaining two blocks, which are 3.0 m long and follow a curved path, the formwork envelope was completely dismantled and a curved envelope was installed.

After completing the concreting of the curved blocks, the secondary lining of the transfer corridor and escalator tunnel was fully completed (Fig. 7).



“Fig. 6 – Formwork of the first block of the upper arch of the escalator tunnel”

At the beginning of 2026, preparatory works were carried out for the systematic grouting, followed by the actual grouting of the space between the waterproofing system and the primary lining. For this grouting, perforated hoses $\text{Ø}18/10$ mm were used, placed on the underlying geotextile. The hoses are led into grouting boxes located in the secondary lining. These hoses are left open at the ends to allow the grout to freely spread into the space.

7. CONCLUSION

The construction of the Gemini escalator tunnel and transfer passage represented an exceptionally demanding project that required a combination of standard procedures and innovative solutions. The presence of petroleum substances underground necessitated modifications to the waterproofing system—LDPE insulation in two layers was used instead of PVC foil, supplemented by a double injection system to ensure reliable protection against pressurized water potentially containing petroleum. Both the excavation and the concreting of the sloped section posed significant challenges.

The use of a special platform for inclined excavation, a custom C30/37 concrete mix, and a finisher confirmed the effectiveness of the chosen technological approach, even under the complex conditions of material and concrete transportation to the placement site. The project demonstrated that thorough preparation, a flexible approach, and collaboration among team members are key to success in constructing underground structures under challenging geotechnical conditions. The experience gained can be used to optimize future metro projects and other underground facilities.



“Fig. 7 – Fully completed secondary lining”

8. ACKNOWLEDGEMENTS

Special thanks go to the entire project team involved in the construction. Further appreciation is extended to the designer of the underground structure, without whose cooperative approach to the design solutions the subsequent implementation would have been significantly more difficult and costly. Thanks are also due to the developers of the mechanical equipment from various sectors, who had to translate the technical and safety requirements into concrete measures. All participants demonstrated incredible diligence, a willingness to engage in untested solutions, creativity, and the ability to improvise in situations that could not have been anticipated during the design phase. Only through teamwork was it possible to complete this technically demanding, though not large-scale, project on time, with high quality, and while maintaining worker safety.

LITERATURE

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