Large temporary secant-piled peanut-shaped shaft constructed for the Alkimos desalination plant in Perth: Design and construction

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ABSTRACT: Stage 1 of the Alkimos Seawater Desalination Plant (ASDP) is being designed and constructed by the Alkimos Sea Water Alliance (ASWA). The project requires a temporary shaft structure for the intake and outfall tunnels, intake pump station, and outfall chambers. This shaft is crucial for the project as the Tunnel Boring Machine (TBM) launch de-pends on its completion. The shaft features a unique peanut-shaped geometry, combining two intersecting circles of 44.5m and 49.0m in diameter, and is 20m deep. This design minimizes the need for intermediate props, facilitating internal work. The shaft walls are constructed using a secant pile temporary wall (SPW). The paper discusses the complex geotechnical and structural design, challenges faced during construction, and how the design was staged to allow early pile wall construction and how the design sequencing facilitated early construction of the pile wall. The report also details monitoring data collected to ensure construction proceeded safely.

1 INTRODUCTION

For the construction of the Intake Building (within the Alkimos desalination plant complex in Perth, Australia), a temporary earth retaining structure is required to reach the foundation support level of the building, where the tunnel portals will be constructed.

To facilitate these works, this structure must not include struts or bracing struts, leaving the largest open space free of obstacles that could hinder the scheduling and execution of tunnel activities and interfere with the future Intake building.

To achieve this, a peanut-shaped containment shaft is developed. It consists of two intersecting cylinders of 44.50m and 49.0m that fit as closely as possible to the geometry of the Intake building. The earth retaining structure is made up of SPW and a total excavation depth inside the shaft of 20.3m.

Figure 1. Temporary Shaft.

The Intake building located inside receives the intake and discharge tunnels from the sea, which are executed using a TBM. Therefore, once completed, the shaft must be free of any obstructions that could hinder excavation, storage, and removal of material, as well as the construction of the Intake building in a second phase, facilitating logistics.

This type of structure (peanut-shaped geometry) has often been used in other projects for similar cases, i.e. the need for large spans for the introduction of TBM: Tiete Shaft in Line 6 Metro in Sao Paulo [1] (4 circular secant shaft D=31m and an excavation of 33m). or Shaped Shaft of Silvertown Tunnel Project in London [2] (4 circular secant shaft D=21.2 m and an excavation varies from 20m to 24 m).

2 GEOTECHNICAL INVESTIGATION / PARAMETERS

The desalination plant is located less than 1 km from the coast. It is placed in a dune field. The ground elevation before starting the work was about 10-20 m above sea level. During the preliminary leveling works, the elevation of the desalination plant is between levels +10.50m and +11.00m.

As part of the geotechnical campaign carried out for the design and construction of the Alkimos desalination plant, due to the complexity of this structure, a more intensive geotechnical campaign was developed for this structure. The campaign consisted of the execution of 9 boreholes with lengths from 45 m to 60 m along the peanut shape of the structure. Additionally, due to the particle size distribution of the sandy layer with no cohesion, four pumping tests were conducted to determine the permeability of the materials, as a significant flow of water towards the excavation was expected. Based on the geotechnical campaign carried out, a geotechnical profile was created, which is shown below.

