Efficient design in the Alkimos intake and outfall tunnels

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ABSTRACT: For the first time in Perth segmentally lined intake and outfall tunnels have been adopted for a desalination plant: the Alkimos Seawater Desalination Plant, which is currently under construction. These tunnels are also the first segmentally lined desalination intake and outfall tunnels in Australia to be predominately in soft soils. The segmental linings posed a number of design challenges that involved design, construction, and operational considerations. These included setting a diameter and selecting an appropriate alignment. These decisions were constrained by a need to provide sufficient space for tunnel logistics and safety as well as hydraulic requirements, balancing minimum cover with a need to minimise intervention pressures, as well as the design challenges of managing significant internal pressures and significant future regrading and development on the land above the tunnel. The design also had to support a tight procurement schedule that saw the first tunnel being launched just over a year after contract signing. This paper describes some of the constraints that led to segmentally lined tunnels being selected and then describes how the design and construction teams worked together to address the challenges and provide a robust, economical, constructible and safe design.

1 INTRODUCTION

1.1 *Project Overview*

The Alkimos Seawater Desalination Plant (ASDP) Project (The Project) will contribute significantly to the Government of Western Australia's vision for Perth as a liveable, waterwise city and respond to several water supply and demand drivers, including:

- A continuing and long-running declining rainfall trend
- A reduction of inflow volume to Integrated Water Supply Scheme (IWSS) dam network
- A 30GL/a reduction in groundwater allocation from the Gnangara Mound in 2028
- A projected 1.3 million population increase and an estimated 125 billion liters per year increase in potable water demand by 2035.

Located in the high growth area of Alkimos to the North of Perth, the Project includes the design, construction, operation, and maintenance of a new desalination plant equipped for 158ML/d (50GL/a) during stage 1, and future proofing for an additional 158ML/d (50GL/a) during stage 2. The scheme also includes the Eglington Groundwater Scheme (GWS), providing an additional 4.9GL/a, or 18ML/d.

The Alkimos Seawater Alliance (ASWA) has been commissioned to undertake the design and construction (D&C) works for the ASDP. The ASDP is proposed to have the following offshore and onshore elements for the seawater intake and brine outtake structures.

- 2.5 km seawater intake tunnel with vertical risers and intake structures on the sea floor.
- 4 km brine outfall tunnel with vertical risers and outfall diffuser structures on the sea floor.

- Seawater Intake Pumping Station shaft (SWIPS), comprising Onshore Intake, Outfall and Pumping Shaft/ combined into a single structure. This shaft/s will serve to launch the TBMs and be the permanent water intake, outfall, and pumping shafts.
- Main Onshore Desalination Plant.

Both tunnels will be installed as segmentally lined sub-sea tunnels using slurry TBMs. Pipe jacking was not considered feasible for the required length. Trenching was rejected due to significant terrestrial and marine environmental impacts, as well as poor previous local experience installing trenched pipe in the challenging local sea state.

