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Numerical analysis and design of an SEM tunnel through jet-grouted Coode Island Silt

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ABSTRACT: Hobsons Bay Main Yarra Crossing Duplication Project is a major project for Melbourne Water involving the construction of a new duplicate sewer and rehabilitation of the existing sewer, currently conveying approximately 30 percent of Melbourne's wastewater. As part of the project, a new tunnel, between the new junction manhole and new siphon inlet shaft, was constructed in very soft to soft, saturated Coode Island Silt. Jet grout columns, including inclined columns around an abandoned sewer overpassing the tunnel, were installed to form a stabilized grouted mass in the tunnelling zone. The project represents a successful integration of soft soil ground improvement and open-face tunnelling through treated ground. It is among the first projects to combine the two in Victoria's tunnelling history. This paper presents a three-dimensional numerical analysis of encountered ground conditions to gain insights into excavation and support performance through fully and partially jet-grouted silt.

1 INTRODUCTION

1.1 *Project background*

The current Hobsons Bay Main sewer siphon, which is a pivotal component of the sewer network for the city of Melbourne, transfers about 30 percent of the city's wastewater to the Western Treatment Plant. It was constructed under the Yarra River between Port Melbourne and Spotswood in the 1960s, replacing the original 1895 tunnel when Spotswood Pumping Station was decommissioned, and is nearing the end of its service life. In September 2021, a project was initiated to construct a duplicate conduit that diverted sewage flows during rehabilitation works of the existing sewer. The duplication component of the overall project was delivered by John Holland for Melbourne Water and was completed in December 2024.

With the existing sewer being relined in 2025, the new duplication and the refurbished siphon will provide greater wastewater flow transfer capacity in parallel and are designed to accommodate flows projected for the year 2071.

1.2 *Project components*

The project works consist of a 678 m long siphon tunnel beneath the Yarra River between the siphon inlet and outlet structures on each riverbank. On the east bank, a new upstream connection structure (UCS) intercepts the original sewer system, isolating and diverting the flow to the new siphon inlet structure (SIS) via a connection tunnel. On the Yarra River's west bank, the siphon tunnel links to the new siphon outlet structure, then to the new downstream connection structure on the existing North Yarra main sewer.

On the east bank, installation of the UCS and SIS structures began with circular shaft construction using secant piles. Secant piles were selected over soldier piles to minimise the risk of the groundwater table lowering during construction, which would induce excessive long-term ground settlement due to depressurisation consolidation in silty ground. Following piling, the tunnelling zone between the UCS and SIS was ground treated. After excavation of the shafts, the connection tunnel was constructed via the sequential excavation method (SEM) between August and September 2023.

1.3 *Ground conditions in tunnelling and shaft base zones*

The project area is located within an estuary consisting of very soft, saturated soils on the east riverbank near the current junction of the Yarra River with Port Philip Bay. The project Geotechnical Interpretive Report (GIR) (WSP Australia 2022) describes the east bank geology as a layer of fill at the ground surface overlying a sequence of Quaternary sediment deposits. One near-surface sediment unit is Coode Island Silt, a dark grey to black, very soft to soft, normally to slightly overconsolidated silty clay expected and encountered at tunnelling depth for the SEM connection tunnel. An extensive site investigation and laboratory testing program provided geotechnical properties for this ground type, suggestive of a very soft and yielding material with undrained shear strength values of only 20 to 50 kPa, negligible effective cohesion, an effective friction angle of 26 degrees, and a drained elastic modulus between 4 and 9 MPa.

The shafts on the east bank were expected to be founded in cohesive Fishermens Bend Silt. The laboratory testing program determined that this material had an undrained shear strength varying between 40 and 125 kPa and a drained elastic modulus of approximately 17 MPa.

