Jetting in confined areas

Cockatoo Island Seawall Seepage Barrier

The remotely located Cockatoo Island iron ore mine off the Kimberley coast in the northwest of Western Australia has been in operation since 1951. The mine was recently expanded up to about 50 m (165 ft) below sea level using staged construction to create a rockfill seawall around the open cut mining operation. Late in 2013, to allow expansion of subsea iron ore mining operations, Wagstaff Piling was engaged to install a seepage barrier through the rockfill seawall and into the underlying seabed sediments.

Aerial view of iron ore mine and new seawall construction site

Earlier stages of seawall construction had used a variety of different construction techniques with varied success, and the history of subsea mining on the island had been plagued with failures, including failures in the slope of the seawall itself, hanging wall failure underneath and inside the seawall, and footwall failures as the ore was mined leaving the rock face inclined at 55 degrees, parallel to the bedding. The current expansion, known as the Stage 4 expansion, was more tightly constrained by the pit geometry and available materials than previous seawall expansions that adopted clay core and sheet pile seepage barrier solutions. In Stage 4, an innovative seepage barrier solution using a grout curtain was selected to provide the necessary cutoff to allow access to high-grade ore, while protecting the mine from inundation by the sea.

Seawall Concept

The open cut subsea mining operation consisted of a 3 km (1.9 mi) long narrow pit along the south side of Cockatoo Island that extended to depths of about 50 m (165 ft) below sea level, and were exposed to the open sea on the south side of the pit. Massive tidal variations of more than 10.5 m (34.5 ft) required a seawall founded

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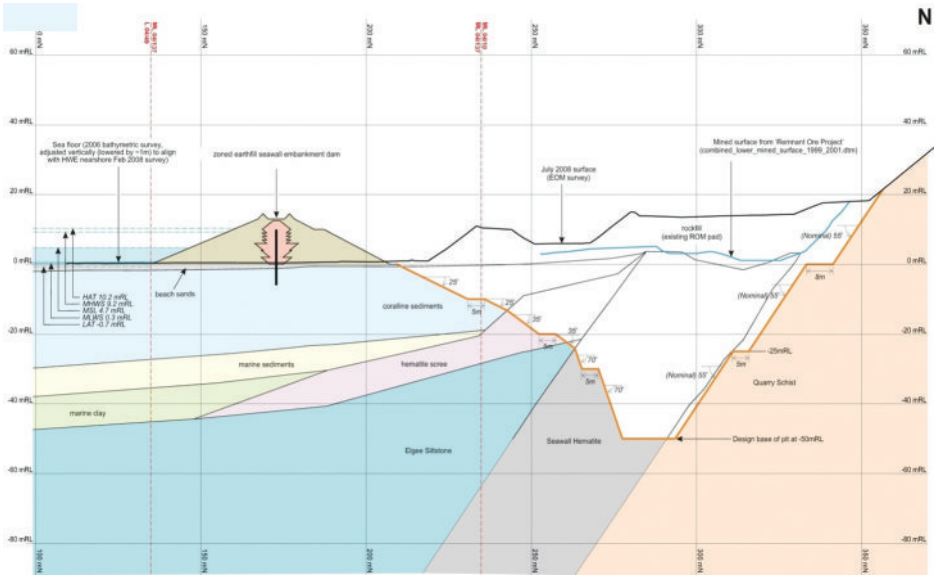
on the seabed, extending upwards to RL+13, to safely protect the pit from the high tide level rising to above RL+10.

Geology

The geology comprises the main ore body known formally as Seawall Hematite, dipping at 55 degrees towards the south into the seabed along the southern side of Cockatoo Island. The high-grade Hematite unit (68% iron content) with a thickness of about 30 m (98.4 ft) was uplifted by regional folding to its current dip angle, which is clearly visible from the air upon approach to the island. Earlier stages of open cut mining commenced in 1951 at an elevation of approximately 130 m (426.5 ft) above sea level, and, by 1985, approximately 2 km (1.25 mi) of accessible ore were removed down to sea level.



Seawall Concept

Embankment Construction

The various stages of seawall are founded on the existing seabed, effectively bearing on the very soft Coralline Sediments. Construction required strictly controlled stages of progressive placement of fill material and loading, allowing strength gain to occur from pore pressure dissipation in and consolidation of the weak Coralline Sediments.

