Fourth Australia - New Zealand
Conference on Geomechanics,
Perth, 14-18 May 1984

Gravity Underdrainage as an Aid to the Consolidation of Red Mud Residue from the Alumina Industry

D.J. GLENISTER
Manager, Residue Development, Alcoa of Australia, Western Australia
and
D.J. COOLING
Civil Engineer, Alcoa of Australia, Western Australia

1 INTRODUCTION

Alcoa of Australia currently produces 4 million tonnes of alumina annually at its refineries located at Kwinana and Pinjarra. New refineries at Wagerup (Alcoa) and Worsley (Worsley Alumina) will commence operations in 1984 and by 1985 total alumina produced in Western Australia should amount to 5.6 million tonnes per year or 21% of the world's production. (Figure 1).

All of these refineries utilize bauxite mined in the nearby Darling Range which by world standards is low grade. For every tonne of alumina approximately 2 tonnes (dry weight) of residues are produced for disposal. By 1985 the bauxite residues generated in Western Australia will account for 40% of the world's total.

Waste disposal from mineral processing industries pose some major environmental problems. In the Western Australian alumina industry this is particularly so for a number of reasons; the volume of waste produced, the location of the refining operations near to population centres and adjacent to some of the State's most productive land, and the potential adverse impact of the caustic waste components with ground and surface water resources.

Some of these problems are general to the alumina industry and over the past few years considerable effort has been made worldwide to develop disposal techniques which lessen the environmental impacts.

The most widely practised form of bauxite residue disposal is similar to mineral tailings disposal in general and involves transportation of the residue solids to the waste impoundment area as a low density slurry. The solids settle into discrete coarse and fine zones and the liquor is decanted and returned to the process. Often the disposal area provides a liquor surface area for process cooling and a reservoir for water catchment during the wet months. A number of problems are inherent with this form of disposal: the saturated mass of residue is difficult to dewater; the amount of caustic pore water and the hydraulic gradient on the base seal of the impoundment makes it difficult and expensive to prevent escape; the low settled density of the fines (red mud) fraction decreases volumetric storage efficiency; the slow rate of consolidation and low strength of the red mud makes rehabilitation for future land use difficult and time consuming.

Prior to 1980 Alcoa of Australia reviewed available techniques to improve these factors and it was decided to investigate the benefits of gravity underdrainage in the disposal of the red mud.

A pilot disposal facility was constructed at the Pinjarra refinery for this purpose and was filled during 1981-1982.