2 CONTROL OF EXCAVATION RISKS

2.1 *Concept design*

Coode Island Silt has very little to no stand-up time from a tunnelling time perspective. This does not allow SEM tunnel passive support systems adequate time to gain sufficient strength and stiffness and to abate soil movements caused by the excavation without robust control of groundwater and ground collapse risks. Risks of consolidation of the silt layer due to groundwater table drawdown, potential excessive groundwater ingress into the tunnel excavation, and large tunnel deformations were all serious concerns. During the design phase, these risks were mitigated by adopting a relatively new option in Victorian tunnelling history (Vincent et al. 2020): jet grouting ground improvement in the tunnelling zone preceding SEM excavation. Delve Underground completed the concept and tender designs for the ground improvement and related project specifications packages.

While not as yielding as Coode Island Silt, Fishermens Bend Silt is a low-strength material. Shaft excavations the size of the UCS and SIS shafts were expected to induce considerable strain and deformation in the material, leading to the potential for hydraulic fracturing of the shaft base and instability. As this was a significant construction risk, a jet-grouted base plug of 3.5 to 4.5 m thick was incorporated in the design of both east bank shafts.

2.2 *Detailed design*

Menard Oceania was appointed by the principal contractor, John Holland, to carry out the detailed design and construction of the ground improvement works—namely, the grout plugs at the base of the UCS and SIS shafts and a treated ground block along the tunnel alignment with dimensions of 7 m high by 7 m wide by 23 m long. The jet grouting specifications required a maximum 1.0 x 10^{-7} m/s hydraulic conductivity, minimum 1.5 MPa unconfined compressive strength at 28 days, and minimum 250 MPa elastic modulus be achieved (Menard Oceania 2022).

The treated ground block was planned to be constructed by overlapping 1.9 m nominal diameter vertical jet grout columns. However, an abandoned diversion sewer traversing over the connection tunnel at less than 1.5 m clearance to the excavation line introduced significant complication and risk to the design and construction of the treated ground block. For the ground improvement works to maximise the extent of treated ground at the underside of the diversion sewer, 2.4 m nominal diameter inclined jet grout columns were adopted. While the risk of a small, potentially untreated soil zone in the tunnel crown area remained, as shown in Figure 1, this construction approach minimised the risk.