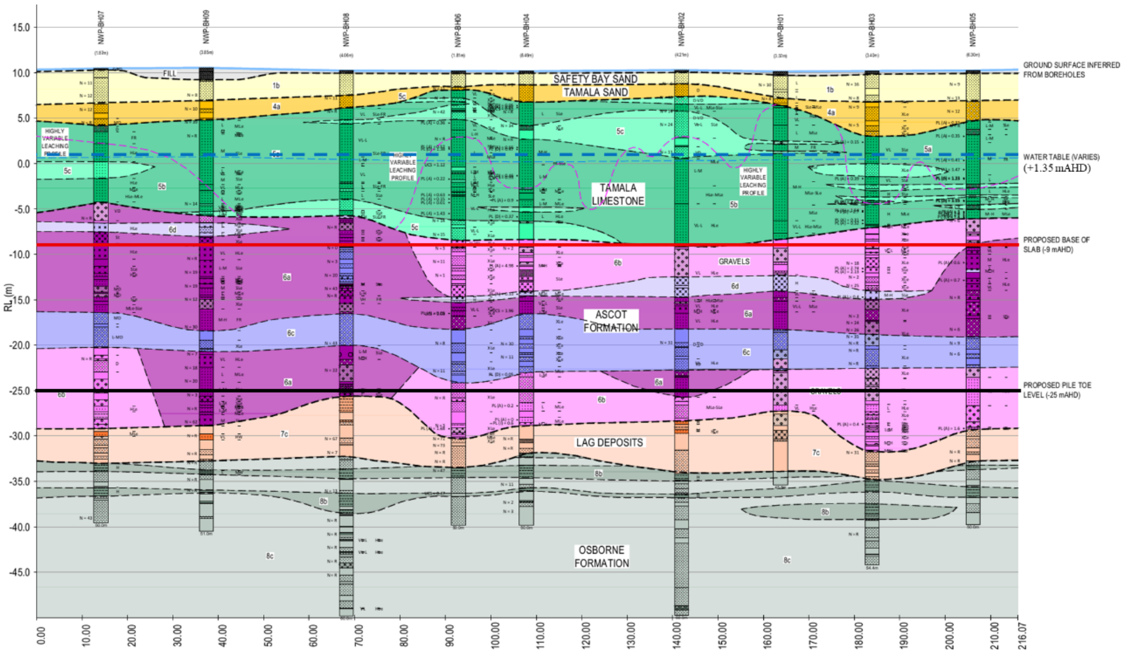

Figure 2. Geotechnical profile

The materials are predominantly granular, with no cohesion. Unit 5a/5b (Tamala Limestone) shows significant cementation, giving it a rocky appearance. However, for design purposes, it has been defined as a granular material with high cohesion, as the boreholes did not ensure continuity in the rock.

A critical factor in the design of this structure is the presence of the groundwater table above the maximum excavation depth. Based on the information from the piezometers and the records of nearby piezometers over several years, the water table level in the shaft area was determined at +1.35 m AHD during the construction process.

The estimated permeability for these levels is high (see table 1). Therefore, detailed assessment of the pumping rate was developed to ensure the excavation stability

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The following table includes the most significant geotechnical parameters

Table 1: Geotechnical parameters.

Geological Unit		γ_b (kN/m^3)	c' (kPa)	φ' (°)	E_d (MPa)	k_H (m/day)	k_V (m/day)
1b	Safety Bay Sand	17	0	34	25	15	1.5
4a	Tamala Sand	17	0	34	40	20	2.0
5a/5b	Tamala limestone	20	80	30	450	150	15
5c	Tamal residual soils	18	0	36	50	20	2.0
6a/6b	Ascot Formation cemented	22	0	35	100	10	1.0
6c	Ascot Formation Unconsolidated	19	0	35	45	10	1.0
7c	Lag deposits	19	0	40	100	4	2.0
8a/8c	Osborne Formation	19	0	40	90	4	2.0

γ_b = bulk unit weight, c' = effective cohesion, φ' = effective angle of friction, E_d' = effective elastic modulus, k_H = horizontal permeability, k_V = vertical permeability

3 OPTIONEERING AND FINAL SOLUTION

In the Alliance Development phase, the intake and outfall shafts were defined as two independent circular shafts with a diameter of 18 meters. Each shaft was designated as the starting point for the TBM for the construction of the tunnels. This implies the necessity to duplicate many of the elements necessary for the operation of the TBM.

To reduce costs and shorten execution time (the shaft is the critical path of the construction), the project's bidding phase proposed unifying the two shafts as an optimized solution. Initially, a circular shaft encompassing both buildings was proposed, but this design presented significant challenges due to its large diameter.

In a second solution, the two buildings were unified with a D-Wall shaft, which would be part of the permanent structure. However, this solution faced issues with waterproofing, as the joints between wall modules did not provide adequate waterproofing for the 100-year lifespan of the structure, requiring additional treatment. Additionally, straight walls required several levels of intermediate struts to reach the planned excavation level, interfering with necessary openings for the TBM. These struts needed to be substantial, and the reinforcement ratio in the D-walls was very high (more than 300 kg/m³).

As a final solution, a peanut-shaped shaft was analysed, allowing the SWIPS building to be constructed inside. This solution has several advantages:

- Since the SPW was temporary, long-term waterproofing is not necessary.
- The ratio of the shaft excavation area to the building footprint is relatively small.
- The final quality of the SWIPS structure is improved and the leakage risk reduced substantially.
- A cylindrical-shaped retaining wall works mainly under compression, reducing the need of intermediate struts, and, more specifically eliminating them entirely in the launch area, facilitating the associated works.