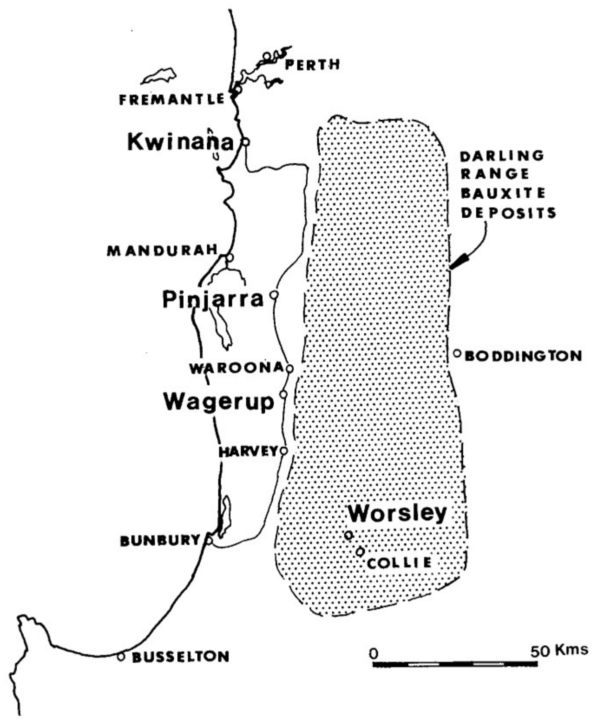

Figure 1 Location Plan

2 BAUXITE RESIDUE PROPERTIES

Bauxite residue is composed primarily of finely divided iron and silica minerals in a caustic solution. The particle size distribution depends upon the bauxite mineralogy and the grinding processes employed. Darling Range bauxite residue is characterized by a high coarse fraction which results from the silica in the bauxite. The coarse fraction is a fine to medium grained sand which is free draining. This coarse fraction represents 35% of the residue produced by the Pinjarra plant, or 1.75 million tonnes per year. The fine fraction, or 'red mud', is a silt and clay sized material which can be difficult to settle and has a slow rate of consolidation in the disposal area. Particle sizing data is presented in Figure 2. The concentration of the caustic solution entrained with the residue solids depends upon the degree to which the mud is washed prior to disposal and is typically in the range of 10-20 grams per litre alkali (expressed as Sodium Carbonate).

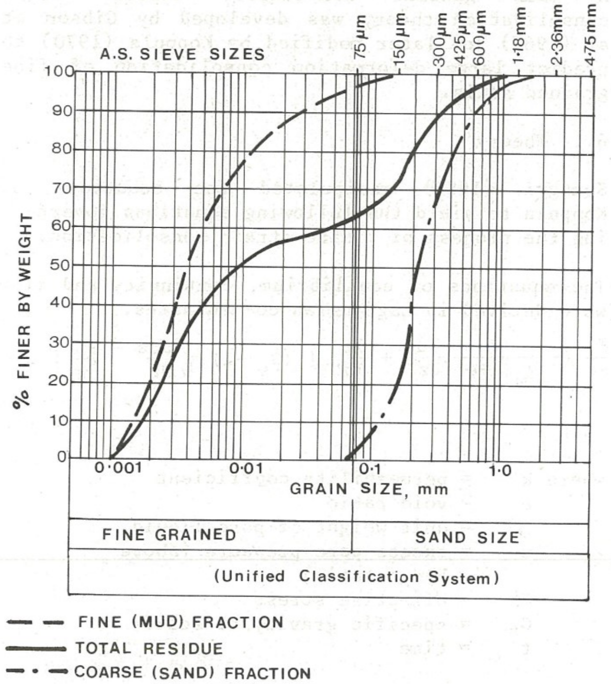

Figure 2 Particle Sizing Data, Pinjarra Residue

3 DESCRIPTION OF THE PILOT UNDERDRAINED LAKE

At Pinjarra, due to the essentially flat landscape and the presence of sands and sandy clay surface soils, the method of construction for residue impoundments is to excavate material from the base to construct full perimeter embankments. The Pilot Underdrained Lake was constructed in such a way adjacent to existing residue facilities. It covered a total area of 10 hectares and had an average depth of 15 metres providing a total mud storage volume of 1.2 million cubic metres. The base drainage system was constructed using the residue sand fraction for the filter layer with a network of slotted polyethylene pipes installed within it. Comparison of the particle sizing data (Figure 2) reveals that the often quoted Terzaghi criteria for filter selection was not met, however the suitability of the residue sand and drainage piping was checked by small scale field trials prior to confirmation of the design.

During filling, only the fine residue fraction was deposited in the lake as a slurry with solids density of approximately 20% (w/w). The free liquor was decanted, first using a bank mounted decant pump and later using a weir. The decant pump required a free liquid suction depth of 2m to achieve the required decant clarity, while the weir could operate with a relatively thin surface liquor layer of 300mm or less.

The lake was filled over a 29 month period at a relatively constant solids input rate with occasional pauses for mechanical maintenance or plant related problems. The residue slurry was discharged into the lake via either of two centrally located discharge towers or from individual spigots located at the banks. Except during final topping off, the surface of the settled mud was submerged due to decant clarity requirements.

