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# Reclamation of a Conventional Tailings Facility for Long Term Dry Stacking Operations in Western Australia

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## Abstract

Residue storage ponds constructed prior to the 1980s were built to the engineering standards that applied at that time. Clay liners were typically used to provide a barrier to flow of contaminants into the natural groundwater system. More recent storage areas include a composite liner consisting of a clay liner and geomembrane and have a drainage layer placed above the liner to reduce the hydrostatic head. This paper presents the engineering design and planning for the conversion of an older residue storage area which had a natural clay liner only into a dry stacking residue storage area to increase the residue storage capacity within the area and at the same time reduce the potential for long term seepage from the area. Field investigations including Piezo-cone Penetrometer Testing (CPTu) and pumping well tests were undertaken. Monitoring instrumentation including Vibrating Wire Piezometers (VWPs) was installed within the saturated residue materials. Dewatering technologies such as deliquoring bores, wick drains and geosynthetic liners between the older deposit of residue and the dry stack deposit were recommended for the control of pore pressures within the existing pond. Numerical analyses to predict the pore-water pressure build-up at the pond base, the influence zone of deliquoring bores, and predicted differential settlements of the surface were also examined.

## Introduction

The Pinjarra refinery is located 80km south of the Perth city and currently owned and operated by Alcoa World Alumina Australia (Alcoa). The Alcoa alumina production adopts the Bayer refining process, whereby bauxite ore mined from the Darling plateau is conveyed down the scarp to Pinjarra, stockpiled and processed. By world standards, the bauxite is of low quality and two thirds of the bauxite ends up as residue materials from the production process. The residue materials are approximately 50% coarse-grained (residue sand) and 50% fine-grained (residue mud). The coarse grained material is mainly used for the construction of perimeter embankments while the fine-grained residue mud is deposited within these impoundments using dry-stacking methods.

The Pinjarra residue site comprises six residue storage areas (RSA's) and the refinery water storage dams which include a surge collection pond, a lake water pond, a cooling pond, a fresh water reservoir and a runoff water storage pond (Figure 1).

The cooling pond is currently used for cooling water supply to the refinery, but will be capped and used for future dry stacking. The cooling pond is approximate 72 Ha and the site was first commissioned in 1972. It is noted that natural clayey materials were used as a liner for the pond. However, the quality of the clay liner is known to be variable and minor sandy zones occur within the clays. The pond basal elevation varies betwen 20.0m and 23.0m (Australian height datum, AHD). The pond has been used for deposition of residue over the years while maintaining water capacity for refinery cooling and storm surge. Residue from the refinery has been deposited mostly in the north end of the pond over the past 37 years. This deposition has been sporadic and has created a mix of mud and sand lenses over the floor that make up the current residue deposit. The northern segment is now covered with approximately 2m thickness of sand and has an average of 21 meters thickness of sediment. The southern segment is used as a cooling water storage and has an average of 13 meters thickness of sediments. The current surface elevation of the northern segment varies between 41.0m and 43.0m (AHD).

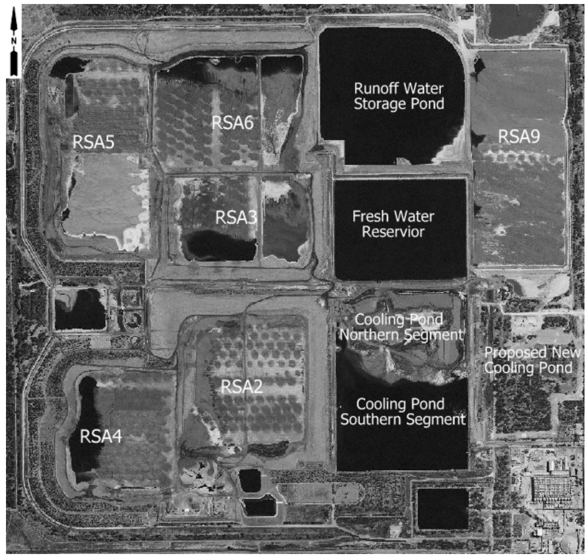



**Figure 1: Aerial Photograph of Pinjarra Residue Site**

In order to provide sufficient residue storage area for future operations and comply with the current enviromental standards, Alcoa proposes to convert the cooling pond into a dry stacking facility (RSA1) and construct a new cooling pond to the east of the site. The conversion to a dry stacking area will be carried out in two stages by dividing the area into a northern and southern segment. The southern segment will continue to provide the refinery with cooling water before the new cooling pond commences operation in 2013. The northern cooling pond segment will provide residue mud drying area from December 2011. This paper summarizes the geotechnical analyses for the first stage conversion (northern segment) and engineering solutions for the management of pore water within the sediments.

# Site Geology

The Pinjarra residue storage facility is situated on the Pinjarra Plain, an alluvial tract up to 10km wide corresponding with the distribution of the Guildford Formation. The underlying foundation soils typically comprise Bassendean sand overlying Guildford Formation. The Bassendean sand is of Aeolian origin generally varying in thickness from less than a meter to in excess of 5m. The sand is typically pale brown to grey, fine to medium grained and reduces in thickness towards the Darling scarp.

The soils underlying the Bassendean Sand typically comprise interbedded alluvial sand and clay deposits, varying in thickness from a few metres to in excess of ten metres. These soils comprise a mixture of gravel, sand and clay derived from the weathering of basement rock (granite/gneiss), which is washed down the escarpment in river systems, forming the alluvial deposit referred to as the Guildford Formation. The soils typically classify as clayey sand (SC) to sandy clay (CL-CH) of medium to high plasticity. The more clayey soils are of low to moderate reactivity with low permeability, and may be utilised as an impervious liner for a residue storage area.

