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

Chemical Grouting of Dam Foundations in Residual Laterite Soils of the Darling Range, Western Australia

D.M. BRETT
Senior Engineer, GHD-Dwyer (W.A.) Pty. Ltd., Western Australia
and
T.R. OSBORNE
Managing Director, GFWA Pty. Ltd., Western Australia

SUMMARY Environmental protection measures incorporated into the construction of the Worsley Alumina Refinery, near Collie, Western Australia, have included the chemical grouting of low permeability soil foundations of a major earthfill dam.

Weathering of the granite bedrock at the dam site has resulted in a laterite soil profile to a typical depth of ten to twenty metres with natural permeabilities measured at from 10^{-4} to 10^{-8} metres per second.

Design considerations required a minimum grout curtain permeability of 10^{-6} metres per second and field trials found that a low viscosity resin grout, injected by the Tube-a-Manchette (TAM) method could achieve this. The development of grouting techniques including TAM design, grout pressure limits, refusal criteria and permeability testing method, are discussed. The production phase of the work is described and final measured permeabilities are analysed.

1 INTRODUCTION

The Worsley Alumina Refinery has been constructed on the headwaters of the Augustus River near the town of Collie in the Darling Ranges of Western Australia.

The refinery processes bauxite by the Bayer process. This process involves the extraction of alumina from the ore using a hot, concentrated caustic soda solution. Approximately three tonnes of ore are processed to produce one tonne of alumina. The remaining 'bauxite residue' is filtered, to remove the majority of the caustic liquid, and is disposed of on site by a dry stacking technique.

Stormwater run-off and leachate from the bauxite residue stacks is expected to contain a proportion of residual caustic soda and a system of dams, channels and groundwater bores has been designed to collect and contain any contaminated water.

The focus of the contaminated water containment system is the Refinery Catchment Lake (RCL). All contaminated water is collected in this lake, formed by the construction of a 29 metre high, 800 metre long earth fill dam. The lake also acts as a cooling pond for the project's coal fired power station and, with the continuing inflow of contaminated water and the evaporation induced by the heat input, the pH and salinity of the lake are expected to steadily increase over the life of the refinery.

Whilst the RCL dam is only the first line of defence against loss of contaminated water, the design ensured that any seepage through the foundations and abutments would be negligible by incorporating a grout curtain.

2 LATERITE SOILS OF THE DARLING RANGES

The rock types found in the Darling Ranges are granites, quartzites and gneisses, often with intrussions of dolerite dykes and quartz seams. Much of the rock has been subject to intense shearing and has been deeply weathered. The degree of weathering has been influenced by the effects of high rainfall, high evaporation, high water tables and the extent of vegetation. Depths to bedrock in the Worsley area have been recorded at over forty metres.

Several weathering profiles have been identified (Gordon, 1964; GHD-Dwyer, 1980) however, in general these are variations on a similar theme comprising a 'layer cake' profile, as shown in Figure 1.

The development of this weathering pattern leads to three major permeable zones;
- the surface laterite profile
- the residual quartz and mica zones above bedrock
- joints and shears in the rock mass

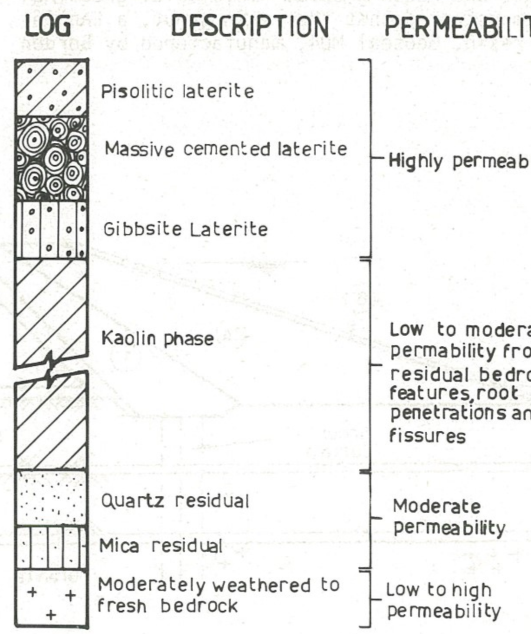

FIG 1 Typical Laterite Soil Profile

Rock features such as quartz seams, joints and shears, remain as weaknesses in the soil profile and tree root penetrations are a further potential source of permeability.