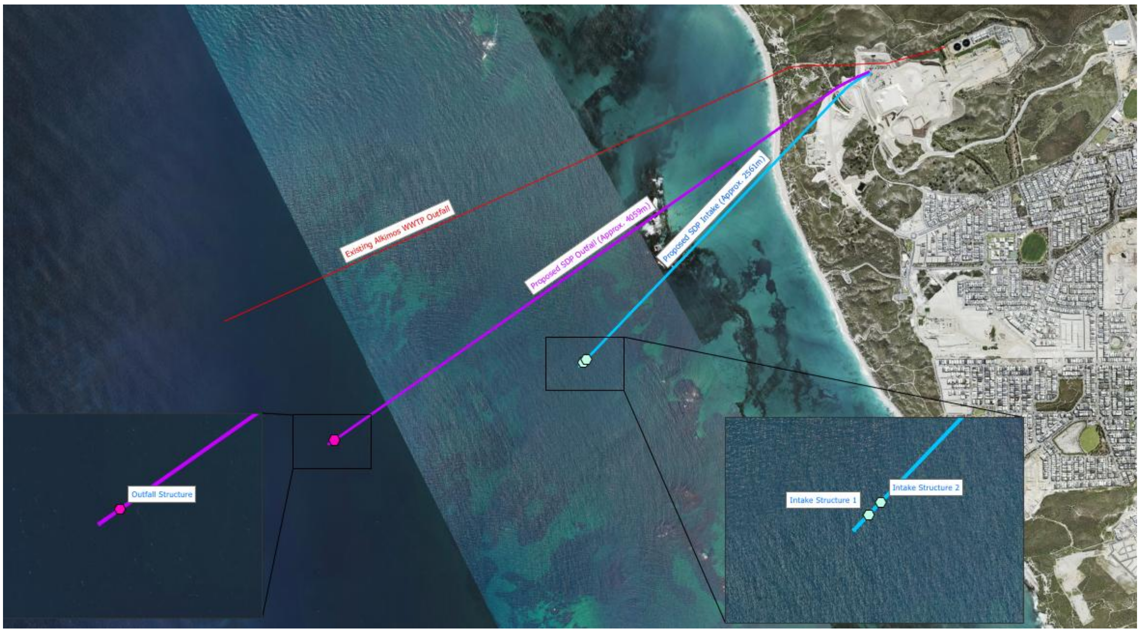

Figure 1. Location of Alkimos Seawater Desalination Plant

1.2 *Functional Requirements*

The TBM tunnel internal diameter (ID) 3.505m is driven by construction stages and space proofing rather than overall hydraulic performance, considering the system hydraulics could manage with a tunnel internal diameter of approximately 2.8m. The key driving construction considerations are.

- To provide the access necessary for the TBM operation and provide sufficient space to run the tunnel trains safely and efficiently.
- Space proofing to dictate the internal diameter of the tunnel for safe access/egress and construction, including ventilation and lighting requirements and to comply with current legislation.
- Providing sufficient space for two trains to pass in the tunnel, and for a train to pass the slurry booster pumps

1.3 *Outfall (Brine Diffusers) System and Requirements*

The brine system primarily consists of the outfall shaft, the tunnel, the riser and the brine diffuser. The brine diffuser is designed with multiple ports to diffuse the brine into the surrounding seawater to meet a salinity of within 0.8 ppt above ambient salinity at a maximum of 100m from the dis-charge point.

Internal water pressure in the outfall tunnel is higher than the ambient seawater pressure due to hydraulic energy losses in the diffuser, riser and tunnel. The majority of the energy losses in the brine system occur at the brine diffuser itself due to the jet velocities required to achieve minimum dilution rates. Thus, diffuser design and configuration have a significant impact on the internal tunnel pressures.