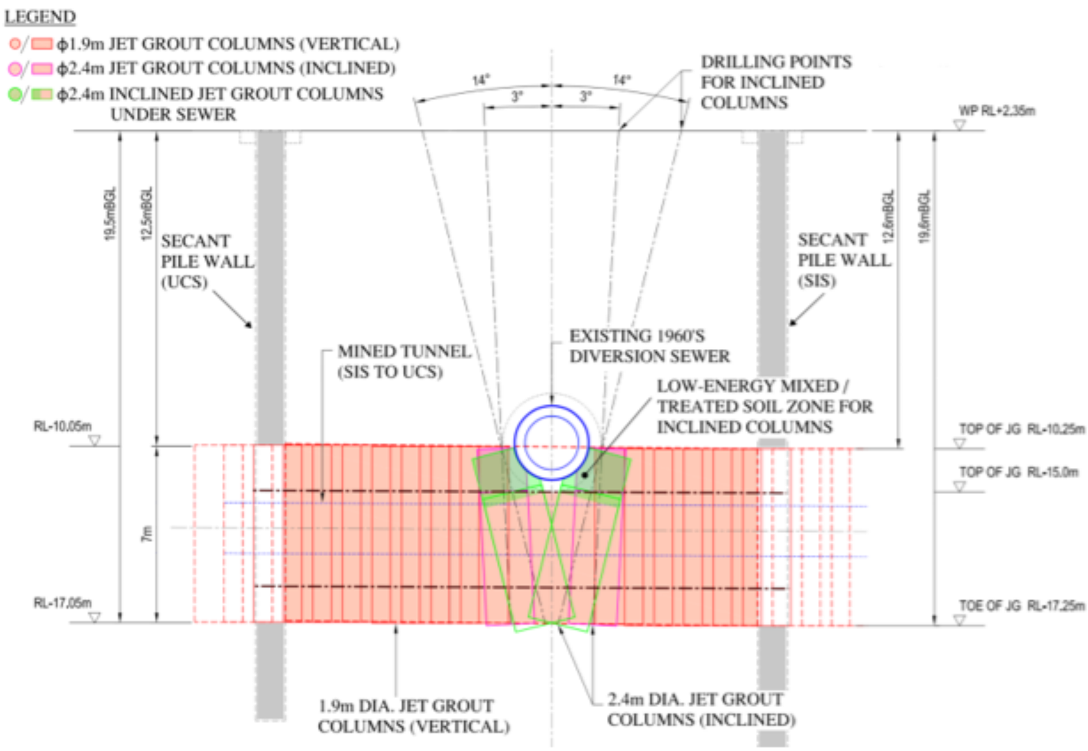

Figure 1. SEM tunnel ground treatment block with inclined jet grout columns (from Menard Oceania 2022).

Consequently, Delve Underground's SEM tunnel temporary support design accounted for two scenarios: (1) fully treated ground and (2) major zones of partially or untreated ground. Design calculations demonstrated that the fully grouted ground mass was generally self-supporting, and only a 100 mm layer of shotcrete, designated support type I, was needed for kinematic support of potential ground wedges. Conversely, the partially treated ground mass retained, to a lesser degree, the risks associated with excavation in soft soil, and accordingly, support type II addressed these risks with pre-support in the form of 6.0 m long steel face dowels at 750 mm spacing, or 6.0 m long hollow steel spiles at 200 mm spacing, with a passive support system of steel sets at 1.0 m spacing with a 200 mm layer of shotcrete. During the construction phase, the contractor added an option where light gauge steel channel-section lagging could be added above the steel sets in support type II to control any potential running ground.

2.3 *Construction*

Because of the uncertainty in the ground improvement achieved under the sewer, the project's success relied on the observational method, in which the relevant support type to be installed in the next excavation advance is selected from a predesigned toolkit of engineered support systems that address the possible geotechnical risks (Peck 1969). Hence, the support type selection (e.g. I-II) is based on observations of the ground conditions encountered during probing and excavation.

Production of jet grout columns began following a test program to adjust equipment and material parameters (e.g. nozzle pressure, water/binder ratio, etc.), which provided evidence of achieving design parameters and initial quality control requirements. Jet grout columns were installed in an overlapping hexagonal pattern. SEM tunnel excavation, with continual forward probing, began from the SIS shaft. Support type I was installed between chainages 0–4.5 m and 8.0–21.0 m measured from the SIS breakout, whereas support type II was installed between chainages 4.5–8.0 m. Further details of construction methods and observations can be found in Kaese and Shafee (2024) and Hubaut et al. (2024).

3 TUNNEL DESIGN

3.1 *Soil-structure interaction analyses*

Given the complexity of the design problem, a three-dimensional (3D) soil-structure interaction numerical analysis was created using FLAC3D to better understand tunnel excavation and support behaviour through the jet-grouted block and the potential for non-treated or partially treated ground underneath the abandoned sewer. The UCS and SIS shafts, abandoned sewer, and connection tunnel were incorporated in the 3D analysis, with the general construction sequence of constructing the abandoned sewer, followed by resetting the displacements to zero, installing secant piles and jet grout for shaft base plugs and SEM tunnel treated zone block, excavating both shafts, breaking out from the SIS shaft, and constructing the SEM tunnel through to break in at the UCS shaft. Figure 2 shows the 3D analysis components as well as the 7 m x 7 m x 23 m jet-grouted block (created by vertical jet grouting columns) for the connection tunnel and a potentially untreated or partially treated zone.

