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Tunnel and marine nearshore ground investigation for Alkimos seawater desalination plant, Western Australia

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ABSTRACT: The Alkimos SeaWater Alliance (ASWA) is designing and constructing Stage 1 of the Alkimos Seawater Desalination Plant (ASDP). This paper describes the 2024 nearshore geotechnical investigation for ASDP Stage 1 and three historical campaigns (2021-2023). It details the groundbreaking methods and marine surveys used for assessing the seabed and underlying geology for the nearshore tunnel alignments. This paper also reviews and compares the success of the geotechnical investigation methods adopted in terms of defining the subsurface geology and interfaces between geological units, obtaining representative samples for laboratory testing, identifying geotechnical risks associated with tunnel design and construction. Challenges unique to nearshore investigations are discussed, including sea state, weather, tides, ecology, and vessel operations. The paper also addresses the complexities of designing a nearshore investigation scope while balancing value for money and comprehensive data collection.

1 INTRODUCTION

The ASDP, located 40 km north of Perth, will deliver 50 GL of drinking water annually in Stage 1, with Stage 2 adding another 50 GL. The nearshore components include the Seawater Intake Tunnel (SIT), Brine Outfall Tunnel (BOT), two Seawater Intake Riser (SIR) structures, and a Brine Linear Outfall Diffuser (BLOD) structure (subject to state environmental approval). This paper focuses on the tunnels.

2 NEARSHORE STRUCTURES

2.1 *Intake and Outfall Tunnels*

The SIT and BOT are 2.6 km and 4.1 km long respectively (see Figure 1) and will be excavated using slurry Tunnel Boring Machines (TBMs) with a 4.185 m excavation diameter. Excavations will start from onshore at the temporary TBM access shaft, progressing seaward. The tunnels will be lined with steel fibre reinforced concrete segments (3.505 m Inside Diameter (ID), 3.905 m Outside Diameter (OD)). TBM shields will be sacrificed at drive completion. For the onshore section of the tunnel, it will be constructed between approximately 4.7 m and 20.6 m below the water table. For the offshore section of the tunnel, it will be constructed below the seabed where water depths below sea level range from 20.6 m to 32.2 m.

2.2 *Seawater Intake Risers and Brine Linear Outfall Diffuser*

Two SIR structures will convey seawater into the SIT. The proposed foundation system for each structure consists of four driven steel tubular piles (1050 mm OD, 40 mm Wall Thickness (WT)) with 8.95 m spacing. These piles extend above the seabed and connect to the SIR structure's head. A driven steel circular liner (3074 mm OD, 37 mm WT) will provide ground support for an1800mm ID Glass Reinforced Plastic (GRP) riser connecting to the SIT. Figure 2 illustrates this foundation system.

The BLOD diffuser expels brine from the BOT into the ocean. It consists of a 135 m long horizontal High-Density Polyethylene (HDPE) pipe supported by twelve driven steel tubular piles (1050 mm OD, 40 mm WT) spaced 10.0-10.5 m apart. Precast reinforced concrete ballast blocks are placed along the BLOD. A steel circular liner (3074 mm OD, 37 mm WT) provides ground support for an 1800 mm ID Glass Reinforced Plastic (GRP) riser connecting to the BOT and supports the precast outfall head joining the HDPE pipe sections. Figure 2 illustrates this foundation system.

Figure 1. Plan layout of Outfall and Intake Tunnel.

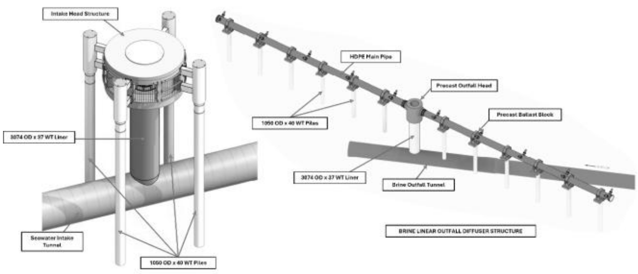

Figure 2. Intake Riser and Outfall Diffuser Structure.