4 MONITORING

The experimental nature of the Pilot Lake meant that a full range of monitoring was carried out during the operating and post-operating periods. Flow measurements combined with rainfall and evaporation measurements gave complete volume and mass balances. Chemical analysis of all flows allowed assessment of interactions with the normal plant operations. Geotechnical monitoring consisted of pore pressure measurements complimented by a full range of laboratory tests on 'undisturbed' and disturbed mud samples.

4.1 Monitoring Stations

Prior to commissioning the Pilot Lake a number of remote monitoring stations were installed within the disposal area. These were designed to provide pore pressure measurements within the drainage layer and at various elevations within the deposit, together with groundwater quality data. (See Figure 3). Two stations were designed with readout terminals located on the embankments to provide data during and subsequent to the filling of the lake. Two additional stations, inaccessable during the filling of the lake, were installed to provide data after filling.

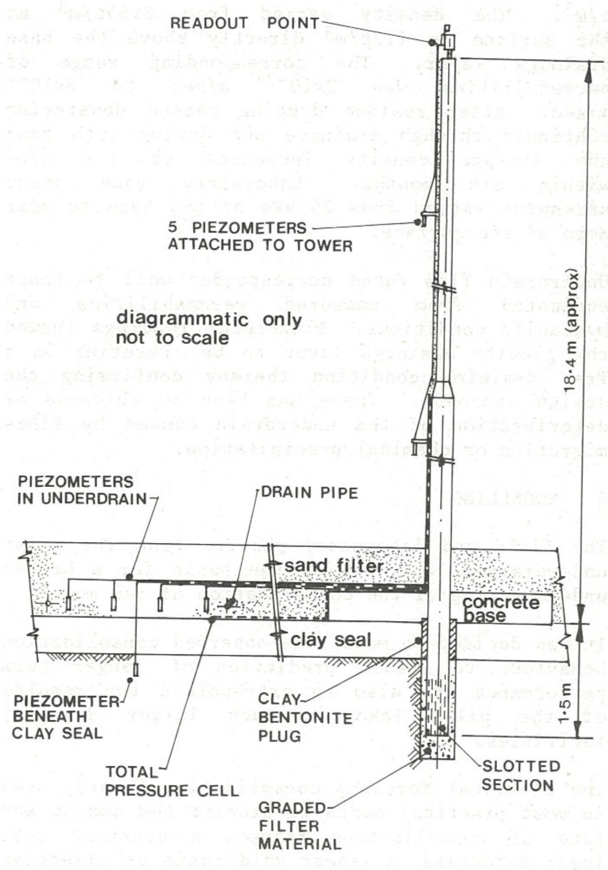

Figure 3 Cross Section of a Typical Monitoring Station

4.2 Solids Density

Deposited volumes were estimated using survey techniques which mapped the settled solids surface. (Echo sounding was the main technique used). These estimates provided a check on the flow volume balance, and together with the flow mass balance gave an indication of the average solids density in the lake.

4.3 Sampling

A number of sampling programmes were completed during the operating and post-operating periods. Samples were collected using an air actuated piston sampler operated from a small drill rig mounted on a barge. Good 'undisturbed' sample recovery was achieved for densities above 55% solids by weight (dry density of 0.88 t/m^3). At lower densities disturbed samples were recovered using a slurry sampler.

4.4 Laboratory Testing

Moisture contents of all samples were determined and dry density and per cent solids calculated. Laboratory vane shear strengths, particle size distributions and permeabilities were measured for selected samples. Chemical analyses were performed on some samples to determine entrained liquor composition.

5 FIELD AND LABORATORY RESULTS

During the operational phase the residue settled and consolidated to an average dry density of 1.0 t/m^3. The density varied from 0.65t/m^3 at the surface to 1.2t/m^3 directly above the base drainage layer. The corresponding range of permeabilities was 2×10^{-7} m/sec to 8×10^{-9} m/sec. After residue dumping ceased dewatering continued through drainage and drying such that the average density increased to 1.1 t/m^3 within six months. Laboratory vane shear strengths varied from 25 kPa at the base to near zero at the surface.