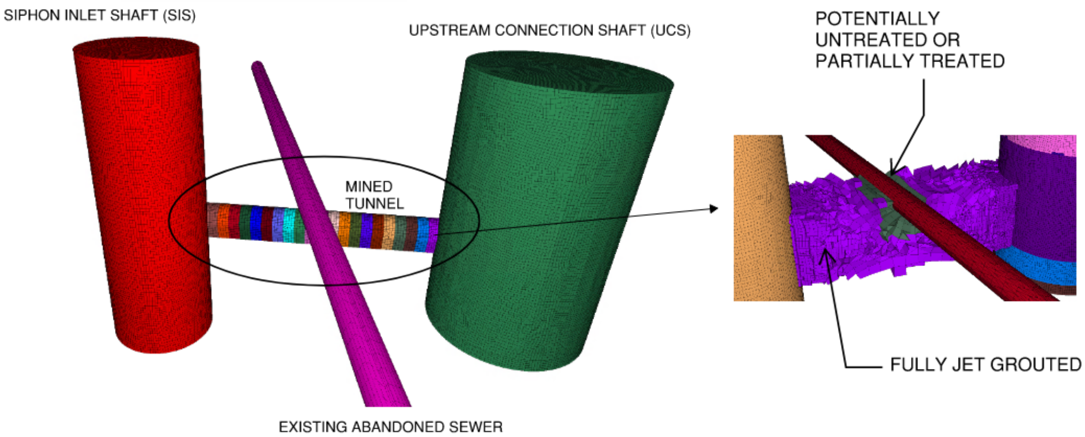

Figure 2. FLAC3D analyses with anticipated ground conditions around the connection tunnel.

Initial analysis was carried out assuming an untreated Coode Island Silt zone around and beneath the abandoned sewer extending to about 1.0 m from the abandoned sewer extrados (see Figure 2). An elastic constitutive model with 150 MPa drained modulus (conservatively assumed to be less than jet grout design value) was assigned to fully treated jet grout block, and a plastic-hardening model with Mohr-Coulomb failure criterion was assigned to Coode Island Silt zone (see Section 1.3 for recommended geotechnical design parameters). Results from the initial analysis indicated tunnel instability with very large ground strains and deformations around the excavated opening beneath the abandoned sewer. This was expected, given that Coode Island Silt does not have sufficient shear strength to be self-supporting, even temporarily. Thus, inclined jet grout columns were recommended and included in the jet grouting program (see Section 2.2) to treat any material in the vicinity of the abandoned sewer.

In an updated analysis, it was assumed that Coode Island Silt zone around and beneath the abandoned sewer is partially treated via the addition of inclined jet grout columns. A conservative approach was adopted in predicting geotechnical design parameters for the partially treated Coode Island Silt by assuming that the stiffness of the natural soil is unchanged, a cohesion increase of 30 kPa and a 15% friction angle increase. This assumption was to be verified by observation and monitoring during the construction of the tunnel. This numerical analysis was performed adopting support type I in the fully treated zone and support type II in the anticipated partially treated zone, as shown in Figure 3.

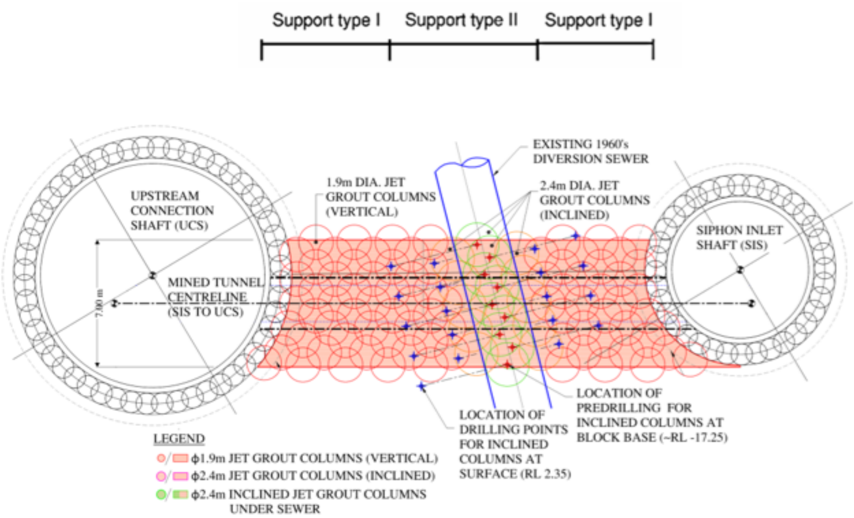

Figure 3. Different support types incorporated in the FLAC3D analysis.