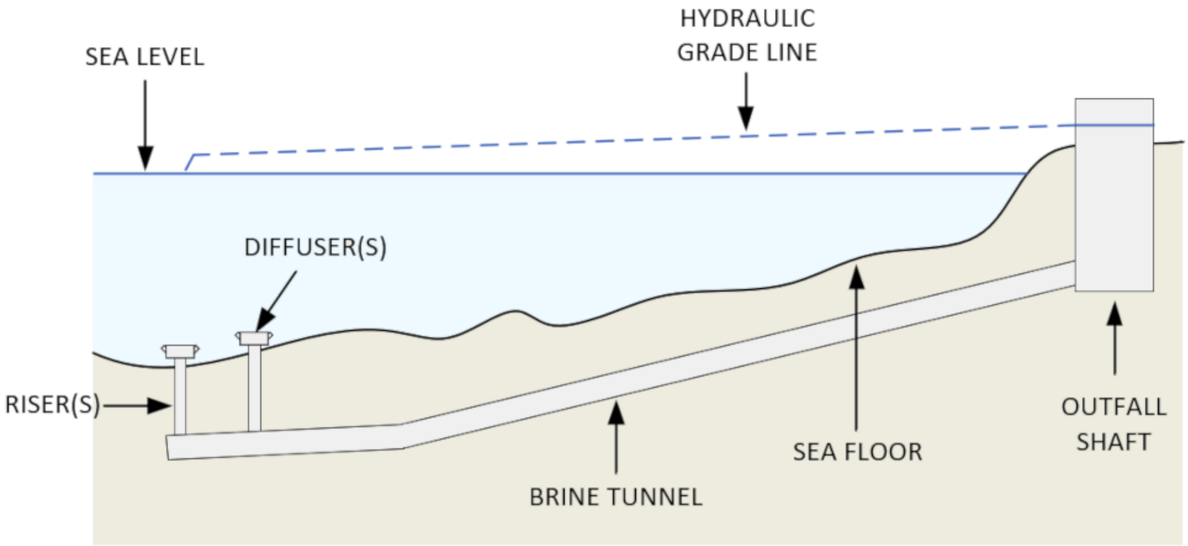

Figure 2. Brine outfall system arrangement

2 DESIGN CHALLENGES

2.1 *Ground Conditions*

The primary engineering geological units encountered along a tunnel face including Tamala Limestone, Ascot Formation, and TQ Sands.

- The Tamala Limestone is of Quaternary geological age underlying the Marine Sediments, three sub-units relating to the degree of leaching and engineering properties varied from Fresh to Residual Soil.
- The Ascot Formation is of Tertiary geological age underlying the Marine Sediments and Limestone. Four sub-units have been determined: Mostly rock strength and cemented materials, mostly soils but with some cemented layers, Variable sand layers and Silt / Siltstone materials.
- The TQ Sands are of Tertiary geological age and only encountered at the outfall tunnel, underlying the Ascot Formation. The unit comprises of predominantly coarse grained (i.e. non-cohesive) materials.

Generally, the Intake Tunnel and the Outfall Tunnel pass underneath Alkimos beach and vegetated sand dunes onshore, and thereafter underneath marine sediments, coral reefs, and ocean water. Both tunnels will traverse the Tamala Limestone early in the drive and pass into the Ascot Formation, which is expected to have lower permeabilities and fewer solution features. From CH2025, the outfall tunnel will pass through mixed ground conditions comprising of the Ascot Formation within the upper portion of the tunnel, and the TQ Sands within the lower portion. Figure 6 presents the geological section along the outfall tunnel alignment.

2.2 *Internal Water Pressure*

One of the unusual challenges of outfall tunnels is the need to design for internal water pressures that exceed the external pressures. In this scenario the tunnel risks going into tension, which requires special features to resist tension such as those described in Harding et al (2014) and Aradas et al. (2016):

- Resist net tension forces by relying on the dowels as illustrated in Figure 3
- Actively resist the tension with permanent bolts and conventional reinforcement

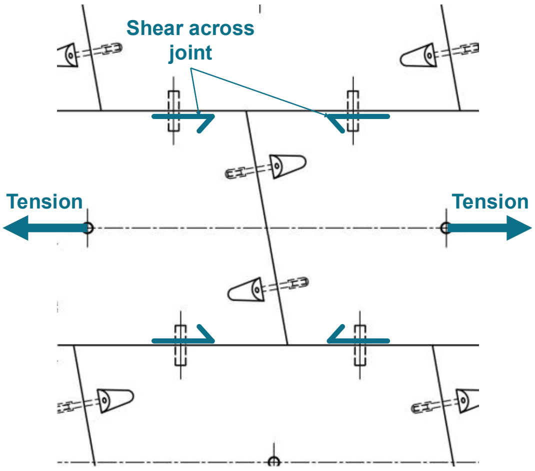

Figure 3. Dowels in the lining acting as a tension transfer mechanism

Using the dowels for the Alkimos project was considered appropriate for resisting tension movements and preventing collapse in an accidental situation where nozzles were blocked and the pressure in the tunnel high, as this scenario was unlikely to occur over the life of the project. However, for normal operation the pressure could change from net tension to net compression several times a day, resulting in the joints opening and closing around 100,000 times over the design life of the project. Under this number of cycles it was possible that the grout/soil/joint interface would deteriorate, leading to loss of structural integrity. Actively resisting the tension by structural means would be difficult due to the aggressive brine conditions in the outfall tunnel. It would also be costly due to the complexities of the connection system and additional thickness required to accommodate two layers of conventional reinforcement.