Various ground retention solutions were evaluated; however, a steel sheet pile wall (SPW) was ultimately selected due to its advantages over alternative methods:

- The presence of rock strata complicates the excavation required for a diaphragm wall (D-Wall), necessitating the use of hydro-milling equipment. This method is significantly more expensive, and the specialized machinery is not readily available.
- The presence of highly permeable soil layers prevents the use of a sequential ring excavation method. Implementing such an approach would require extensive and costly groundwater control treatments to reduce flow and mitigate the risk of piping.

4 DESCRIPTION OF THE FINAL SOLUTION

This structure features a very large peanut-shaped geometry of two partial intersecting circles of 43.3m and 47.8 m in diameter. To support both earth and water pressures, a SPW was constructed as an earth-retaining structure. The wall was constructed using 1200 mm diameter piles, spaced 750 mm apart, and with a length of 35 meters. Unreinforced piles were constructed using 20 MPa concrete, while reinforced piles were made with 40 MPa concrete. A total number of 14 Glass Fiber Reinforced Polymer (GFRP) piles have been installed in the location where the TBM are to be launched.

The piles are located at an elevation of +10.00 m AHD, with the maximum excavation level at -10.30m, resulting in a total excavation depth inside the shaft of 20.3 m. The embedment of the piles below the maximum excavation level was 14.7m.

Three levels of bracing are provided for the SPW, consist of a waler beam section of 0.8x1.0m and props of significant dimensions: 27 meters in length with sections of 2x2m and 2x2.5m. There is an additional bracing, exclusively at the intersection of the cylinders, like a slab supported on the ground with a section of 6 x1.5m.

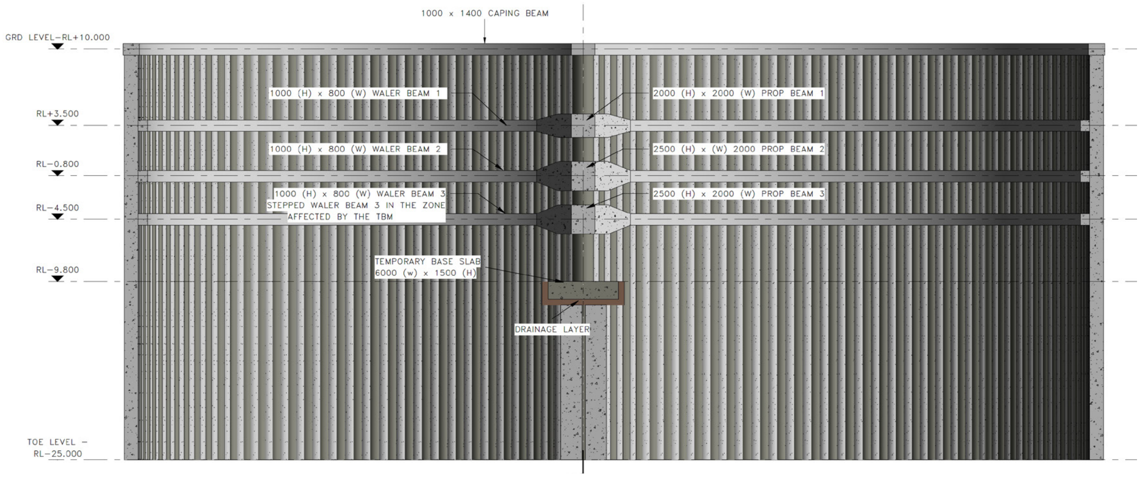

Figure 3. Temporary shaft elevation.

5 CALCULATIONS PERFORMED

5.1 *Plaxis2D/3D modelling*

Due to the complexity of the work, the modelling of the structure and its completion on the ground has been carried out using the Plaxis 2D and Plaxis 3D programs. Multiple analyses have been conducted to adequately understand the behaviour of the structure.

Firstly, an axisymmetric model was created in Plaxis 2D to understand the behaviour of a circular shaft with a diameter of almost 50 meters. This was essential in determining the magnitude of the loads acting on the pile wall. It was observed that the circumferential loads would be much greater than usual for a circular shaft of this diameter. The magnitude of these loads prevented the use of low-strength concrete (<5 MPa) for unreinforced piles. It was found that concrete with a simple compression strength of 20 MPa was necessary for unreinforced piles.