3 DESIGN OF THE GROUT SYSTEM

To assess the effect of grouting on seepage past the dam, a detailed seepage analysis was carried out using a finite element program, RESEP, developed at Sydney University. The programme was expanded to enable analysis of a mesh of 622 nodes. This was necessary to enable the combination of seepage through both the embankment and the foundation.

Features of the dam are;
1) Upstream and downstream earth shells.
2) An inclined core of selected earthfill.
3) An inclined chimney drain.
4) A horizontal blanket drain comprising a gravel centre sandwiched between two sand filter layers.
5) Relief wells at the downstream toe.

For the purpose of seepage analysis, features of the foundation were modelled as:
1) Impervious rock at average 20 metres.
2) Cut-off trench to 3 metres intercepting surface permeable features.
3) Optional one metre thick sand layers at depths of 9 metres and at 19m (above rock level).
4) Optional single row (3m) or double row (5m) grout curtain.

These features and the permeabilities assigned for analysis are shown in Figure 2. Results are summarized in Table 1.

The results clearly indicated that, if the permeable features synonymous with the weathering profile of the Darling Range, and detected in the site investigation programme, were continuous, then significant seepage could result. Also the results clearly indicated that the potential seepage was virtually eliminated by grouting.

Prior to the design stage some preliminary trial grouting had been carried out using cement, silicate and resin grouts. This trial grouting had demonstrated that the resin grout, a tannin based resin, Geoseal MQ4, manufactured by Borden Chemicals, was both effective in reducing soil permeability and was relatively easy to use. The resin and catalyst (caustic soda) are supplied in powder form in pre-weighed bags. They are mixed together with water using conventional grouting equipment. Viscosity for the 12.5% solution used is quoted as 2 centipoise (cp).

Due to the instability of uncased boreholes in the foundation soils, injection of grout by the Tube-a-Manchette (TAM) technique was found most practical.

During design a comprehensive literature search of chemical grouting references was undertaken. The search was relatively unsuccessful in identifying grouting projects in similar conditions.

The final philosophy which emerged for the grout curtain design was to specify an initial single row of grout holes with primary holes at 8 metre centres and compulsory secondary holes at 4 metres. Pre-grouting permeability tests, of 2 metre soil stages, were required at alternate primary holes.

Initial grout results would be used to:
1) Develop a detailed understanding of soil permeabilities at the site.
2) Determine the extent of final grouting necessary.

Due to the lack of available information of practical grouting techniques for work of this type, the specifications were drawn up on a performance basis with the Contractor to be chosen on the basis of expertise in the field. A detailed development programme was specified as part of the grouting contract.

4 DEVELOPMENT OF GROUTING TECHNIQUES

4.1 Summary

On site development work commenced with laboratory testing aimed at confirming manufacturers information about the viscosity, setting times, stability and effect of the grout on site soils. This work was followed up with practical field testing of alternative grouting techniques. Techniques chosen were further modified with field experience during production.