Seawall fill material comprised locally quarried quartzite and sandstone. The material was notoriously variable, heterogeneous and anisotropic. Permeability characteristics of the fill material were therefore difficult to predict both laterally and vertically within rockfill that was placed to form the seawall embankment. Placement criteria during low tide windows also meant that fines would be washed out more predominantly in the lower sections of seawall due to the massive movement of seawater across the construction zone during tidal cycles.

Cutoff Wall System Selection

Construction of the first seawalls (Stage 1) commenced in 2002, and Stages 2 and 3 followed and kept mining operations going until 2012. These earlier stages of seawall construction involved the placement of the rockfill obtained from the local quarry and during mining activity, combined with a low permeability clay core and filter zone material, and some sheet piling. Between 2003 and 2009, there were at least three major preventable failures associated with the first three stages of seawall construction, all causing the suspension of mining activity and major recovery work. The Stage 4 expansion needed to take advantage of the previous lessons learned to avoid any repeat of the earlier failures.

Stage 4 required a new 261 m (856 ft) long seawall to be constructed. A rockfill seawall would again provide the structure for and stability of the barrier wall, but not the water cutoff properties required. The seawall cutoff would need to extend from elevation RL+12 down into the Coralline Sediment aquiclude, where a suitable cutoff toe level was determined to be about elevation RL-5.

Wagstaff Piling proposed the idea of injection grouting, which had the advantage of requiring light rigs and a batch plant that are relatively easy to mobilise, with ongoing raw material supply feasible by road and by barge to the island. The grouting method was developed based on a previous Wagstaff project that involved grouting of a rockfill seawall in Gladstone, Queensland. In that case, a rockfill seawall with limited fines was grouted successfully to create a seepage barrier using rapid gelling chemical grout to fill the voids, thereby preventing dredged fines from washing out through the seawall during tidal cycles.

A significant advantage of grouting was that the seawall could be raised simply without the need of fines or clay core material, and then a grout curtain barrier injected centrally through the rockfill would provide sufficient seepage cutoff. The grouting was proposed to be done along the wall alignment using a combination of techniques, as summarized below.

Stage 1 - Permeation Grouting

Permeation grouting would be performed in the upper seawall fill materials from a depth of 0 to 10 m (0 to 33 ft). Using percussion drilling techniques, a top hammer drilling rig would bore through the rockfill with fluid flushing techniques, and then a rapid gelling grout formulation of bentonite, cement and chemicals (sodium silicate) would be injected into the borehole.

Stage 2 - Jet Grouting

From a depth of about 10 to 17 m (33 to 66 ft), utilizing the passage of the holes already drilled for the permeation grouting, jet grouting would be performed below the seawall in the lower seawall hematite sands and coralline sediments, beneath the permeation grouted upper seawall fill.

Technical Solution – Execution of the Grouting Works

The conditions encountered proved to be extremely variable and required constant monitoring and change of technique. The key techniques found to be required during construction are described below.

Stage 1 - Permeation Grouting in the Upper Seawall Rockfill Material

A line of grout holes at a center-to-center spacing of about 1 m (3.3 ft) was proposed to form the seepage barrier, with grouting extending to a depth of about 17 m (56 ft) below the top of the seawall. Top hammer drilling techniques were used to penetrate the 12 m (40 ft) deep rockfill to seabed level, and permeation grouting carried out within the rockfill to fill voids and stabilize material around grout holes. The local 10 m (33 ft) high tidal fluctuations meant that tidal washout of fines and grout would be a major risk, and so a combination of cementitious and chemical grout was used to create rapid gel times.

Top hammer drilling proved to be similar to that anticipated in the area of the new seawall construction, although large portions of the grout alignment turned out to be located over tapering transitions to the existing seawalls. In these transitions, large boulders and possible waste debris formed the encountered obstructions, which made top hammering through the fill much more challenging. The volume of grout taken in each hole was extremely variable, with drillhole circulation to surface the best indicator of permeable zones, porosity, cavities, etc.