Therefore, the most efficient design would rely on the effective ground pressures acting on the tunnel to provide additional pressure to resist the tension. Estimating this ground pressure can be difficult because most analytical methods for establishing the ground loads on the tunnel tend to overestimate the ground loads, as this results in higher hoop loads and bending moments and a more conservative design. However, for outfall tunnels this can lead to unconservative designs: where the analysis overestimates the load and indicates there is sufficient effective stress to resist the ground loads but in reality there is not.

To ensure that the load was not over-estimated, analysis was undertaken to establish the minimum ground load on the lining using a Plaxis 3D model that simulates the TBM face pressure, annulus pressure and grout pressure to establish the loads in the lining following TBM construction. Ground loads were expressed as a proportion of the surplus effective stress above face pressure defined as:

$$Restrained\ relaxation = \frac{effective\ pressure - face\ pressure}{insitu\ pressure - face\ pressure}$$

Expressing the relaxation this way allowed a more accurate lining load to be obtained in Plaxis 2D by applying the face pressure as an all round pressure to the excavated annulus and then relaxing the lining by the required percentage. This approach was validated by comparing the 2D models to 3D, for critical sections and load scenarios, while allowing a large number of other scenarios and sections to be evaluated, including a comprehensive sensitivity analysis.

As a result of the analysis the minimum effective load on the lining was 48 kN/m under the worst operational load, providing just enough axial force to maintain gasket pressure and prevent the joint opening.

2.3 Brine Diffuser Configuration

2.3.1 *Type of Diffusers*

Brine diffuser ports may be arranged along a linear diffuser or clustered radially around one or more rosette diffusers. These potential configurations are shown visually in Figure 4. There are examples of each type of diffuser in Australia – Sydney, Melbourne and Adelaide's desalination plants use rosette diffusers and Perth's other desalination plant uses a linear diffuser.

Research by Abessi and Roberts (2014) shows that for both linear and rosette diffusers, the ports and risers should be adequately spaced to avoid individual jet merging. If jet merging occurs, the effective dilution is reduced. Where jet merging cannot be avoided, Roberts proposes dilution reduction factors to account for the reduction in dilution as a result of jet merging. For rosette diffusers, it has been found by Abessi et al. (2016) that there is some jet merging for all rosette diffusers tested, so a dilution reduction factor is recommended to be applied to rosette diffusers depending on the number of ports – from a 27% reduction for 4 ports to 50% reduction for 12 ports (Roberts, 2018). As a result, higher port velocities and higher energy losses are required for rosette diffusers to meet the same dilution criteria compared to a linear diffuser with adequately spaced ports.

2.3.2 Rosette vs linear diffuser outcomes for the Alkimos Desalination Project

The tender design for the Alkimos Desalination Project proposed two rosette diffusers each with 7 ports. Subsequently, during design development, a linear diffuser was investigated for its ability to achieve improved dilution at lower port velocities. The two designs are compared in Table 1 below.

Design flow case results for internal tunnel differential pressure for both the linear and rosette diffuser designs are shown in Figure 5 below. The rosette diffuser design resulted in significantly higher port differential pressures than the linear diffuser design. This is primarily due to the required application of a dilution reduction factor of 0.64 for a 7-port rosette design, which means that smaller ports with higher velocities are required to achieve the same dilution.

For the rosette diffuser design, several flow cases resulted in differential pressures exceeding the maximum for the tunnel lining of 2.7m (27 kPa net internal pressure). Additionally, higher port velocities have been associated with shear mortality of marine micro-organisms (Roberts, 2018), so the lower velocities from the linear diffuser present an environmental benefit.