Underdrain flow rates corresponded well to those estimated from measured permeabilities and hydraulic conditions. Piezometer readings showed the gravity drainage layer to be operating in a free draining condition thereby confirming the design approach. There has been no evidence of deterioration of the underdrain caused by fines migration or chemical precipitation.

6 MODELLING

The field and laboratory results from the pilot underdrained lake provide the basis for a better understanding of the consolidation of red mud.

It was decided to model the observed consolidation behaviour to enable prediction of longer term performance and also to extrapolate the results of the pilot lake to much larger disposal facilities.

The classical Terzaghi consolidation theory, used in most practical cases to predict the amount and rate of consolidation assumes a constant soil layer thickness, a linear void ratio vs effective stress relationship and constant coefficients of permeability and compressibility. During the consolidation of red mud, large changes in void ratio occur causing the coefficients of permeability and compressibility to change by orders of magnitude. The Terzaghi theory can be used to model these large deformations by incremental adjustment of the soil properties and layer thickness but this has limited application. The problem is further complicated during the filling of the lake.

A more general non-linear, finite strain consolidation theory was developed by Gibson et al (1967) and later modified by Koppula (1970) to predict large deformation consolidation of fine grained soils.

6.1 Theory

Somogyi (1980) manipulated the equations of Koppula to yield the following equations governing the process of finite strain consolidation.

The equations of equilibrium, continuity and flow were derived in Lagrangian co-ordinates.

$$\frac{\partial}{\partial z}\left(-\frac{k}{\gamma_w(1+e)}\frac{\partial u}{\partial z}\right) + \frac{de}{d\sigma'}\left[(G_s-1)\gamma_w\frac{d\Delta z}{dt} - \frac{\partial u}{\partial t}\right] = 0 \qquad \ldots(1)$$

where k = permeability coefficient
e = void ratio
γ_w = unit weight of pore liquid
u = excess pore pressure (above hydrostatic)
σ' = effective stress
G_s = specific gravity of solids
t = time

and Z is an independent variable given by

$$z(a) = \int_o^a \frac{da'}{1+e(a', o)} \qquad \ldots(2)$$

where 'a' is an independent variable in Lagrangian co-ordinates.

In terms of the independent volumetric variable, Z, a particular point in the deposit is identified by the volume of solids between it and a predescribed datum. The use of a volumetric variable avoids a distance co-ordinate which would be dependent on the state of the particles (viz void ratio).

Closed form solutions to equation (1) have not yet been developed. A finite difference numerical solution was adopted by Somogyi (1980) and has been used as the basis for computer programs which solve equation (1) for a specific case. The solution method requires the specification of the constitutive relationships of the consolidating material (namely compressibility and permeability).

Carrier (1982) has shown that the compressibility and permeability relationships for many mineral wastes can be expressed conveniently and accurately by the following power functions:

$$e = \alpha\left[\frac{\sigma'}{P_{atm}}\right]^{\beta} \qquad \ldots(3)$$

$$k = \mu\,\frac{e^{\upsilon}}{1+e} \qquad \ldots(4)$$

where P_{atm} = atmospheric pressure and α, β, μ, ν, are empirical coefficients determined from laboratory and field tests.

For red mud in the pilot underdrained lake the following compressibility and permeability relationships were found to provide the correct magnitude and rate of consolidation respectively to match field observations:

$$e = 1.965\ \sigma'^{-0.1} \quad \ldots (5)$$

$$k = 3.60 \times 10^{-9}\ \frac{e^{4.10}}{1+e} \quad \ldots (6)$$

where σ' is measured in t/m^2 and k in m/sec. The coefficients were derived from the field measurements of density, pore pressure and permeability, and laboratory oedometer and triaxial measurements of compression and permeability.