Drilling of grout holes

Borehole stability was difficult to achieve in the often loose rockfill. Many top hammer drilled holes needed to be redrilled and grouted a second time to create the stable passage for the later jet grouting. The rapid gelling properties of the sodium silicate and the cement grout mix were essential to achieve a collared and stabilized hole through the rockfill, especially with the large volumes of tidal seawater flowing continuously in and out as the tides changed, and, more particularly, during the spring tides where a 10 m (33 ft) tidal variation would occur during a 6 hour period.


Redrilling and grouting during high tide

Stage 2 - Jet Grouting in the Lower Seawall Sands and Coralline Sediments

Following the permeation grouting, the collared boreholes were reopened to perform jet grouting using the duplex system in a single pass. Initially, the jet grouting was focused below the seabed to provide the cutoff through the highly permeable coral reef debris and into the Coralline Sediments. Subsequently, the jet grouting was extended upwards to within 2 to 3 m (6.5 to 10 ft) below the working surface to overlap the permeation grouting into the seawall fill to overlap with the earlier permeation grouting.

Jet grouting proved to be very effective in the sediments beneath the upper seawall rockfill, which was reflected in the volume and nature of the uphole circulation (returning fluid) during the jet grouting. The returning volumes up through the seawall fill over successive phases of grouting provided similar initial indications and confidence of filling of the void spaces and of achieving continuity between grout columns at depth.


Jet grouting during high tide

Soil/Cement/Bentonite Capping Trench

An excavation made to inspect the tops of the grouted columns revealed that grouting effectiveness close to the platform was diminished, which was anticipated due to the reduced overburden pressure at shallow depths and just beneath the working surface. Utilising the batch plant and the site excavators, a trench was cut from surface down to the top of the grout columns at a depth of about 3 m (10 ft). A cement/bentonite grout capping trench was installed using slurry trenching techniques to complete the barrier up to the platform level. Cement/bentonite grout was placed to a depth of about 1 m (3.3 ft) from the top of the platform. Below the cement/grout, the fill with larger rock particles were screened out, and then finer material was placed and mixed with the excavator bucket to create a slurry mix of cement, bentonite and rockfill. By observation, this capping trench proved to be a simple method to provide a cutoff within the upper 3 m (10 ft), where the continuity of the jet grouting was found to be difficult to achieve.

Logistics

Supply logistics were critical in this remote location. Limited barges, tight scheduling due to tides, and other general freight deliveries to the island mine meant that material supply dictated the progress onsite. Ultimately, the quantity of materials required (predominantly cement) determined the progress and duration of the works, given the barging availability and capacity. At times, the freight choices and project progress was determined simply by comparing the urgency for cement versus the urgency for other supplies needed to sustain the workforce.

Aerial view of dock and seawall construction site

Cement

The predominant material required was cement, with about 4,000 tonne (4,410 ton) required during the 10 month duration of the works. Bulk cement containers carrying about 22 tonne (24 ton) each were rolled on and off barges and delivered to the silos at the seawall batch plant immediately adjacent to the works.

Bentonite

Approximately 200 tonne (220 ton) of sodium bentonite was supplied in 1.2 tonne (1.3 ton) bulker bags primarily from an ex-mine in central Queensland, was delivered by road some 4,500 km (2,800 mi) across the top of Northern Australia to Derby port, and then barged over to the site.

Sodium Silicate

Approximately 240 tonne (265 ton) of liquid sodium silicate was used, which was supplied in 20 tonne (22 ton) bulk liquid containers.

Mix Design And Installation Parameters

Permeation Grout

Cement, bentonite and sodium silicate chemical was combined to create the mix as described below.

- Part A - Sodium silicate mixed with hydrated bentonite/water
- Part B - Cement and water prepared and combined with hydrated bentonite/water mix just prior to use

Using parallel plunger pumps of equal performance, the Part A and Part B mixes were combined in equal parts with an equal flow rate through a "Y" fitting just behind the drill rig. Once combined through the "Y" fitting, the grout would be reactive and subject to gel within 10 to 20 seconds after exiting the drill string, where it would lose velocity as it progressed within the drill pipe. The speed of the gel could be varied by varying the components of Part A and Part B. A Hutte 605 drill rig with top hammer percussion was used with percussion drilling bits, where flushing of the fluid grout mixture occurred during drilling. Maintaining the drilling rods were difficult due to the aggressive conditions.