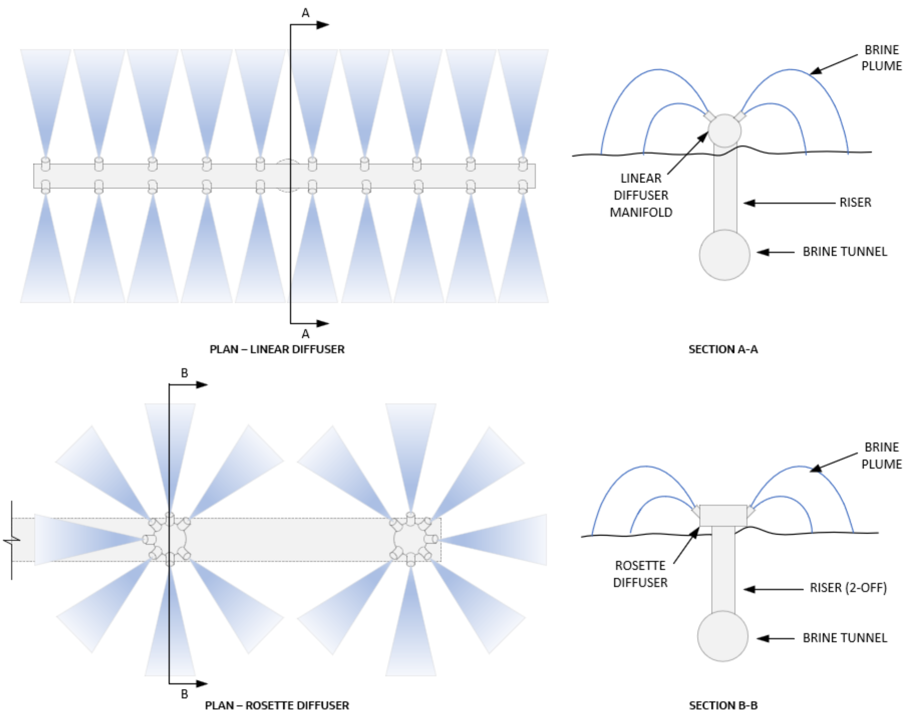

Figure 4. Type of Brine Diffusers

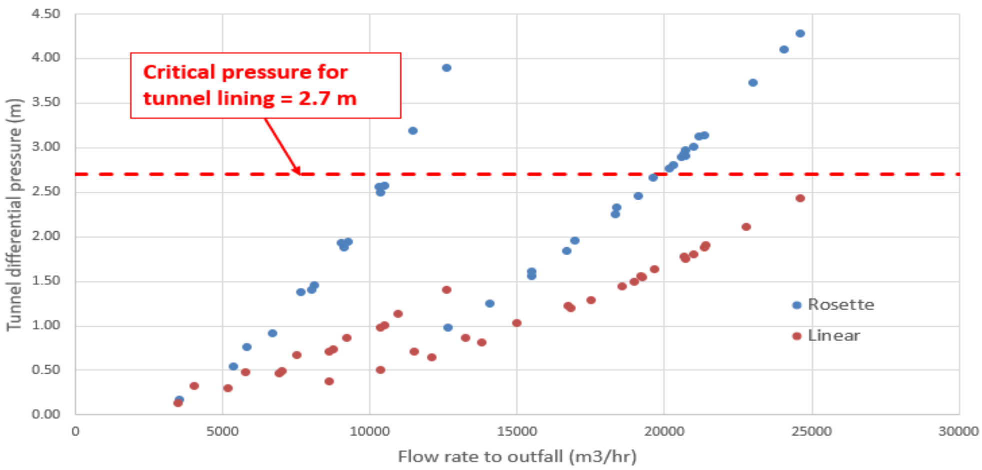

Figure 5. Tunnel differential pressure for rosette and linear diffuser designs

Table 1. Rosette vs liner diffuser design parameters

Parameter	Rosette diffuser design value	Liner diffuser design value	Unit
Number of ports	14	20	Nos.
Port internal diameter	270	308	mm
Port angle from horizontal	40	45	degrees

3 ALIGNMENT AND TBM SELECTION

The alignment was selected to provide the best possible conditions for productive operation of the TBM, while minimising maintenance. The main criteria were:

- Avoid the Tamala limestone as far as possible due to the risk of high permeability/voids that could make interventions very difficult
- Avoid the potentially contaminated soil in the Osborne formation as far as possible
- Provide sufficient cover to prevent blowout
- Avoid local low points if possible

The TBMs launch into the Tamala Limestone, so to minimise the length of tunnel in this deposit the TBMs immediately decline into the Ascot formation. Once in the Ascot formation they follow a very shallow grade (0.35%) to the intake or outfall location, maintaining sufficient cover to prevent blowout.