3 GEOLOGY

The Alkimos site's surface geology is characterised by the Holocene Safety Bay Sand onshore, forming dunes up to 40 m AHD and 25 m thick, and Marine Sediments offshore, a variable layer of shelly sand and gravel up to 9.7 m thick. Both units are relatively recent formations, with the Safety Bay Sand continuing to develop today and the Marine Sediments subject to ongoing wave and current action.

Underlying these surface layers is the late Pleistocene Tamala Limestone, a widespread formation that creates the Spearwood Dune System and offshore reefs. This variably cemented carbonate rock mass, interlayered with uncemented sand bodies, is found beneath the Safety Bay Sand onshore and the Marine Sediments offshore, sometimes exposed as reefs.

The Tertiary Ascot Formation underlies the Tamala Limestone. It consists of carbonate calcareous materials with variable properties, likely representing shallow marine to lagoonal environments. Below this, along the outer part of the Outfall Tunnel alignment lies the informal late Tertiary 'TQ-Sand' unit (possible Rockingham Formation), situated between the Ascot Formation and the underlying Cretaceous Osborne Formation.

4 SEABED CONDITIONS

The marine area features discontinuous shallow reef networks parallel to the coastline, separated by deepening lagoons offshore. Reefs range from several metres above sea level to 18 m below sea level on parts of the outer reef, while inter-reef depressions reach depths of 25 m below sea level.

5 HISTORICAL NEARSHORE INVESTIGATIONS

5.1 *Phase 1 & 2 (2021)*

The Phase 1 and 2 marine investigations included both geotechnical investigations and geophysical surveys. The geotechnical investigation involved drilling six boreholes between 0.3 km to 2.0 km offshore in water depths of 3 m to 12 m. The boreholes were drilled to depths of 28.5 m to 37.7 m using a drilling rig mounted on a four-legged Jack-Up Barge (JUB). The investigation included soil and rock laboratory testing for material classification, strength/stiffness properties, Acid Sulfate Soil (ASS) and palynological assessment.

Geotechnical investigations were undertaken between 12 November 2018 and 8 March 2019. The boreholes were drilled using rotary mud-flush drilling rig. Borehole collars were established on the seabed with PW 140mm casing to stabilise the primary drill string against currents and waves. PW casing was also reamed downhole to stabilise boreholes at depth if required. Boreholes were advanced using PQ3 triple-tube diamond coring to retrieve soil and rock core samples for geological logging and laboratory testing.

The geotechnical investigation experienced logistical challenges due to operating the JUB in open-ocean swells and wind driven seas which resulted in substantial weather downtime.

Swell conditions resulted in standby events due to limitations associated with barge towing even though the investigation occurred during the Summer where swell conditions in Perth are typically smallest. Problematic swell conditions commonly persisted for days to weeks and impacted mobilisation, demobilisation, and transfer of the JUB to borehole locations. The variable bathymetry, shallow reef systems are thought to have increased swell conditions (wave height and steepness) associated with the Perth Metropolitan coastline.

Wind or wind-driven sea states also resulted in standby events again due to limitations of barge towing, however these were typically short durations in comparison to the problematic swell conditions. Wind conditions in the Alkimos project area were commonly associated with the ‘typical summer wind patterns’ experienced along the Perth metropolitan coastline, comprising offshore winds in the morning followed by strong onshore winds (sea-breezes) and increasing sea-states in the afternoon. As such, minimising the impact of wind was able to be managed more effectively than the impact of swell, with daily operations commencing at dawn to maximise the potential working hours available prior to the onset of coastal sea breezes.