Jet Grout

The injected grout mix comprised a combination of hydrated bentonite with cement and water at a water-to-cement (w/c) ratio of 0.98, with a cement content of 763 kg per cubic meter (47.6 lb per cu ft) and a bentonite content of 15 kg per cubic meter (about 1 lb per cu ft) of mix. The jet grout was installed using the duplex system, with air injected at a pressure of 8 to 10 bar (116 to 145 psi) and grout injected at a pressure of 300 bar (4,350 psi). Typical installation technique and parameters included flushing downwards at low pressure (no jetting) and then jetting upwards at

Flushing the system prior to jet grouting

a pressure of 300 bar (4,350 psi), with an approximate grout flow of 230 liter/min, an upwards velocity of 25 cm/min (0.8 ft/min), and a rotational velocity of 6 to 8 rpm. The jetting nozzles used were 2 x 3.5 mm (2 x 1/8 in) in diameter, the typical targeted jetting energy was 40 MJ/m, and the aim was to achieve a grout column of 1.2 to 1.5 m (4 to 5 ft) in diameter.

Slurry Capping Trench

The slurry mix used consisted of bentonite at 25 kg per cu m (1.6 lb per cu ft), cement at 468 kg per cu m (29.2 lb per cu ft) and water at 840 liters (222 gallons). When rockfill fines were added to the slurry mix, the final mixture consisted of bentonite at 8.3 kg per cu m (0.5 lb per cu ft), cement at 156 kg per cu m (9.7 lb per cu ft), water at 280 liters per cu m (214 liters per cu ft), and rockfill fines.

Verification

Verification of the success and effectiveness of the grouting proved to be difficult, with a variety of methods attempted, including falling/rising head testing, excavation of observation trenches, diamond core drilling and water level monitoring. The most successful methods of verification are described below.

Piezometers

The strategic use of standpipe piezometers placed along the inside of the grout alignment to the depth of the base of rockfill proved to be a reliable verification technique. The standpipes were installed at the start of the grouting process at approximate intervals of 10 m (33 ft) and offset from the landward side of the grout alignment between 3 and 10 m (10 and 33 ft). Vibrating wire piezometer sensors were installed into the standpipes and attached to data loggers at the surface, and recorded water levels at 20-minute intervals throughout the works. The data loggers were programmed to send data, via telemetry, to a central computer, which could be accessed remotely over the internet.