When subject to internal pressures it can be tempting to make the alignment deeper to secure more axial load and improve tension resistance. However, for Alkimos this would result in very deep tunnels (over four bar water pressure), making interventions longer and more hazardous due to the increased pressures. Furthermore, Aradas (2016) showed that deeper alignments can actually result in lower effective ground pressures on the tunnel due to higher ground strengths. The same was found with the Alkimos alignment, where one of the critical sections was in a full face of limestone where the ground was largely self-supporting. Therefore taking the TBM below the Ascot formation was ruled out. The alignment of the outfall tunnel is outlined in Figure 6.

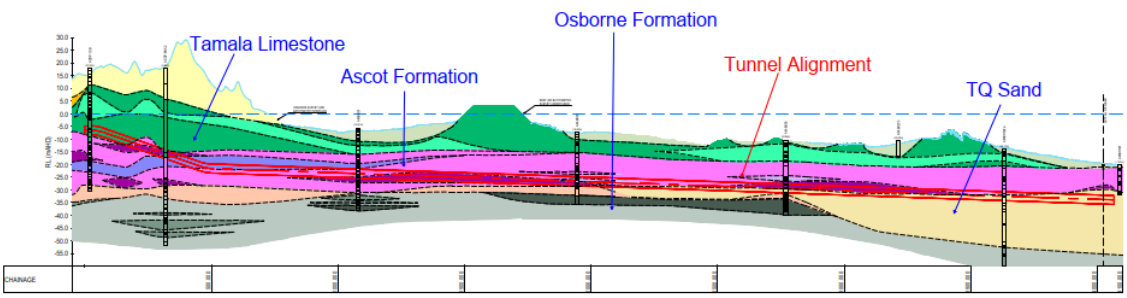

Figure 6. Outfall tunnel alignment (Intake tunnel is similar but shorter)

4 DESIGN SOLUTIONS

4.1 *Ring Configuration*

A tapered universal ring type with internal diameter of 3505mm and external diameter of 3905 mm with lining thickness 200mm and a nominal ring length of 1300mm was adopted. There are a total of 6 segments of each ring. The circumferential joints are connected by 12 Nos of dowels, distributed in an alternating pattern of 28° and 32° which repeats every 60°. This differs from the traditional uniform 30° pitch and it only permits 6 build positions, spaced at 60°.By placing the 28° gap in the middle of the segment on the trailing edge and between the joints on the leading edge, the joints must be placed between the dowels of the previous ring as illustrated in Figure 3. Building the ring with the joints in the same location is not physically possible as the dowel recesses do not align as shown in Figure 8. This ensures the dowels can assist in resisting the tension required, as described in Section 2.2.

The radial/longitudinal joints are connected by 2 Nos of bolts, distributed equally. The radial and circumferential joints are flat joints. The taper was designed as +/- 10 mm based on minimum horizontal radius of 600m and corresponding theoretical design radius of 254m. The segments are equipped with a gasket groove for an elastomeric waterproofing gasket on the extrados side of the joint contact face. Figure 7 below presents the ring configuration viewed from the trailing edge.