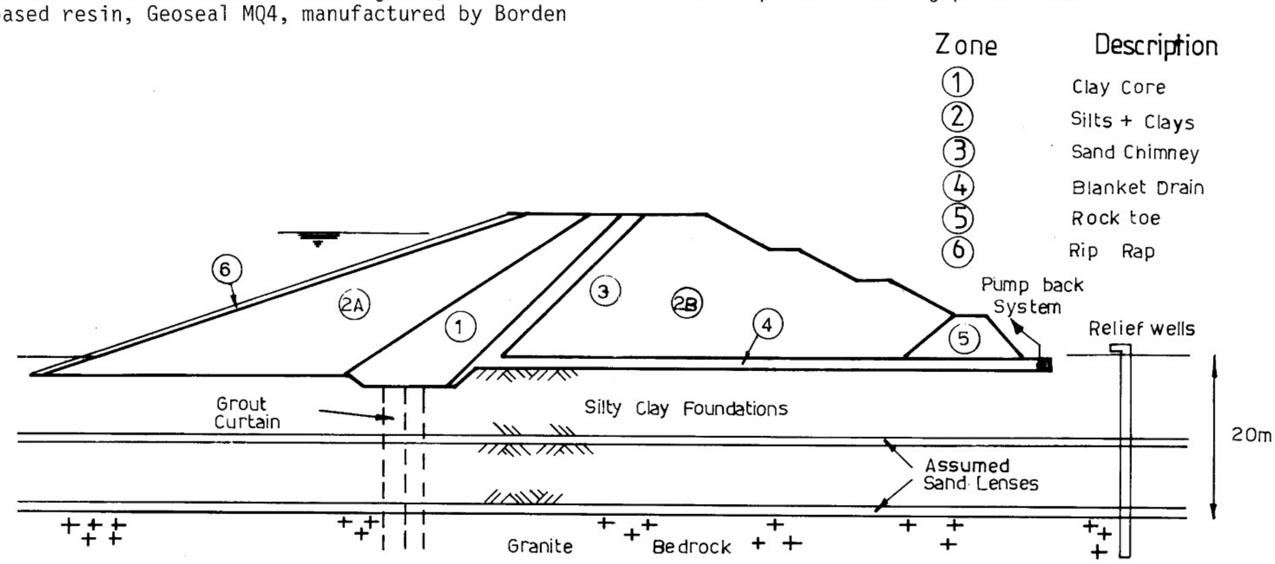

FIG 2 RCL Dam - Typical X-Section (NTS)

TABLE 1

RESULTS OF SEEPAGE ANALYSIS

FOUNDATION CONDITIONS ASSUMED	CALCULATED SEEPAGE (Ml/year)					
	NO GROUTING		SINGLE ROW CURTAIN		MULTIPLE ROW CURTAIN	
	TOTAL	BYPASS	TOTAL	BYPASS	TOTAL	BYPASS
Homogeneous, Isotropic foundation $Kc=10^{-6}$ m/sec $Kgc=10^{-7}$ m/sec	63	1	45	1	38	1
Soil layer over rock $Ks=10^{-4}$, $kgs=10^{-7}$ m/sec $kc=10^{-6}$, $kgc=10^{-7}$ m/sec	213	18	77	5	56	3
2 sand layers K as above	406	40	100	8	67	6

Note: Bypass means seepage flow escaping other collection systems at the downstream toe of the dam. Ks denotes permeability of sand, Kgs denotes permeability of grouted sand. Kc denotes permeability of silty clay, Kgc denotes permeability of grouted silty clays.

4.2 Viscosity

Viscosity measurements were made using a Baroid viscometer and 4.75 mm aperture Marsh Funnel. Results of 3 to 5 cp were consistently achieved on first mixing.

4.3 Temperature Effects of Gelling

The manufacturers information on the effect of temperature and concentration on setting times was confirmed by site testing.

Figure 3 summarizes the effect of various curing temperatures on gel-time, using a 12.5% solution.

For the purpose of this project, the grout was considered gelled when a viscosity of 6 cp was reached. At this viscosity the effective penetration ability of the grout was greatly reduced over that of fresh grout.

As can be seen from Figure 3 the gel-time decreases with higher curing temperatures and is also shortened for high mixing temperatures. Due to relatively long hook up times (up to 75 minutes), low average takes per stage, and the long length of grout distribution pipelines, this feature proved particularly important in determining the volumes of grout that could be mixed at any time.

It was found that the heat of hydration during mixing increased grout temperatures dramatically, from 15°C to over 30°C at times. Artificial cooling, using ice added to the mix water, was effective in reducing batch temperatures, thus giving longer pot life and enabling larger batches to be made.

4.4 Grout Stability

Testing of grout stability proved difficult with the limited site laboratory facilities, however, some success was achieved by placing grout samples in various solutions, intended to represent future groundwater conditions, and by analysing the change in solution properties with time. The results are summarized in Table II. Reduction in pH in each case was thought to be due to the absorption of CO_2 from the atmosphere during testing.