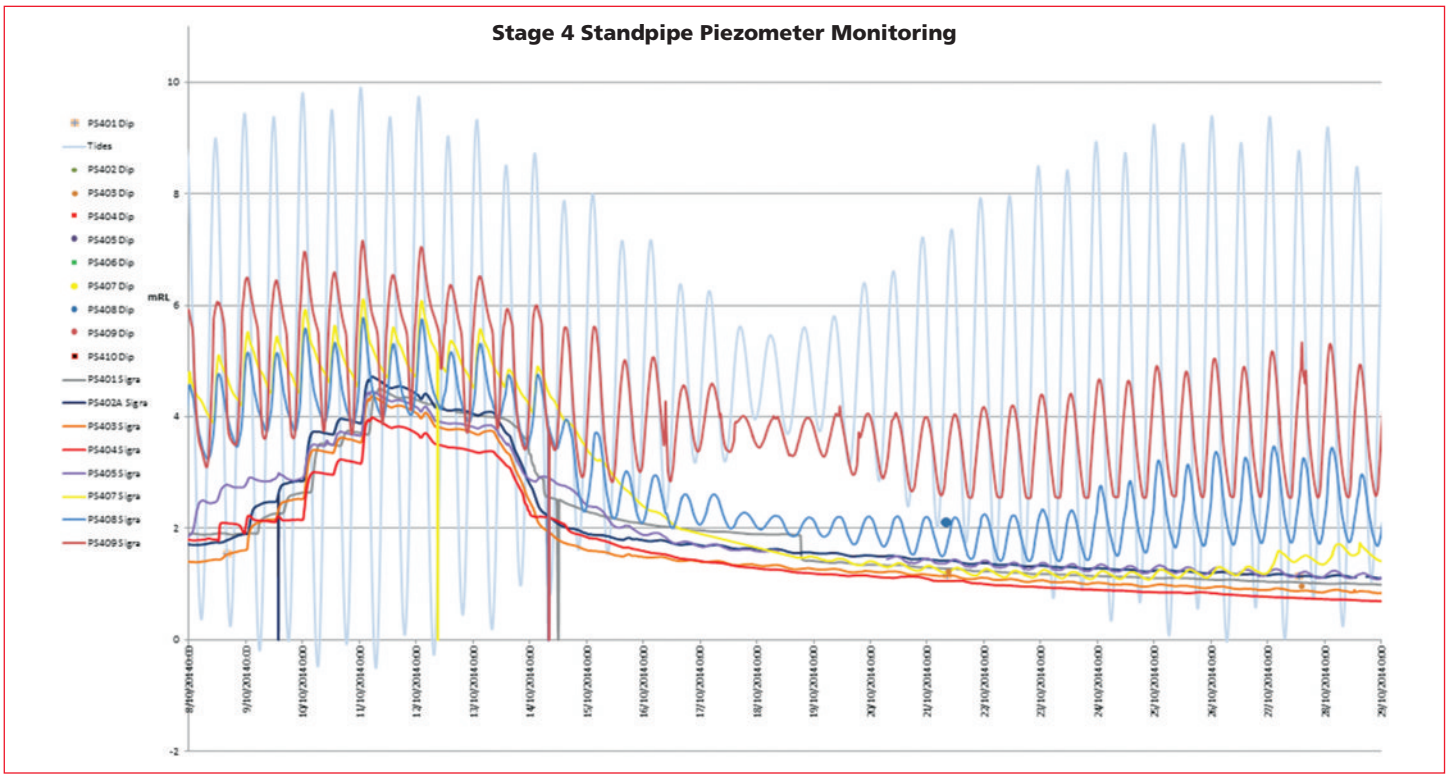
Groundwater levels on the landward side of the seepage barrier were observed to diminish significantly as the grouting progressed and the hole spacing tightened to 1 m (3.3 ft) on center. Sensor readings indicated initial coupling of groundwater and tide levels; however, decoupling (or significant reduction) was observed in the latter stages during grout curtain closure. A typical series of piezometer readings during a three week period of tidal cycle (i.e., spring tide to spring tide) is shown in the graph below. In the graph, the second cycle of spring high tidal movement shows significant changes in groundwater behaviour, including a delayed response to tidal rise and fall, and a progressive reduction in the magnitude of the rise and fall of groundwater within certain standpipes as the grout curtain continued to be sealed.

Uphole Circulation

The observed behaviour of the fluid returning to the surface during jet grouting operations was a significant early indicator of success. Primary holes were grouted at center-to-center spacing of about 4 m (13 ft). It was noticed that, during grouting of secondary infill holes at 2 m (6.6 ft) spacing and, more noticeably, while grouting tertiary infill holes at 1 m (3.3 ft) spacing, progressively more fluid would return to surface, which was seen as an indication of the progressive success of the grouting. There was a distinct pattern of behaviour that would not only indicate success, but would also highlight porous areas, which likely corresponded to zones where variations in the seawall fill existed.

Final Spring Tide Testing

More convincing verification was by observation of performance inside the seawall on the first spring tide after the nominal closure of the grout curtain. At this stage, the grouting plant and equipment was maintained on location in standby mode, in the event that additional grouting was required. The performance during the spring tide testing was considered suitable and fit for purpose by the



client, and the order to demobilise plant and equipment was given. In the following months, with the seepage barrier in place, mining operations were able to safely access the seawall hematite ore body and progress with drilling, blasting and excavation below sea level.

Conclusions

1. The combination of grouting techniques and the ability to vary techniques along the alignment in response to the conditions found led to the success of the grouting.
2. The use of rapid gelling chemical grout combined with top hammer percussion drilling through the seawall rockfill proved to be an essential method of collaring the holes, which, in turn, would allow the passage of the jet grouting drill string.
3. Jet grouting was proven successful by the end result, and was an effective way to grout both the sediments underlying the seawall and the seawall fill itself, following the initial permeation grouting.
4. Tidal water movement was a constant factor and more pronounced during spring tide variations, so the use of rapid gelling grouts were an essential aspect of the success of the grouting works.
5. The grouted solution was a progressive and relatively adventurous proposal, but, with the excellent cooperation of all interested parties, the result was proven to sufficiently reduce and control the seepage through the seawall, which allowed the safe advancement of the Stage 4 pit below sea level.

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