# Groundwater Conditions

There are three aquifer systems below the Pinjarra residue area. The Cattamarra aquifer and Leederville aquifer are two deep aquifer systems. The Cattamarra aquifer is termed the Yarragadee aquifer in the Perth region because the major contributing geological unit is the Yarragadee Formation. The Cattamarra aquifer is approximately 40m~120m below the natural ground level.

The Leederville aquifer is generally comprised of clayey strata interbedded with sandstone and siltstone. The Leederville aquifer is about 15m~120m below the natural surface. The Superficial aquifer is above the Leederville aquifer and water levels may vary seasonally in the Bassendean sand and underlying Guildford clay formation. The level of the Superficial aquifer varies between 0m and 15m below the natural ground level.

# Residue Profiles

Cone Penetrometer Tests with Pore Pressure (CPTu) measurements were performed at the site to determine the subsurface distribution of coarse and fine residues at the northern segment of cooling pond. Two typical CPTu profiles are shown in Figure 2. CPT16-09 is located on the northern perimeter of the cooling pond while CPT23-09 is located near the centre of the northern segment of the cooling pond. It is noted that a significant thick layer of residue sand was deposited at the northern boundary while thick mud was intersected at the center of the northern segment. The residue distribution was formed by deposition of coarse and fine residue along the northern section of the area. The coarse residue settled quickly after deposition whereas the finer residue was transported in the centee of the area with the decant water. The finer residue then settled slowly to form a thick low strength clayey silt horizon.

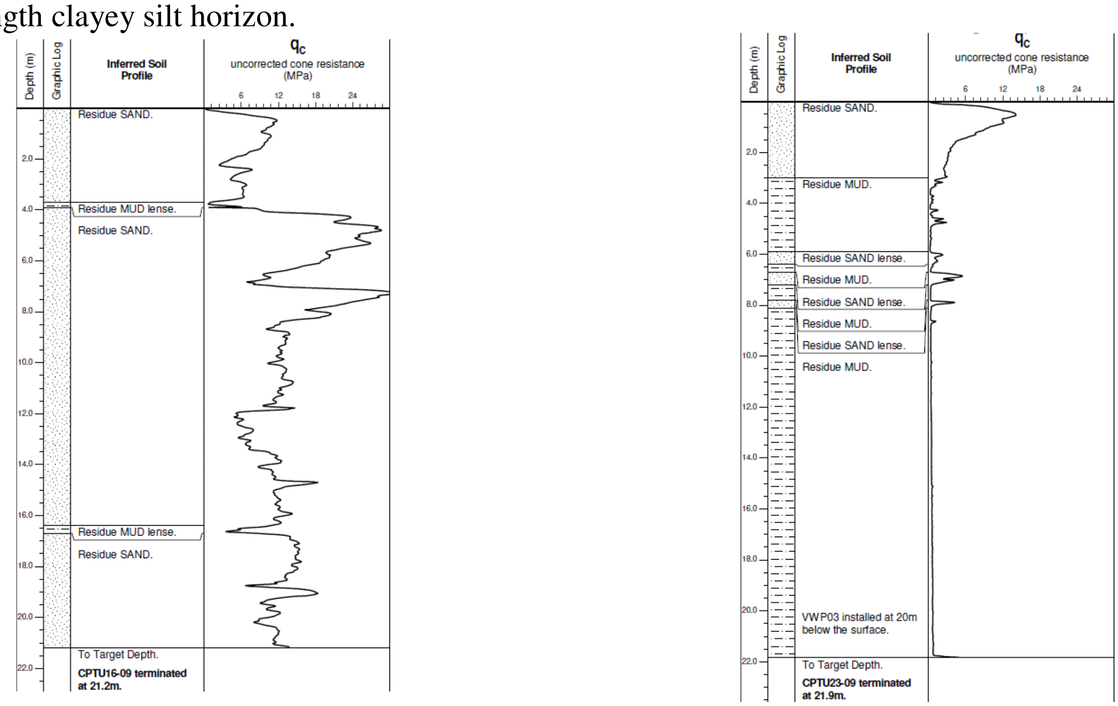



**Figure 2: Typical Residue Profiles at Cooling Pond Northern Segment**

Based on the CPTu results, contours of residue sand and residue mud were developed and are shown in Figure 3 and Figure 4 respectively. A north-south section through the northern segment of the cooling pond (Seciton A-A′) is presented in Figure 5. The liquor level at the northern segment is at 40.0m (AHD), which is apprxoimately 2.0m below the residue surface.