In the Plaxis 2D program, it is common to model walls as "plates" elements, which do not consider the transverse rigidity of the wall for obtaining vertical loads. In a Plaxis 3D model, the use of isotropic "Plates" results in horizontal loads (bending moments, shear forces) that cannot be developed in a SPW, as there is no transversal reinforcement connecting these elements. Additionally, since this wall is made with piles of two different deformation modules, the behaviour of the whole is not homogeneous.

To determine the deformation module for compression loads in horizontal and vertical directions, a volumetric element modelling of a pile wall in Plaxis 3D with the planned configuration was performed, as shown in figure 4.

Figure 4. Modulization SPW in theorical position (left) and outside the theoretical position (right)

This wall consists of piles with two different deformation moduli, corresponding to concrete strengths of 40 MPa (E = 32,800 MPa) and 20 MPa (E = 24,000 MPa). Simulations also included piles installed within planned tolerances but outside theoretical positions. Results showed that the vertical deformation modulus is primarily controlled by the stiffer, higher-strength piles (around E = 29,800 MPa), both for theoretical and tolerance-based positions. Horizontally, the deformation modulus is closer to that of the 20 MPa piles, with values significantly lower (60 %) when accounting for installation tolerances.

Due to the lack of continuous transverse reinforcement, shear transfer horizontally is limited, so the wall mainly resists stresses along the reinforced piles. This was modelled by reducing transverse shear modulus (G_{12} and G_{23}) near zero, except for vertical shear (G_{13}), kept at 70% of its actual value.

Three SPW types were modelled in Plaxis 2D/3D to assess pile tolerance effects:

- Type 1: Theoretical parameters.
- Type 2: Horizontal stiffness reduced to 10% of theoretical.
- Type 3: Horizontal stiffness at 10% and vertical second moment of area at 33.3% to simulate cracking.

To ensure structural behaviour met design criteria for the large shaft, three perimeter waler beams were proposed at specified levels and modelled as beam elements supporting the SPW plates. These beams reduced vertical loads on piles by acting as stiff “false struts” and absorbed part of circumferential loads, especially in models with lower horizontal stiffness.

Another important element in the design of this shaft is the struts (o props) located at the contact area between the two circular shafts. These elements serve to maintain the continuity of each shaft's circumference. They function to maintain circumferential integrity around each shaft. Given the large loads applied and the ~30 m span between supports, a robust cross-sectional design is required. The connection of these elements with the rest of the structure has been made as a joint, modelled as "node to node" elements in the Plaxis model, as they are only subjected to axial loads in addition to their own weight.

The connection between the SPW and the struts is made through two 1.80 m diameter piles called King Piles, located at the intersection of the two circles that form part of the shaft. Due to the defined characteristics of the SPW, the circumferential load cannot be transferred to the struts through vertical shear at the contact between reinforced and unreinforced piles, as it does not provide sufficient resistance to be considered. Therefore, the only feasible mechanism is through vertical bending of the reinforced piles. This results in very high loads on the king piles, reaching reinforcement quantities of 2.6% steel. This element has been modelled in Plaxis 3D as a beam.

5.2 *Structural elements*

The main structural elements contributing to the arching behaviour of the shaft are the props. There are four props in total. The first three props are beams connected with the waler beam rings, providing support to the SPW along the peanut shape. The props' dimensions vary from 2.0m to 2.5m in height, 2.0m in width, and 30m in span. The waler beam maintains a constant cross-section of 0.8 m in width and 1.0 m in height, except at the prop connection points where the height is increased to accommodate additional reinforcement. The fourth prop is a slab over the ground, 1.5m thick and 6m wide, mainly supporting the piles at the circle intersection.

Finally, the capping beam at the top of the excavation provides continuity and ensures that all the pile heads displace similarly.