The geophysical survey employed various techniques including Multibeam Echosounder (MBES), Side Scan Sonar (SSS), Sub-bottom Profiler (SBP), seismic refraction, electrical resistivity, and magnetometer survey covering an area from the coastline to 5.5 km offshore. MBES and SSS covered an area of about 8 km^2 with the remaining geophysical surveys covering about 30 km and 112 km along linear lines. The geophysical survey involved liaison with the Department of Primary Industries and Regional Development to coordinate with active lobster research. The study area is a marine habitat to the Western Rock Lobster with lobster pots present during the geophysical surveys.

5.2 *Phase 3 (2023)*

Phase 3 comprised a geotechnical investigation to address data gaps with the investigation focusing on acquiring geotechnical data along the proposed outfall tunnel alignment, 2.0 km to 3.5 km offshore, and at the outfall riser locations. Three boreholes were drilled, two near the proposed outfall riser location (3.5 km offshore) and one about 2.5 km offshore. Borehole depths ranged from 5.9 m to 26.4 m. Laboratory tests were carried out on the samples recovered and included classification tests, rock tests and ASS testing.

An assessment of alternative methodologies was carried out to identify drilling methods that were less susceptible to unfavourable weather and sea state. Methods assessed were a heave-compensated drillship, subsea drilling rig operated remotely from a support vessel (PROD) and subsea drilling rig operated by divers with support from the surface. Considering commercial, technical and logistical factors the subsea diver-operated drilling option was chosen. Initially a floating barge (TAMS9) was used to support operations, however the local metocean conditions and sea-state characteristics were found to be very challenging for operating the barge. The floating barge was demobilised, and a DP1-class supply vessel (Offshore Supplier) was used to support operations and with significantly improved operability in the metocean conditions.

Boreholes were drilled by TAMS utilising a subsea mud-flush drilling rig operated by commercial divers. Diving and drilling operations were supported from the barge TAMS9 and Offshore Supplier.

Drilling conditions were found to be very challenging most notably in the thick TQ-Sand deposits where borehole collapse, bogging/binding of the drill string and sand 'rushing-up the drilling rods' resulted in mechanical issues and slow progress. The geotechnical investigation was terminated early due to the slow progress (approx. 4m per day) and vessel availability.

5.3 *Phase 4 (2023)*

Phase 4 included both geotechnical investigation and geophysical surveys. The geotechnical investigation was carried out using a Portable Remote Operated Drill (PROD) for borehole drilling and Cone Penetration Testing (CPT) at three locations 2.6 km to 3.4 km offshore. Five boreholes were attempted, reaching depths of 11.9 to 46.03 m. The Normand Ranger, a 91 m long vessel with a draft exceeding 7.9 m, supported operations in wave heights up to 2.5 m and wind strengths of 25 knots.

The PROD involved remote operation from the vessel, with telemetry, power, and drilling fluids supplied via umbilical lines. Drilling techniques included wash boring, piston sampling, rotary coring, and CPT, adapted to ground conditions.

Geophysical surveys utilised Multi-Phase Echo Sounder (MPES) bathymetry, sidescan sonar, boomer SBP, Continuous Marine Seismic Refraction (CMSR), and Multi-channel Seismic Refraction (MCSR) profiles. Comparison with Phase 1 data showed relatively stable seabed conditions, with most areas showing less than 0.5 m variance. Rocky areas remained stable, while sandy areas exhibited some deposition or scour.

Boomer SBP and MCSR were moderately effective in correlating with certain geological formations, though distinguishing between Tamala Limestone and Ascot Formation proved challenging due to similar seismic characteristics and variability in material strength with depth, thus not providing sufficient resolution and reliability. CMSR provided potential correlations with in situ strength through p-wave velocity measurements, but once again the resolution was not always reliable.