It is usual to determine, through laboratory testing, the material constitutive relationships, with which predictions of consolidation are made. The predictions are then verified by field tests with the necessary refinements to the relationships being made. In the above case the results from both laboratory tests and field measurements have been combined to establish the relationships of equations (5) and (6).

6.2 Modelling Results

With the appropriate initial values, impoundment boundary conditions and solids input rate, the numerical solution will generate the pore-pressure profile which will be present at any specified time during the filling of the lake, or during subsequent quiescent consolidation of the material in the lake. The effective stresses corresponding to the modelled pore pressures are calculated from the following definition of effective stress, used in the derivation of equation (1),

$$\sigma'(z,t) = \sigma_b(z,t) - u(z,t) \quad \ldots (7)$$

where σ_b is the buoyant stress. The values of void ratio and permeability follow from equations (5) and (6). These can then be used to determine the deposit density profile and underdrain flows.

The modelled pore pressure profiles and density profiles at the completion of filling have been plotted on Figures 4 and 5 respectively. The corresponding field measurements have been included for comparison. Figure 6 shows the modelled and recorded underdrain flows during and subsequent to the filling of the lake.

The model assumes a constant solids input rate of 8,600 dry tonnes of residue per week with a filling period of 130 weeks, continuous operation of the underdrain and a 2m surface layer of liquor from which the decant pump operates. Although the operation of the disposal lake deviated from these steady conditions, the variations had little effect on the overall modelled consolidation. The major variation was in the operation of the underdrain. It was not commissioned until 25 weeks after the commencement of filling, and pumping from the underdrain sump was intermittent at times due to pump breakdowns.

The model output shows very good agreement with field observations. Similar agreement has been achieved at various times during the filling of the lake. The model thus provides a tool for the accurate prediction of consolidating red mud and can be used in the design and optimization of future residue disposal facilities.