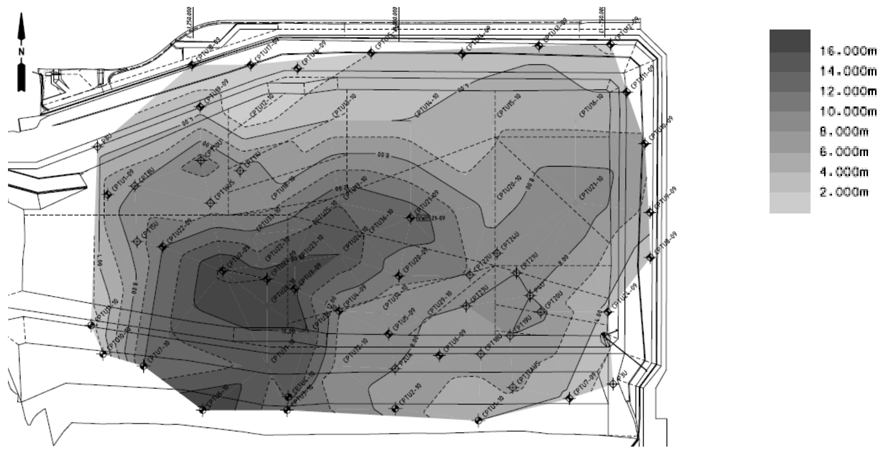



**Figure 3: Contours of Residue Mud Thickness at Northern Segment of Cooling Pond**

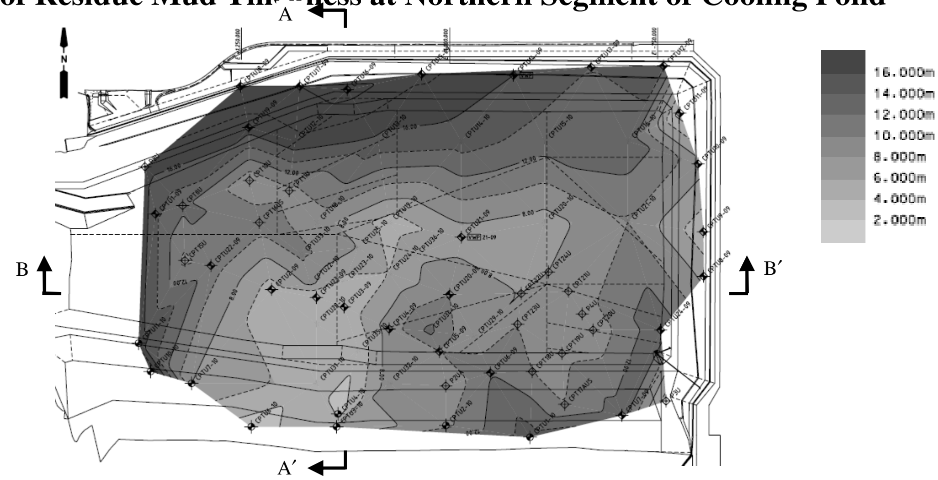



**Figure 4: Contours of Residue Sand Thickness at Northern Segment of Cooling Pond**

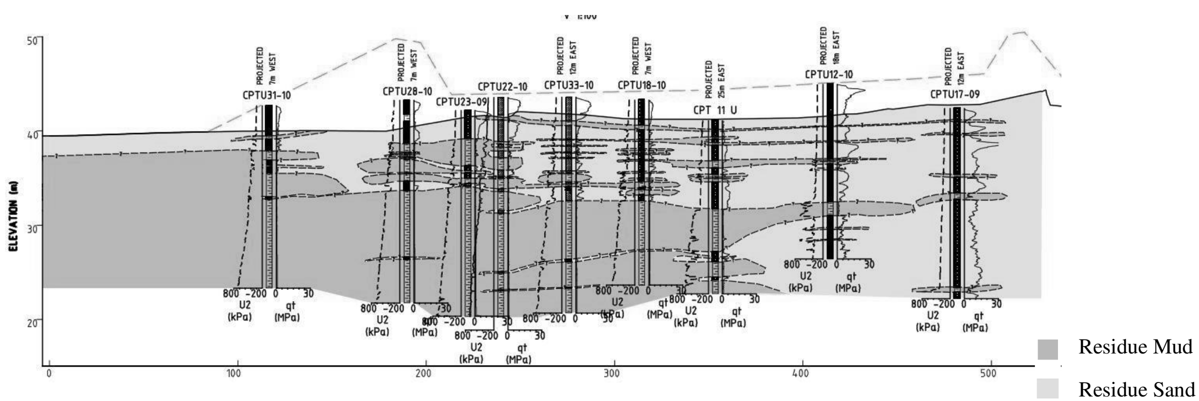



**Figure 5: Section A-A′ through Northern Segment of Cooling Pond (A-A′ Refer to Figure 4)**

## Geotechnical Parameters of Residues

Residue mud and residue sand are the by-products from the alumina refining process. The residue sand typically classifies as a silty sand (SM) to poorly graded clean sand (SP) in accordance with the Unified Soils Classification Sysytem (USCS). The sand is red brown in colour, fine to coarse grained with angular to subangular quartz particles. The results from historical laboratory testing (URS,2003) indicates that the residue sand has an effective friction angle (φ') of 38°.

The residue mud is typically dark red to red-brown in colour, and classifies as a medium to high plasticity silty clay (CI-CH) in accordance with the USCS. The residue mud typically has a liquid limit of 55 to 66 and a plasticity index of 27 to 32 (Cooling & Elias, 1994).

The respresentative particle size distributions for the residue mud and residue sand are shown in Figure 6.