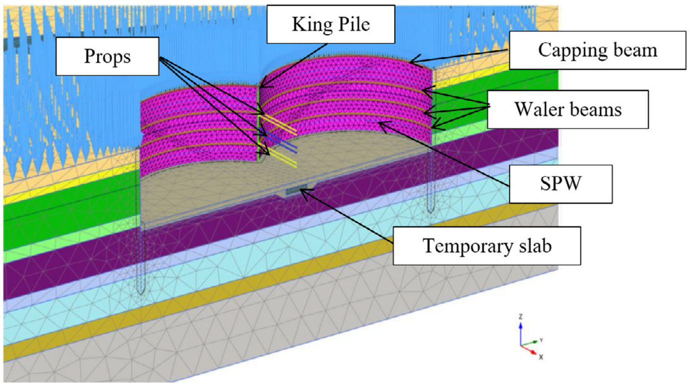

Figure 5. Plaxis 3D Model and structural elements

6 CONSTRUCTION PROCESS

This structure constituted the critical path in the Alkimos project schedule, as tunnelling activities could not commence until the maximum excavation depth was achieved. Consequently, the construction process was executed continuously, without interruptions during weekends or nighttime.

A total of 308 piles were installed, comprising 136 reinforced concrete piles of 1200 mm diameter, 152 unreinforced concrete piles of 1200 mm diameter, 14 GFRP piles of 1200 mm diameter, and two reinforced piles of 1800 mm diameter. The pile installation presented several technical challenges. Given that the unreinforced piles exhibited higher-than-typical strength for a steel sheet pile wall (SPW), it was necessary to formulate a concrete mix with delayed strength gain to minimize resistance during drilling for the installation of the reinforced piles.

As part of the SPW system, strict verticality control was mandatory. Any deviation could generate gaps in the wall, resulting in water ingress and groundwater infiltration into the excavation. Therefore, pile specifications mandated that the first 20 meters be constructed using temporary casing, with a verticality tolerance of less than 5 mm per meter. Beyond this depth, piles were executed without casing, allowing a verticality tolerance of up to 10 mm per meter. These stringent tolerances ensured sufficient pile overlap along the entire length, maintaining the integrity of the wall within the maximum allowable limits.

These rigorous construction requirements necessitated continuous verticality monitoring of the casing for each pile, along with SHAPE testing, which reduced overall construction productivity. During excavation, the correct execution of the piles was confirmed, with only minor water ingress observed at limited pile joints.

Excavation within the shaft was carried out in five phases, each aligned with the installation level of the waler beams. Excavation commenced in early December 2024 and was completed by March 2025. The principal challenge during excavation was the unexpectedly high strength and continuity of the Tamala Limestone layer. Despite prior geotechnical investigations, its resistance exceeded expectations, necessitating the use of hydraulic hammers for rock removal.

The excavation process proceeded in four phases, each advancing to the execution level of the waler beams and props. Excavation was continued until the structural elements reached 80% of their design strength.

Another critical aspect of the construction process was managing water infiltration from the base of the excavation. According to the calculations made and the estimated permeability parameters in the project, a maximum flow rate of 120 l/s was expected. Measurements showed that the maximum pumping flow rate was about 60 l/s.

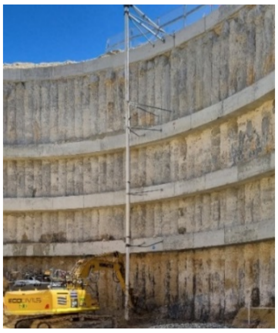

Figure 6. SPW and waler beam

Figure 7. Tamala Limestone rock

7 MONITORING

7.1 *Monitoring plan*

The complexity of the structure implies a monitoring plan for the structure to verify the correct behaviour of the shaft during its construction. A total of 8 inclinometers, settlement control points in the shaft's influence zone, 32 optical prisms on the beams, and over 150 strain gauges inside the beams have been included. All elements are automated, providing real-time excavation data.

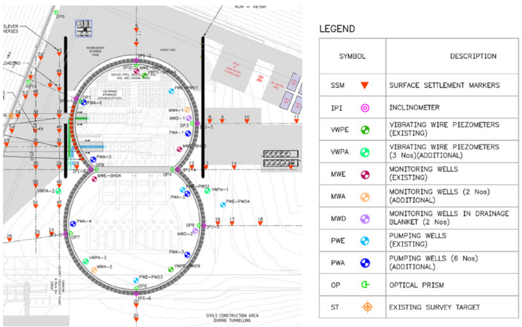

Figure 8. Monitoring plan layout.

7.2 *Monitoring carried out*

Since the start of the excavation works, continuous monitoring of all installed elements has been conducted. As expected, displacements were observed during the excavation phase; however, these movements stabilized once excavation activities ceased and coincided with the concreting stages of the waler beams and struts.