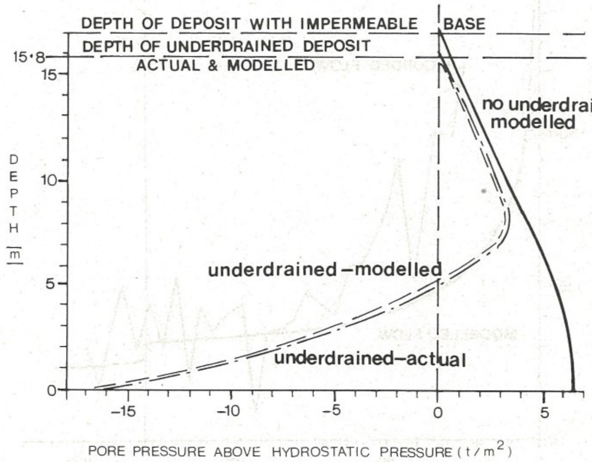

Figure 4 Pore Pressure Profiles

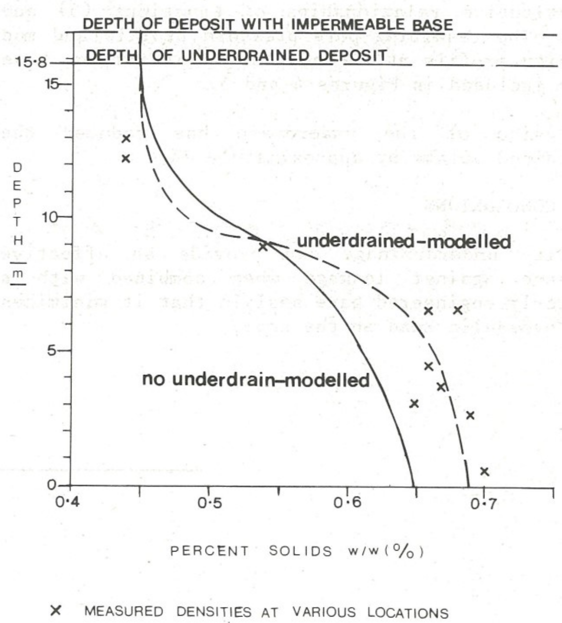

Figure 5 Density Profiles at Completion of Filling

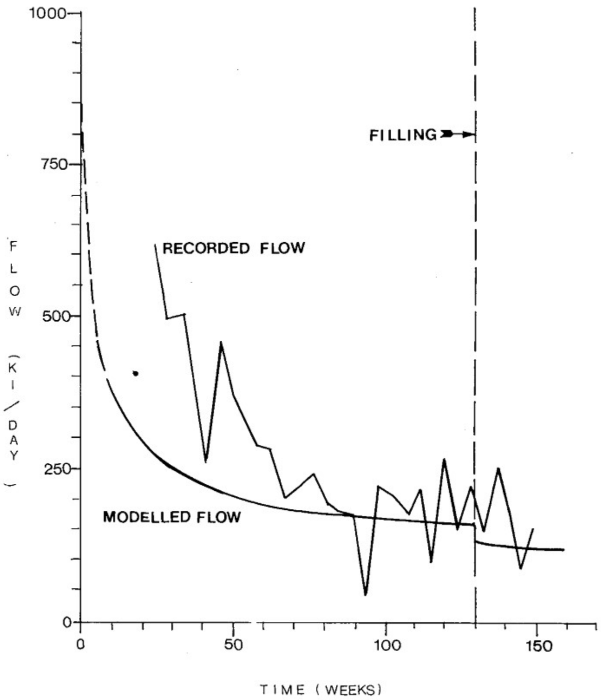

Figure 6 Underdrain Flows

6.3 Consolidation Without Underdrainage

To gauge the performance of the gravity underdrainage system as an aid to consolidation, the boundary conditions to the model were altered so as to represent a lake with an impermeable base. Filling of the lake was again simulated with consolidation being controlled by the constitutive relationships of equations (5) and (6). The resulting pore pressure profile and mud density profile at the completion of filling have been included in Figures 4 and 5.

Inclusion of the underdrain has reduced the contained volume by approximately 7%.

7 CONCLUSIONS

Gravity underdrainage can provide an effective defence against leakage when combined with a properly engineered base seal in that it minimizes the hydraulic head on the seal.

Provision of gravity underdrainage results in significant improvement in the consolidation of red mud residue from the bauxite processing industry.

A large scale pilot facility such as that constructed at Alcoa's Pinjarra refinery is an ideal way to evaluate gravity underdrainage. Based upon the results achieved a gravity underdrainage system has been incorporated into new red mud disposal facilities at the Pinjarra, Kwinana and Wagerup refineries.

Underdrainage can be provided economically using the coarse residue fraction for the base filter.

A mathematical model based upon finite strain consolidation theory has been developed and checked against observed field behaviour. This model can be used with confidence to predict consolidation of red mud under a variety of conditions. It will be used to predict performance of new larger scale underdrained lakes.

REFERENCES

Carrier, W.D., (1982). Predicting Consolidation of Phosphatic Clay Waste, presented at Conference on Consolidation and Dewatering of Fine Grained Particles, University of Alabama, U.S. Bureau of Mines, Tusacaloosa, Alabama.

Gibson, R.E., G.L. England and M.J.L. Hussey, (1967). The Theory of One Dimensional Consolidation of Saturated Clays, Geotechnique, Vol. 17, pp 261-273.

Koppula, S.D., (1970). The Consolidation of Soils in Two Dimensions and with Moving Boundaries, thesis submitted to the University of Alberta, in partial fulfillment of the requirements for the degree of PhD.

McNabb, A., (1960). A Mathematical Treatment of One Dimensional Soil Consolidation, Q. Appl. Maths, Vol. 17, No. 4, pp 337-347.

Somogyi, F., (1979). Large-Strain Consolidation of Fine Grained Slurries, Wayne State Uni, Department of Civil Engineering, Detroit, Michigan.