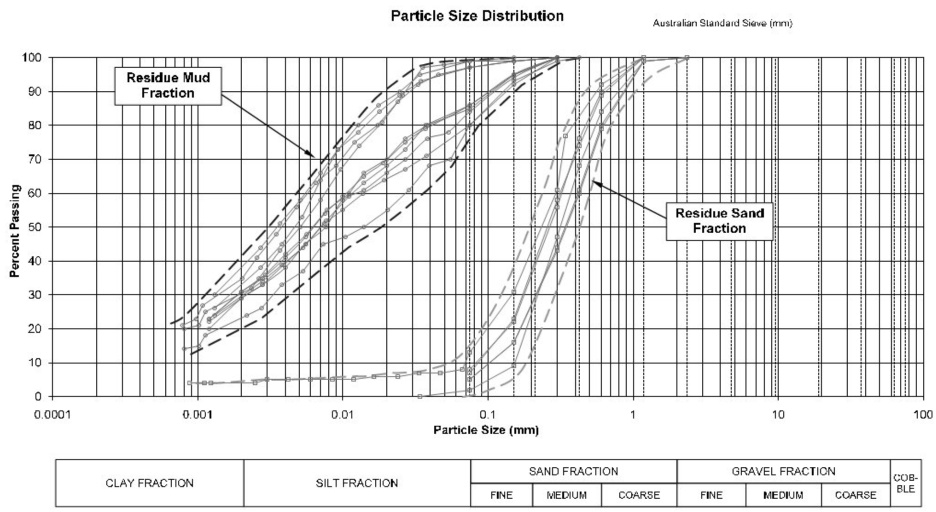



**Figure 6: Bauxite Residue, Particle Size Distribution**

Based on the CPT results, the average undrained shear strength of residue mud is approximately 20 kPa. The correlation of undrained shear strength to the overburden pressure ($S_u/\sigma'_v$) is 0.13.

A pumping well test was carried out at the site to measure the permeability of the residue sand (Figure 7). The derived permeability of the residue sand is approximately $4.0\times10^{-5}$m/s which correlates well with previous site data.


**Figure 7: Pumping Well Test in Progress**

CPTu dissipation testing on residue mud were performed to measure the in-situ horizontal permeability of the residue mud. For seepage and consolidation modelling, knowledge of the vertical permeability was required. Previous investigatory work and field measurements indicated that the vertical permeability is typically one order of magnitude less than the horizontal permeability. This enabled a correlation between the dissipation testing and vertical permeability to be established.

The geotechnical paramters of residue mud and residue sand are summarised in Table 1.

**Table 1: Summary of Geotechnical Parameters for Residues**

| **Material** | **Effective Shear Strength** | | **Un-drained Shear Strength (kPa)** | **Horizontal Coefficient of Permeability $k_h$ (m/sec)** | **Vertical Coefficient of Permeability $k_h$ (m/sec)** | | |
|---|---|---|---|---|---|---|---|
| | **Cohesion (kPa)** | **Friction Angle (Degree)** | | | **Lowest** | **Average** | **Highest** |
| Residue Sand | 0 | 38 | - | $4.0 \times 10^{-5}$ | - | $4.0 \times 10^{-5}$ | - |
| Residue Mud | - | - | 20 kPa or $S_u/\sigma'_v$ =0.13 | $1.0 \times 10^{-8}$ ~$9.7\times10^{-8}$ | $1.0 \times 10^{-9}$ | $5.9 \times 10^{-9}$ | $9.7\times10^{-9}$ |

# Basal Pore Water Build-up due to Residue Operations

Based on Terzaghi's consolidation and effective stress theory, any additional loading imposed on the current surface is initially supported by the pore water and not the soil skeleton. In the sand layer, water is squeezed out rapidly due to the high permeability. Therefore, sand particles support the load shortly after application. However, in the underlying residue mud layer, the time taken for the pore water pressure to fully dissipate is significantly longer due to the lower material permeability. Since the residue operations are continuous over many years, high water pressure could develop in the saturated mud due to the load applied by future dry stacking activities. As there is no sand drainge layer above the basal natural clay liner, the increase of the pore water pressure near the floor of the facility could potentially introduce seepage into the underlying groundwater system.

According to Alcoa's long term facilities plan, the final tailings capping elevation is 80m (AHD), or approximately 38m above the current cooling pond crest elevation of 42m (AHD). It is expected to take 30 years to reach the design elevation based on an average annual residue filling rate of 1.2m per annum (~16,000t/yr/ha).

Although the average annual residue filling rate is about 1.2m, the deposition rate is not consistent throughout the year (i.e. thick pours and time left latent for consolidation and drying before depositing the next layer of residue). However, to simplify the model analysis, the load from the stacked residue was increased in four discrete stages throughout the year. Each stage is equivalent to a 0.3m thick residue layer. The load from the residue was applied to the foundation instantaneously.

Finite difference code FLAC was used to determine consolidation within the residue deposit. The numerical model was based on the CPTU23-09 soil profile as shown in Figure 2. The pore water pressure under the tailings operations for 30 years is shown in Figure 8.

It is noted that the amount of pore water pressure increase is significantly influenced by the mud permeability value. The maximum build-up in pore water pressure occurs for the lowest permeabilty case. As the inital pore water pressure is 190 k Pa, the maximum pore water build-up could be 370 kPa, or 180 kPa greater than current static pore water pressure. A possible 55kPa pore water build-up is obtained for the case with the average permeability.

The pore water pressure increases over the initial years, eventually reaching equilibrium and a constant maximum pore water pressure. These results may be explained by the following equation.