3.2 *Analysis results and field observations*

Numerical analyses suggested that in the support type I fully treated zone (with vertical columns), tunnel deformations would be negligible and maximum principal stresses would be less than the factored unconfined compressive strength of the jet-grouted material. However, the analyses predicted that in the support type II partially treated zone (with inclined columns), despite the passive steel sets and shotcrete being within capacity, approximately 20 mm of tunnel convergence could be expected at the crown beneath the abandoned sewer. Therefore, these were the most critical tunnel advance cuts and were to be monitored carefully during construction. Figure 4 shows the predicted vertical deformation at the final stage of SEM tunnel construction, with the lower bound assumption of a partially treated zone extending 1.0 m beyond the abandoned sewer extrados.

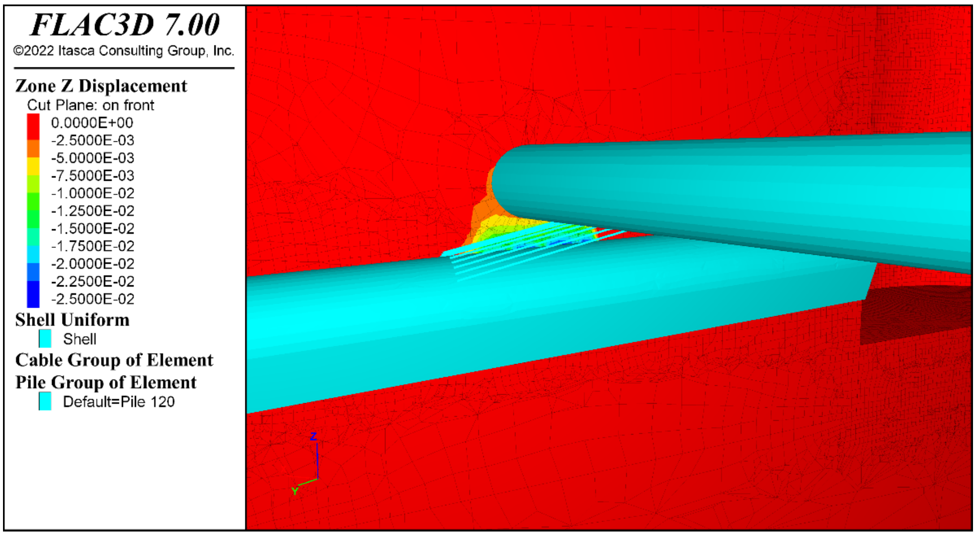

Figure 4. Vertical deformation contours (metres) after SEM tunnel construction.

During construction, it was observed that the ground zones beyond the abandoned sewer (support type I zones shown in Figure 3) were fully treated, with only minor (less than 5 percent of the exposed face) untreated Coode Island Silt inclusions being noted. Tunnel construction in this zone was completed with smooth cut profiles, negligible overbreak, and no notable challenges. This observation correlated well with design analyses results. However, an interesting on-site observation was that the ground treatment around the sewer was successful: the extent of the partially treated zone around and beneath the abandoned sewer was notably less than the 1.0 m extent design assumption affecting about four to five 1.0 m advances. The semi-treated zone was limited to the two cuts directly beneath the sewer centreline. Field observations at these cuts showed that about 15 to 20 percent of the exposed face was composed of untreated inclusions, primarily concentrated in the crown. Figure 5 shows examples of two tunnel face conditions for each support type.

In-tunnel convergence monitoring was not conducted during construction due to space limitations and confidence in design. However, surface movements were monitored above the tunnel during construction and marginal (near zero) settlement was recorded, which was in line with numerical analysis results.