6 DETAILED GEOTECHNICAL INVESTIGATIONS

6.1 *Phase 5 Investigations (2024)*

ASWA conducted a gap analysis to identify what further geotechnical investigations were required to inform detailed design. Detailed investigations were carried out to address data gaps, improve understanding of ground conditions, refine geological and geotechnical models, enable additional sampling and testing, support derivation of site-specific characteristic design parameters, and reduce geotechnical risk. The planning of the investigations considered the time of year where sea conditions were favourable, completed boreholes out of sequence targeting the critical intake and outtake structures and the commissioning of a JUB with variable leg length which suited a range of water depths.

6.1.1 *Method of Investigations*

6.1.1.1 Nearshore Boreholes

The geotechnical investigation was carried out from April 3 to May 16, employing an Edson 3000 rig mounted on a four-legged JUB. Nine boreholes were drilled to depths ranging from 26 m to 30 m below the seabed using PQ3 coring equipment. Adverse weather conditions led to the cancellation of two planned boreholes.

JUB positioning involved tow vessels to push the barge into position followed by lowering the JUB legs. The barge and drill rig's position were verified using onboard Differential Global Positioning System to ensure placement within 10 meters of the proposed coordinates. The barge was then jacked up to an operational height determined by the Barge Master, allowing sufficient air gap below the pontoons to accommodate anticipated tidal cycles and wave heights.

The drilling process began with lowering the casing just above the seabed and taking a deck-to-seabed measurement. Once the casing reached the seabed, PQ coring commenced using mud flush recovery. The boreholes were cased over the full depth of drilling.

Laboratory testing included classification tests, chemical tests, and rock testing (point load strength index, Uniaxial Compressive Strength (UCS), Cerchar abrasion, Brazilian indirect tensile strength).

Figure 3. JUB.

6.1.1.2 Geophysical Survey

The geophysical survey included MBES for bathymetry, SBP using a pinger, CMSR, and MCSR surveys. Additionally, a focused MBES and SSS survey was performed within a 200 m radius of the proposed riser locations.

7 INVESTIGATION OUTCOMES

7.1 *Boreholes*

The outcomes for the boreholes drilled as part of the 5 phases of investigations are described in the subsections below.

7.1.1 *Operational Challenges*

The ASDP intake and outfall tunnel drilling investigation faced significant challenges due to sea state, water depth variations, and presence of reef structures. The detailed investigation succeeded despite these obstacles, attributed to favourable sea state conditions, appropriate plant and equipment selection, effective team communication, and strategic flexible borehole planning. When the weather and sea state was poor, boreholes closest to shore were drilled within shallow water depths. When the weather and sea state were favourable, boreholes farthest from the shore were drilled in deeper water.

7.1.2 *Poor Sample Recovery*

Poor sample recovery was observed in several boreholes, particularly in the Ascot Formation, due to incompatibility between the rotary core drilling method and material properties. In both historical and detailed investigations, much of the Ascot Formation was recovered as carbonate/calcareous rock gravel, with possible matrix washout during drilling. This resulted in uncertain cementation levels and unreliable Rock Quality Designation (RQD) values, especially in poorly recovered zones. For the detailed investigations, where possible, materials in the Ascot Formation were assigned Duricrust Mass Grades as per AS1726:2017.

A high-level assessment of sample recovery across the five investigations is presented in Table 1, showing meters drilled and associated core loss. The use of a Jack-Up Barge (JUB) with a conventional drilling rig provided the lowest percentage of core loss (17% to 23%), while the Diver Operated Rig and Portable Remote Operated Drill (PROD) resulted in higher percentages of core loss (25% to 40%). The Phase 1 and 5 drilling investigation included casing each borehole over its full depth, which improved mud drilling returns and is the likely reason for less core loss.

Table 1. Marine Investigations Core Loss Assessment.