Based on consoldiaton theory, the degree of the consolidation is defined as (Das, 2008):

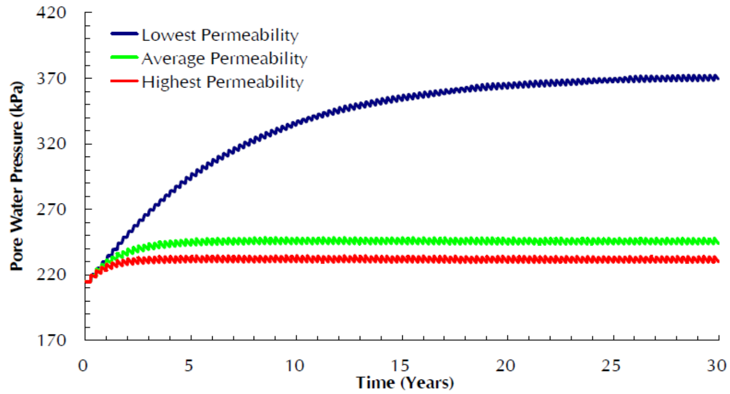



**Figure 8: Pore water Pressure at the Pond Base due to 30 Years of Tailings Operation**

$$U_z = \frac{\text{excess pore water pressure dissipated}}{\text{initial excess pore water pressure}} = \frac{\Delta u}{u_i} \quad \textbf{(1)}$$

The degree of the consolidation $U_z$ is proportional to the non-dimensional time factor $T_v$, which is defined by the following equation (Das, 2008):

$$T_v = \frac{C_v t}{H^2} \quad \textbf{(2)}$$

where $C_v$ is the coefficient of vertical consolidation, H is the drainage distance and t is the time for consolidation.

The values of $C_v$, H and t are all constant values for a given material (residue mud in our case). From equation (1) and (2), $U_z$ and $T_v$ are also constant values. Therefore, the dissipated water pressure after each stage is linearly related to its initial excess water pressure. During the first several years, the initial excess water pressure increases and in the meantime, the dissipated water pressure also increases. This causes the pore water pressure to reach an equilibrium at which point no further water pressure built up occurs.

A two-dimensional (2-D) consolidation analysis was also carried out to investigate the pond basal pore water pressure under the influence of the thick sand zone along the pond perimeter and the higher horizontal mud permeability. The section was established based on the residue distribution along the Section B-B′ as shown in Figure 4. Figure 9 shows the section residue profile while Figure 10 shows pore water pressure distribution for the 30 years of tailings operations. It is noted that the average residue mud permeability was adopted in the numerical model. The final pore water pressure in the centre thick residue mud (5.9 $\times 10^{-8}$ m/s) is approximately 245 kPa, which is similiar to the pore water increase from the one dimensional (1-D) model.

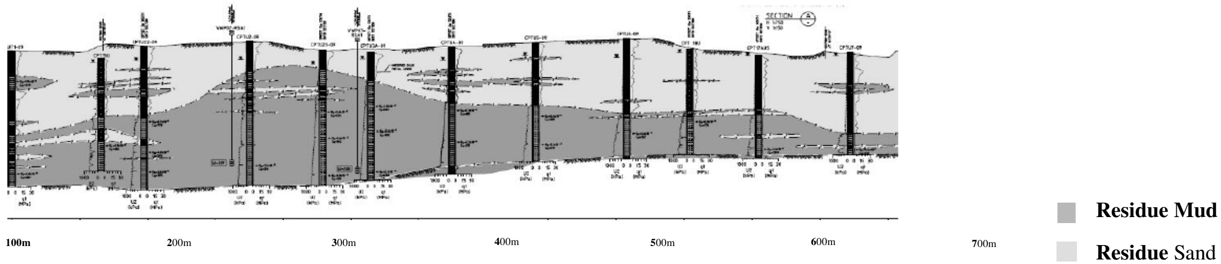
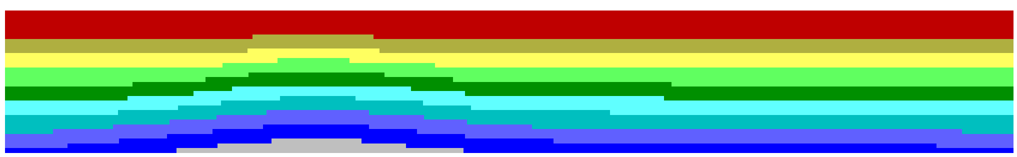



**Figure 9: Residue Distribution along the Section B-B′ (B-B′ Refer to Figure 4)**



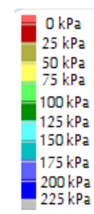



**Figure 10: Pore Water Pressure Distribution for 30 Years of Residue Operations**

# Proposed Engineering Solutions

The pore water pressure at the floor of the area comprises of static water pressure and the pore water pressure build-up due to residue loading. The static water pressure is influenced by the following issues:

- The amount of liquor at the cooling pond; and
- Direct rainfall, decant water and clean water from the sprinkler system on surface which will recharge the underlying residue.

A composite system is required to reduce the static water pressure and the pore water pressure build-up. A system is needed to reduce the source of seepage in the existing storage and therefore reduce both the seepage rate and seepage quantity that would otherwise occur due to ongoing residue deposition. The system comprises of the following engineering facilities:

- Deliquoring bores installed on the northern and eastern embankment of cooling pond, upstream of the containment embankments;
- Wick drains installed at the centre of the cooling pond in areas of thick residue fines; and
- Geosynthetic liner installed on the current residue surface.

The deliquoring bores are most effective around the perimeter of the storage, but due to a limited 'zone of influence', are less effective towards the centre of the storage. The deliquoring bores work on a continuing basis to reduce the quantity of contamination source in the existing storage.