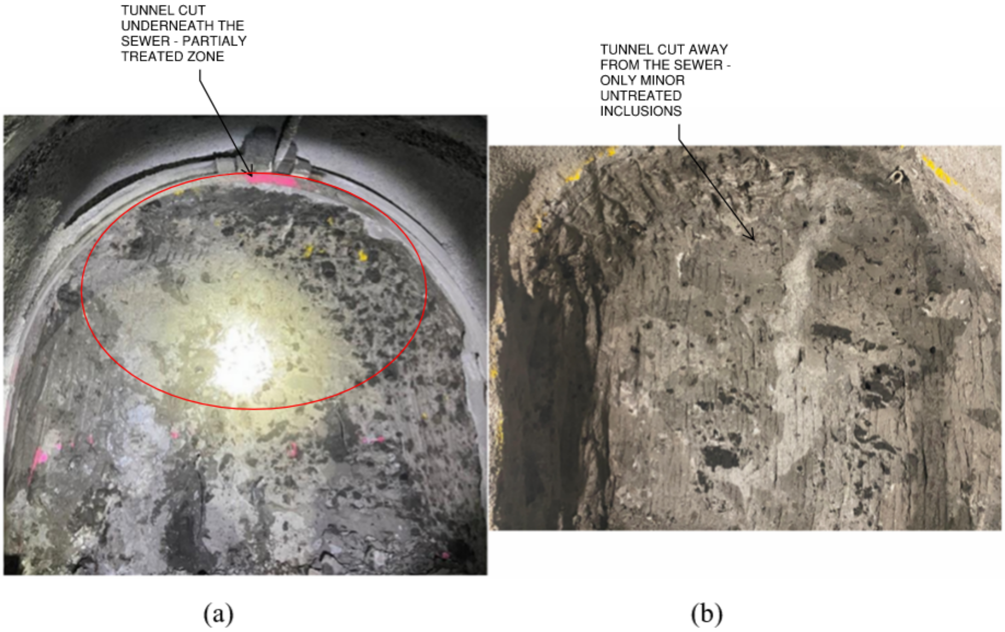

Figure 5. Example of tunnel face conditions from (a) support type II zone and (b) support type I zone.

3.3 *Numerical analysis of actual partially treated zone*

A post-construction numerical analysis was performed with a modified extent of partially treated zone, limited to a V-shaped area just beneath the sewer based on field observations, as shown in Figure 6. Analysis results suggested lesser deformations in the partially treated zone and lower structural demands on the support elements, as seen in Figure 7. Unfortunately, a detailed numerical analysis was not possible to estimate equivalent shear strength properties of the partially treated zone due to a lack of deformation monitoring while excavating underneath the sewer.