Year	Phase	Methodology	Total Drilled (m)	Core loss (m)	Core Loss (%)
2021	1	JUB & Conventional Drilling Rig	188	44	23
2023	3	Diver Operated Rig	55	14	25
2023	4	PROD	179	71	40
2024	5	JUB & Conventional Drilling Rig	255	43	17

7.1.3 *Quality of Data Recovered*

The investigation provided sufficient data for the development of the Engineering Geological Model. The team balanced the cost of additional drilling against obtaining further insights into the subsurface conditions, considering the high variability within each geological unit. While the broad distribution of relevant geologies was established, finer sub-unit distribution remained variable.

ASWA determined that the developed Engineering Geological Model was suitable for detailed design, despite the investigation's scope being more limited compared to investigations typically conducted for tunneling projects of this nature. For example, boreholes for tunnel infrastructure are typically spaced between 50 m and 150m. Eurocode 7 (BS EN 1997-2) provides guidance on the spacing of exploratory holes for long linear infrastructure (roads, railways, pipelines, or tunnels) advising on spacings ranging from 20 m – 200 m. For this project, the borehole spacing ranged from 50 m to 600m with 50m spacing at the critical SIR and BLOD structures and the 600m spacing along the tunnel alignment between the shore and 1km offshore in the reef area.

7.2 *Cone Penetration Testing*

CPTs were conducted from the PROD. Due to the variable strength of the subsurface material with depth, CPTs often refused after short depths of penetration. Following refusal, the CPT was removed, the hard layer drilled out and the CPT attempted again. The CPT data, whilst sparse, was useful for interpreting material parameters in units comprising loose to dense granular units or uncemented layers within rock strength units.

7.3 *Geophysical Survey*

7.3.1 *Multibeam echo sounder (MBES) for bathymetry*

The 2019 bathymetric data was unsuitable for the assessment of seabed features and seabed types because the data had been provided at a low-resolution cell size of 1 m and the overall poor quality of the dataset. The 2022 bathymetry contains strong motion artifacts in the order of 7cm total amplitude (+/- 3.5 cm) along the nadir (directly below the MBES transducer), and 30 cm (+/- 15 cm) along the outer beams, however, this data was fit for the purpose of levelling the associated geophysical interpretation to AHD. The 2022 bathymetry data was supplied at 50 cm cell size and provided a useful comparison with the Surrich 2024 data, showing close agreement with the ripple seabed structures observed indicating this ripple structure is invariant over time.

7.3.2 *Side Scan Sonar (SSS)*

The SSS mosaics over the intake and outfall risers provided in the order of 200% to 300% coverage within the 200m radius boundaries. The data had some distortion due to wave motion; however good coverage was achieved (>200%) meaning there were > 2 swaths available for inspection which provided ability to interpretate Seabed Features.

7.3.3 *Sub-bottom profiling (SBP) using a pinger*

Pinger SBP is a seismic reflection technique similar to Multichannel Seismic Reflection (MCSR). The key distinction lies in the pinger-type source, which offers higher resolution, but lower penetration compared to Boomer or Sparker sources used in MCSR. Pinger SBP lines were conducted typically at 12.5 m spacing with a higher density of 5 m coverage over the riser sites. This tighter line spacing aimed to detect potential hazards for jack-up barge operations during riser construction.

The Pinger SBP chosen was an Innomar Medium instrument and is a single transducer with heave correction and provides tolerance to turns and swell conditions. However, acquisition was particularly difficult in the area southwest of the reef on the intake alignment, where 2.2 m swells and breaking waves were encountered. Depth of penetration was primarily limited by the presence of cemented material or coarse sediments, such as gravels or thick beach sands exceeding 5 m in thickness. These geological factors, combined with the challenging sea conditions, influenced the overall effectiveness and depth of the Pinger SBP survey, and therefore limited the usefulness of the data obtained.

7.3.4 *Continuous Marine Seismic Refraction (CMSR)*

CMSR is a technique which measures the velocity “Vp” of a wavefront along a streamer towed behind an airgun. CMSR data could not be acquired across the shallow reef, and the sections were broken at this location. The CMSR method requires at least 100 m of travel at the start of the line, with the streamer at operational altitude above the seabed, and the vessel on-line, to establish good streamer geometry before the data is fit for use. To minimise lost data between the beach and the shallow reef, each line was run in both directions and the data merged before calculation of the Vp section.