The maximum displacement recorded was minimal—approximately 10 mm—for excavations reaching depths of 20 meters, resulting in negligible ground settlements in the vicinity of the shaft. Compared to the predicted values, displacements were significantly lower below the first waler beam, although slightly higher in the upper sections.

During the dewatering process inside the shaft, a drawdown of approximately two meters was observed in the external groundwater level. This behaviour had been anticipated and was accounted for in the design of the dewatering system.

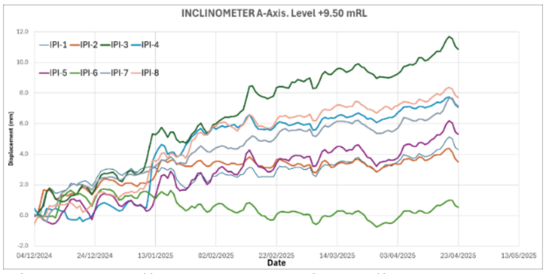

Figure 9. Inclinometer A-Axis readings.

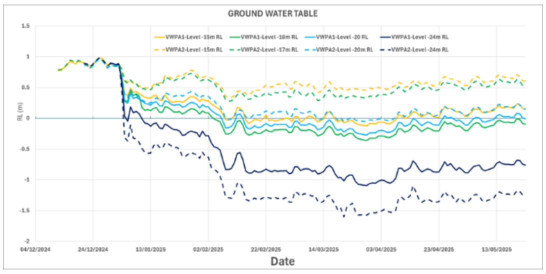

Figure 10. Ground water table outside shaft

After analysing the data, it was concluded that the effect of concrete shrinkage due to temperature drop (the capping beam was executed in summer), along with a 50 m diameter shaft, causes a temperature drop of about 15ºC to produce displacements in the head of the wall of more than 7 mm towards the excavation.

The following graphs show the head displacement of two inclinometers and the ambient temperature. A clear homotheory between the movements and the temperature is observed.

This effect was not accounted for in the design of the WB, as it was not a force specifically dimensioned for the WB structure. However, in the case of the props, the temperature-induced effect necessitated an increase in reinforcement

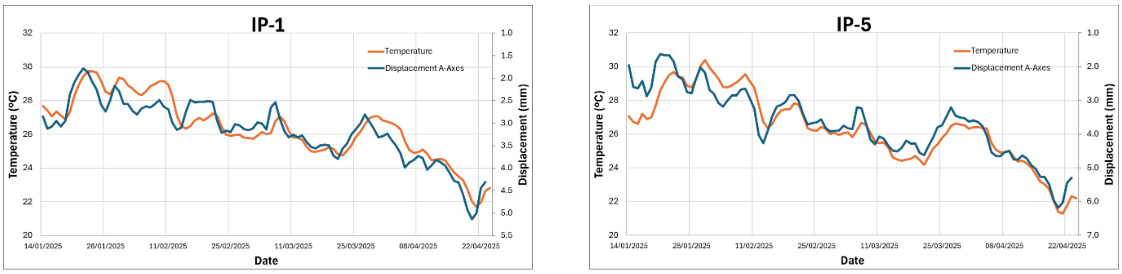

Figure 11. Head displacement at inclinometer 1 and 5 due to temperature variation.

8 CONCLUSION

The design of a peanut-shaped shaft has involved significant challenges due to the following design conditions:

- The requirement to perform an excavation exceeding 20 meters in height and 13 meters below the groundwater table.
- The particle size distribution of the soil leads into a high permeability, resulting in a very high rate of water flow.
- The design required a large interior space, free from bracing elements, for a shaft approximately 50 meters in diameter.
- The novelty of the peanut-shaped geometry for these dimensions.

An interdisciplinary team (geotechnical and structural engineers) carefully analysed the ground and load conditions to develop a robust solution that met all design requirements, while also being developed under a tight timeline due to the project's constrained construction schedule.

Despite these challenges, the construction was completed within the scheduled time, which did not cause any delay in the desalination plant works. The results obtained from the monitoring have proved the validity of the design.

This solution size (50 m diameter) has been adapted for this project based on the geotechnical conditions and the groundwater level position (12 meters). For excavations with a higher groundwater level, the maximum shaft diameter must be adjusted accordingly.

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