The wick drains are traditional ground impovement methods to speed up the consolidation process and therefore increase the shear strength of fine grained material. Wick drains are used to reduce the pore water pressure increase and are most benefitial towards the centre of the storage, in areas that are beyond the 'zone of influence' of the deliquoring bores. The wick drains work as the quick response to any incremental loading (ie with each pour).

The wick drains also serve to improve the effectiveness of the deliquoring bores (and vice versa), as they help provide an additional flow path to allow liquor in residue fines zones to find a sand zone, where it can thereafter be drawn off by the deliquoring bores.

The liner is required to prevent transport water in the future residue from seeping into the existing materials potentially reversing the effects of the wicks and deliquoring bores.

The geotechncial analyses needed to address the specific design tasks are summarized as follows:

- Determination of the zone of influence and numbers of deliquoring bores required for the northern segment of the cooling pond;
- Determination of the area required for wick drains and spacing of wick drains; and
- Evaluation the integrity of the liner under load from dry stack residue.

# Geotechnical Design

## Influence Zone of Deliquoring Bores

Based on the estimated subsurface residue profile and derived permeability for the residue sand, the deliquoring bore design was carried out using the finite difference code FLAC. Both axisymmetric and two-dimensional models were analysed. The pore water pressure distributions of two models are illustrated in Figure 11 and Figure 12 respectively.

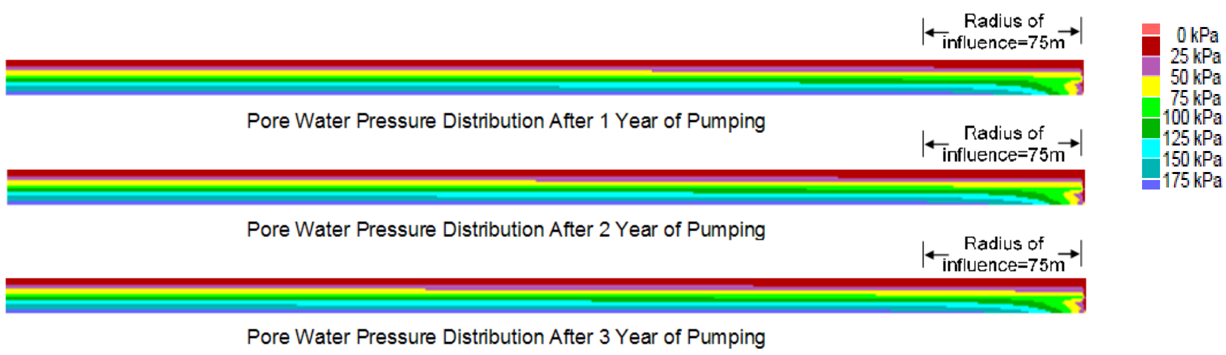



**Figure 11: Pore water Pressure Distribution Due to Deliquoring Bore (Axisymmetric Model)**

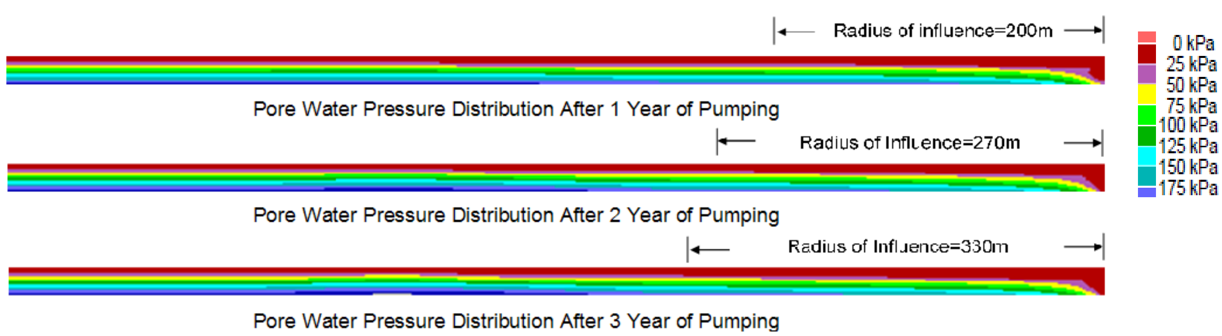



**Figure 12: Pore water Pressure Distribution Due to Deliquoring Bore (2-D Model, Bore Spacing of 150m)**

The radius of influence is approximately 75 m for the first three years for the axisymmetric model. These values are about one fourth of the results obtained from two-dimensional numerical simulations. It is believed that the effect of pumping is greatly exaggerated in a 2-D model. This effect is also greatly decreased when the water is flowing into the well in all directions in an axisymmetric model.

The actual conditions for the cooling pond dewatering bore configuration are estimated to fall between these numerical models. The compacted perimeter embankment of the cooling pond would prevent seepage from the north and east from flowing into the bores. Therefore, water flowing into the deliquoring bores will be mainly from saturated zones internal to the cooling pond perimeter, and therefore the zone of influence is likely to be $180^0$ rather than $360^0$ (as is the case for the axisymmetric model).

A pumping test was performed within the cooling pond. The groundwater drawdown at the pumping bore as well as at observation wells was measured. The results from pumping tests suggest that the radius of influence in five hours was approximately 55m.

Based on the analysis, the deliquoring bores are likely to have a radius of influence between 50m to 200m. Considering site specific data such as interbedded residue mud zones within the residue sand, it was recommended that a design radius of influence of between 75 to 150 m be used for the design. Five deliquoring bores were installed in the northern segment of the cooling pond.