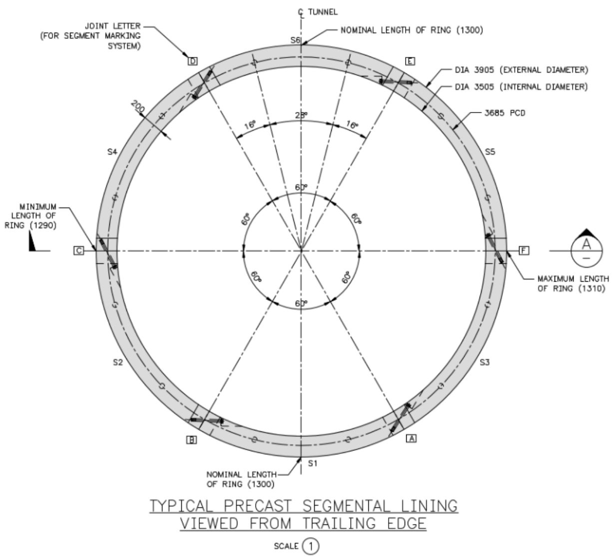

Figure 7. Ring configuration

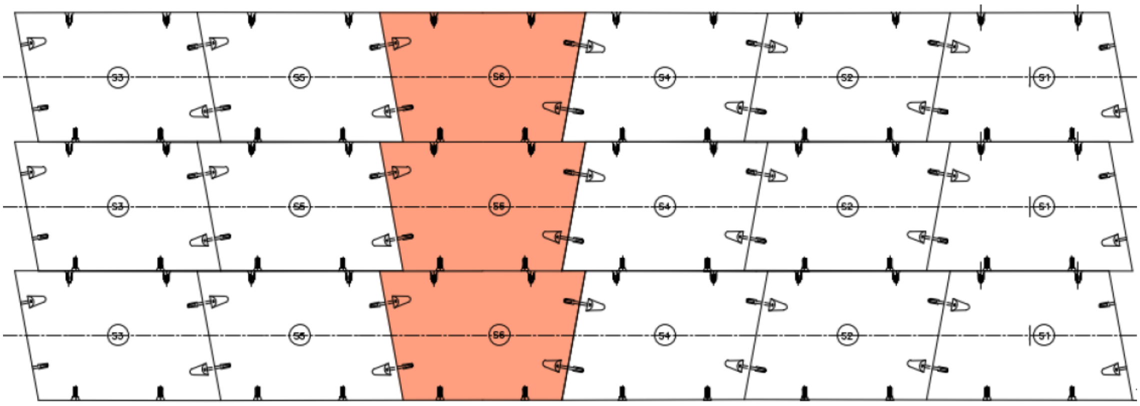

Figure 8. Segment built to the same orientation: dowel locations do not match (not physically buildable)

4.2 *Lining design*

The 2D and 3D models mentioned in the sections above on internal pressure were also used to calculate the moments and axial forces in the lining. Some sections subject to significant cut and fill post tunnel construction to facilitate future development. This generated significant moments and made it necessary to place restrictions on the amount of cut and fill in some locations.

The joint strengths in the deepest sections were at the limit of fibre reinforced joint capacity. In order to prove the joint capacity a novel method for calculating joint eccentricity accounting for both ground loads and build tolerances as described by Harding et al. (2025) was used.

5 CONSTRUCTION CONSIDERATIONS

The intake and outfall bored tunnel construction activities are on or near the critical path and need to be executed productively with minimum associated risks along the entire alignment and the interfaces with other underground structures. A shallow alignment improves risers, tunnel, and shaft constructability. The supports the efficient erection of the lining while still meeting the stringent requirements on accuracy of build as follows:

- Use of a six-segment trapezoid/parallelogram ring, which is proven to build quickly and accurately due to the inclined joints and evenly sized segments.
- Use of dowels on the circumferential joint, which help align the rings while eliminating the need for bolts and the time required to install them, as well as being configured to render undesirable ring build combinations unbuildable.
- The placement of ferrules evenly around the rings provides fixing points for tunnel services, eliminating the need for drilling into the concrete and associated health hazards.

6 CONCLUSION

The design of the segmental lining for the Alkimos intake and outfall tunnels offers an economical solution as summarized below:

- The outfall tunnel is subjected to tension as the internal water pressure acting on the lining exceeds the external pressure. The most efficient design approach was considered by applying minimum face and grout pressure to ensure effective pressures, and then minimizing the pressure losses in the outfall system to minimize net internal water pressures.
- Estimating the ground loads using analytical methods overestimates the ground loads and leads to unconservative design, matching previous research.
- Distributing circumferential dowels in an alternating pattern of 28° and 32° which repeats every 60° can restrict building the rings with joints in the same locations, ensuring the dowels can assist in resisting the tension required in the accidental case.

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