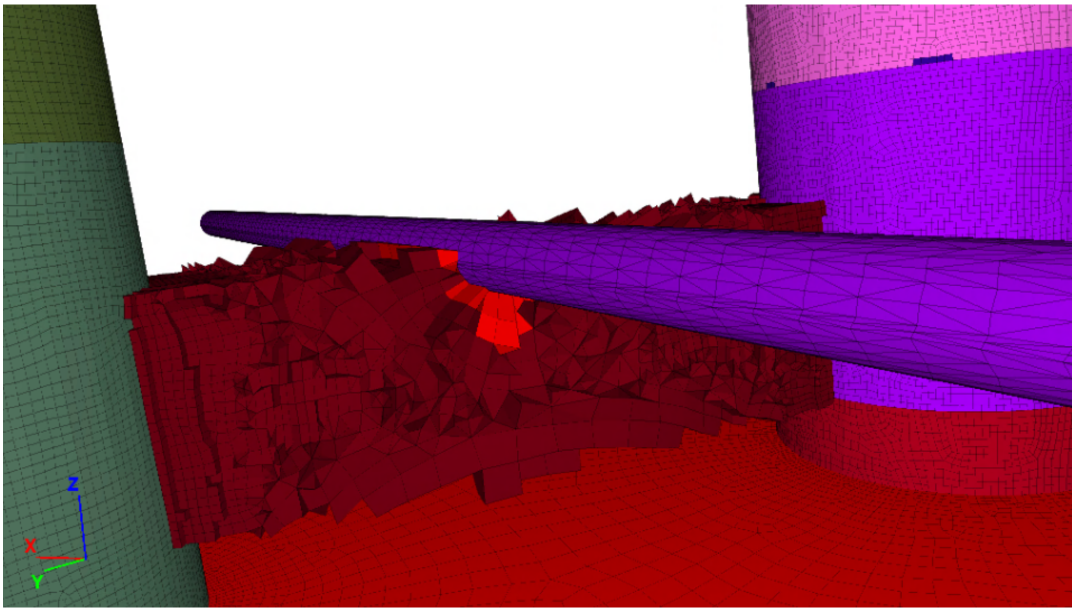

Figure 6. Numerical analysis of SEM tunnel construction with observed partially treated zone during construction.

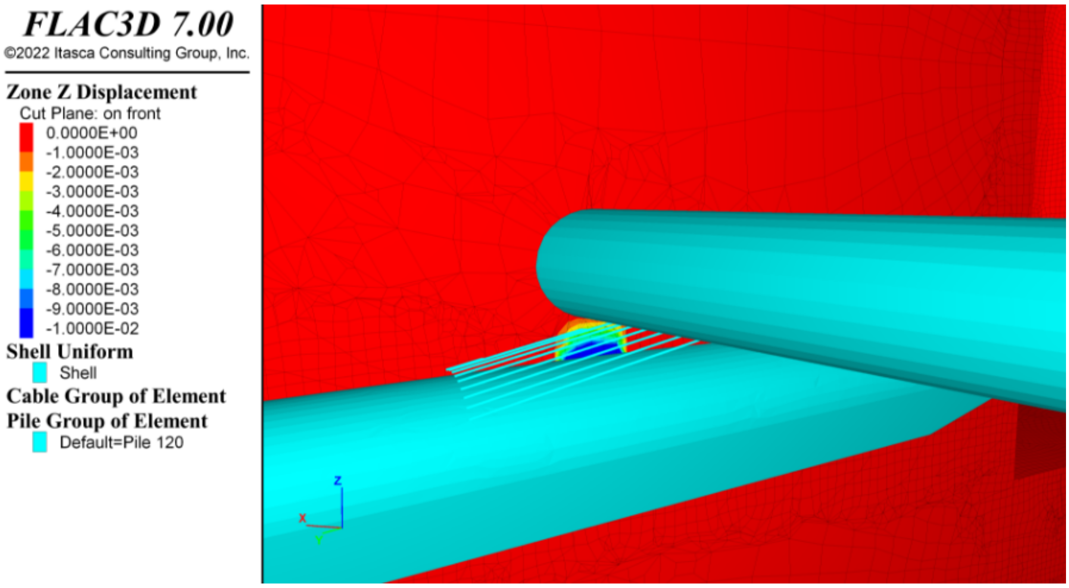

Figure 7. Vertical deformation contours (metres) after SEM tunnel construction with observed partially treated zone during construction.

4 CONCLUSION

The Hobsons Bay Main Duplication upstream connection tunnel stands as one of the pioneering projects in Victoria, successfully combining soft soil ground improvement using jet grouting with subsequent SEM tunnelling through the treated ground. Numerical analyses during the design phase and construction observations confirmed that the ground improvement works significantly reduce the risks of tunnelling through saturated, highly compressible soils, even when passing just 1.5 m beneath an existing sewer through partially treated ground. While observational methods adopted in this project successfully managed potential geotechnical risks, the project could have benefited by adding extra support types to the design, assuming a variety of scenarios for the partially treated zone and potentially reducing the project's tunnel cost.

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