## Wick Drain Design

The design for the wick drain system required the prediction of the rate of dissipation of excess pore water pressures using radial seepage into vertical drains as well as evaluating the contribution of the vertical drainage. For vertical drains the overall average degree of consolidation ($U_{ave}$) is the result of the combined effects of horizontal (radial) drainage and vertical drainage. The combined effect may be determined using the following equation (Das, 2008):

$$U = 1-(1-U_v)(1-U_h) \quad \textbf{(3)}$$

Where: $U_h$ is average degree of consolation due to horizontal drainage; and

$U_v$ is average degree of consolation due to vertical drainage.

The radial consolidation due to wick drains is influenced by the spacing between wick drains, soil permeability, construction disturbance (smear zone factor) and the performance of the wick drains (drain resistance factor). The design of the wick drains was calculated using Barron's formula (FHWA, 1986):

$$t = \frac{D^2}{8C_h}(F_n + F_s + F_r) In \frac{1}{1-U_h} \quad \textbf{(4)}$$

Three different factors including the Drain Spacing Factor ($F_n$), Soil Disturbance Factor ($F_s$) and Drain Resistance Factor ($F_r$) were used in the wick drain calculations. Based on the obtained soil parameters, a wick drain spacing of 3.0m was recommended. The combined effect of wick drain and deliquoring bores is shown in Figure 13.

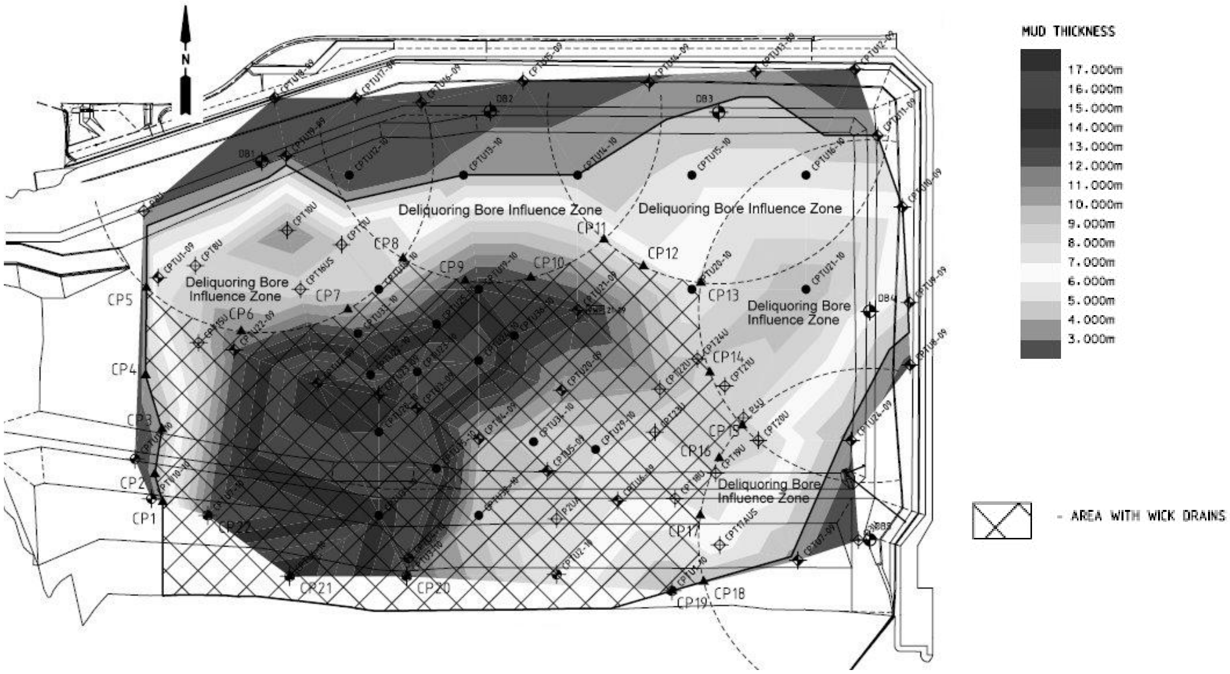
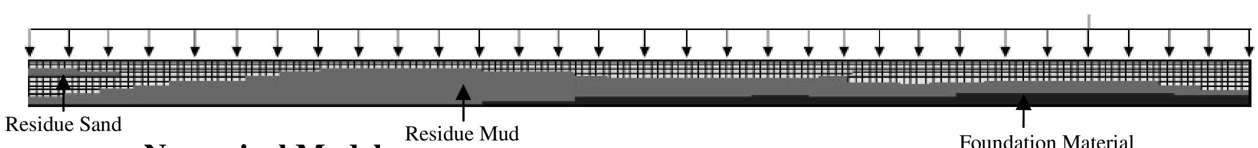



**Figure 13: Recommended Area for Wick Drain and Proposed Deliquoring Bores**

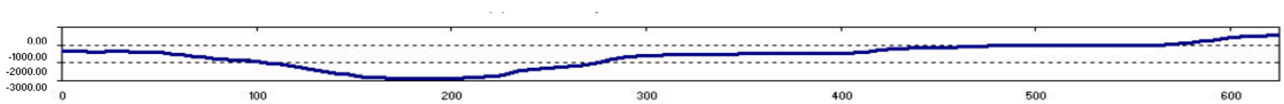
## Liner Integrity

It is proposed to install a separation layer between the future dry stacked residue material and underlying wet residue. The separation layer would comprise a synthetic High Density Polyethylene (HDPE) liner system sandwiched between two layers of sand. As shown in the subsurface cross section, there is a significant variation in the thickness of residue mud and sand within the cooling pond footprint. During initial studies excessive differential settlement due to rapid changes in the lateral and vertical distribution of residue were identified as a potential risk.