7.3.5 *Multi-channel Seismic Reflection (MCSR)*

Multichannel Seismic Reflection (MCSR) is a seismic reflection technique similar to Pinger SBP. The pinger-type source offers higher resolution, but lower penetration compared to Boomer or Sparker sources. The multi-channel processing approach was chosen over traditional single-channel SBP for its ability to suppress artifacts, thereby improving interpretation quality. The processed datasets comprised five parallel lines at 12.5 m spacing along the alignments, with an additional five perpendicular lines over the riser sites.

Initial work utilised a boomer source at low speed to leverage its high-quality wavelet using the latest seismograph and streamer technology. Data was acquired along center lines using both shallow and deeper streamer tow depths. Analysis revealed good subsurface imaging in deeper seabed areas below -10m AHD; however, minimal penetration was achieved in shallow water, particularly where Tamala Limestone was exposed at the seabed. Subsequently, a sparker source was trialed, achieving deeper imaging in challenging conditions, including shallow water and extensive rock seabed.

Data acquisition was conducted at low vessel speed, with the vessel traveling into the seas to maintain optimal streamer geometry. However, during sea state trials, low vessel speed resulted in compromised streamer geometry due to periodic surging and stalling on overtaking swells.

7.4 *Geotechnical Risks*

Geotechnical investigations identified geotechnical risks including rod drops indicating potential small karsts, loss of drilling fluids indicating potential karsts or high permeability materials and mixed face conditions in the Tamala Limestone and Ascot Formation. The mixed face conditions pose risks to TBM operations in terms of controlling face pressures and stability of formations. No significant rod drops were recorded during the investigation with one record noting an 80 mm rod drop (the maximum recorded) during the investigation confirming potential small cavities.

The loss of drilling fluids was a regular occurrence during drilling in the Tamala Limestone and Ascot Formation which confirms the potential for encountering high permeability materials during the TBM operations. Drilling fluid losses appeared to be contained within the respective geological formations.

8 CONCLUSION

The ASDP project has undergone extensive nearshore geotechnical investigations through five phases from 2021 to 2024. These investigations have been crucial in developing a sound understanding of the complex geological conditions along the intake and outfall tunnel alignments.

The investigations employed a variety of methods, including borehole drilling from a JUB, diver-operated seabed rigs, PROD, cone penetration tests (CPTs), and multiple geophysical survey techniques. Each method contributed relevant data, despite challenges such as poor sample recovery in some formations and operational difficulties due to sea state, bathymetry, and water depths. Fully cased boreholes drilled from a jack-up barge using coring techniques and mud flush return resulted in the least amount of core loss and most reliable data for defining subsurface conditions and interfaces between units. The geophysical data, namely the seismic reflection and seismic refraction data, typically had poor resolution due to variable strength materials with depth and was therefore the least reliable in defining subsurface conditions and interfaces between units.

The phased approach to investigations allowed for iterative refinement of the geotechnical model, addressing data gaps and reducing uncertainties. While budget constraints limited the scope of investigations compared to typical tunneling projects, the data collected was deemed sufficient for developing an Engineering Geological Model suitable for detailed design.

Key challenges encountered included poor sample recovery in the Ascot Formation, variable strength of subsurface materials affecting CPT performance, and operational difficulties due to environmental conditions. Despite these challenges, the investigations provided valuable information on subsurface stratigraphy, material properties, and potential geotechnical risks.

The combination of borehole data, CPT results, and some geophysical data has provided a sound understanding of the nearshore geology, including the identification of key geological units and interfaces between the Tamala Limestone and Ascot Formation. This information has been essential for the design and construction of the intake and outfall tunnels and associated marine structures.

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