Differential settlement analysis was carried out to estimate the maximum tensile stresses and strains developed in the HDPE liner. The HDPE was modelled as a structural element with zero compressive strength and bending stiffness to represent its flexibility. An interface model was used to simulate the sliding between the soil and liner. The typical section with varying residue mud and sand thickness used in the analysis is Section B-B, as shown in Figure 9. The result of numerical simulations (Figure 14) indicates that the maximum settlement could be 2.5m and maximum strain developed in the HDPE liner could be 0.4%, which is within the strain limit of 1% for HDPE. Therefore, it was concluded that a HDPE liner could be used as a separation layer in the cooling pond.




**(a) Numerical Model**



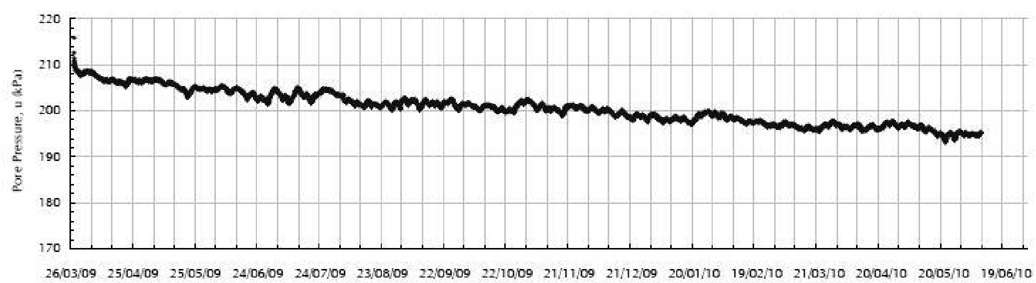

**(b) Settlement Profile along the Section (mm)**

**Figure 14: Model for Differential Settlement Analysis**

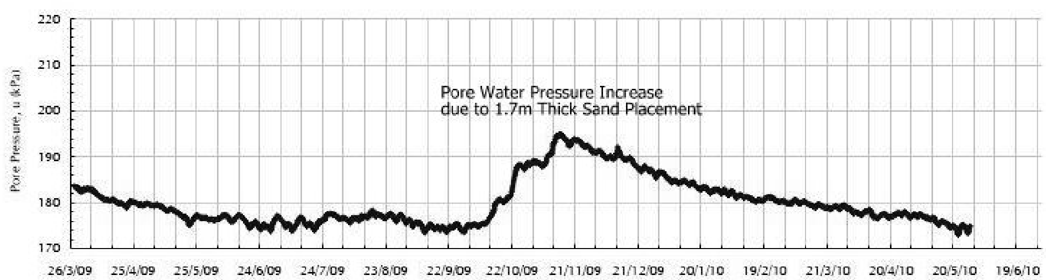
# Field Monitoring

Three Vibrating Wire Piezometers (VWP's) were installed in the northern segment of the cooling pond during 2009. The VWP's were used to continuously monitor variations in pore water pressure near the base of the deposit. The pore water pressure results for two such instruments at VWP23-09 and VWP21-09 are presented in Figure 15. Table 2 lists the variations of surface floor level between March 2009 and May 2010. From the results there was an approximate 20kPa pore water pressure increase near VWP23-09 between 10 October 2009 and 15 November 2009. The pore water pressure increase is consistent with the increase in elevation of the sand floor. Table 3 indicates that approximately 1.7m thickness of sand was placed at the location of the VWP23-09. The generated pore water pressure slowly dissipated, reducing to 178kPa by May 2010. It took approximate 6 months for the pore water pressure to fully dissipate. The time for 50% dissipation was approximately 1,440 hours.

VWP21-09 data indicates that the pore water pressures gradually decreased from 210kPa to 200kPa between March 2009 and May 2010. It is difficult to determine the reasons for the pore water pressure change at VWP21-09, however there is general agreement that the cooling water inflow into this area was reduced, thereby allowing accumulated water to flow into the foundation which in turn recharged the static water table.




**(a) VWP 21-09 Data between March-2009 and June-2010**




**(b) VWP 23-09 Data between March-2009 and June-2010**

**Figure 15: VWP Monitoring Data**

**Table 2: Surface Floor Variations of VWPs**

| VWP No. | At the Time of VWP Installation (m, AHD) | Current Elevation (m, AHD) | Surface Sand Placement (m) |
|---|---|---|---|
| VWP21-09 | 44.0 | 43.4 | -0.6 |
| VWP23-09 | 41.3 | 43.0 | 1.7 |

The field monitoring data indicate that the pore water pressure at the base of the area will increase due to the surface sand placement. The site data has confirmed the conclusions from the previous consolidation analysis.

# Conclusions

The proposed conversion of the existing cooling pond to a dry stacking residue site needed to address the potential for increased seepage from the existing saturated residue into the underlying aquifers. To address this issue, deliquoring bores are proposed along the perimeter residue sand to reduce the liquor head. Furthermore, wick drains are proposed in the central thick mud zone to promote consolidation of these poorly draining materials and avoid pore water build-up near the base. Finally, an HDPE liner was proposed as a separation layer to limit surface water recharging the underlying wet residue. This composite system is currently being installed and monitored to determine effectiveness.

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