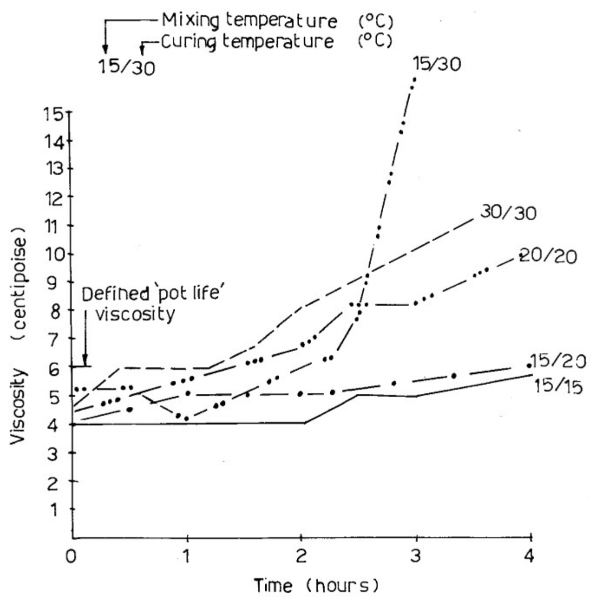

FIG 3 Effect of Mixing and Curing Temperature on resin Viscosity

Whilst both colour and TDS are higher for sample 5 the concentration of this solution was well above expected levels in the lake. Results for other caustic solutions are equivalent if not better than those for pure water.

These tests were seen as confirming manufacturers advice that the grout was stable in the range of alkaline conditions thought possible at the site.

4.5 Tube-a-Manchette Design

The specified Tubes-a-Manchette (TAMs) were 32 millimetres diameter PVC class 9 pipes with rubber 'valves' at 300 millimetres centres. Early trials proved that, at the early high grouting pressures in rock, the class 9 pipes were not sufficiently strong. Later TAMs were 40 millimetre diameter class 18 PVC which proved satisfactory. At the RCL dam the TAMs were used for rock grouting as well as for soil grouting.

TABLE II

GROUT STABILITY TESTING

Sample No.	Solution	Properties measured after 10 days			
		Phenols (mg/l)	pH	Colour (platinum-cobolt Scale)	T.D.S.
1	water (pH7)	0.15	7.9	2800	2600
2	NaOH;4mg/l(pH9)	.1	7.5	2000	2000
3	NaOH;40mg/l(pH11)	.1	8.2	2800	2300
4	Na_2CO_3;40mg/l(pH10)	.1	7.6	2200	2100
5	Na_2CO_3;400mg/l(pH12)	.1	9.3	3600	2500
6	water without grout	.1	7.5	15	210

Another unusual use of the TAMs on this project was that 3 valves were pressurized simultaneously. Several tests were carried out, using TAMs encased in steel and PVC pipe sections, which conclusively demonstrated that all three valves opened at very low internal pressures. A diagrammatic representation of the TAM system used is shown in Figure 4.

4.6 Grout Pressures

Initial trials were carried out using both cement/bentonite and resin grout injected at pressures of 50 D in rock and 5 D, rising to 'ground fracture' pressure, in overburden (D was the depth in metres to the stage being grouted). These pressures were added to the 'opening' pressure of the TAM valve.

Valve 'opening' was defined as the pressure applied to the stage to cause discernable flow at the injection flow meter.

'Ground fracture' pressure was defined as the pressure causing ground fracture. This was expected to be indicated by a sudden increase in flow rate at the injection flow meter.

Initial field trials indicated that valve opening pressures were very high, up to 100 D kPa. These pressures were so high that they masked other measurements attempting to detect ground fracture pressures.

Following grouting of a trial section by this technique, measured permeabilities were found to have increased, by up to a factor of 10 where initial permeabilities were low.

Accurate testing of TAMs cast in steel pipe sections, described earlier, indicated that valve opening was actually occurring at very low pressures; in the order of 20 kPa. This was confirmed in the field by using a more accurate flow meter and by carefully monitoring pressure rise.

The data being collected indicated that:
a) TAM valves were opening at low pressure.
b) Grout takes per stage in the majority of the foundation soil were very small.
c) Ground fracture of, initially low permeability soils was detrimental to permeability.

Accordingly the grouting pressures were reduced to 15 D in soil and 30 D in rock. Opening pressures were assumed neglible and were not considered further. This led to considerable simplification of the task of operators of the grouting equipment.

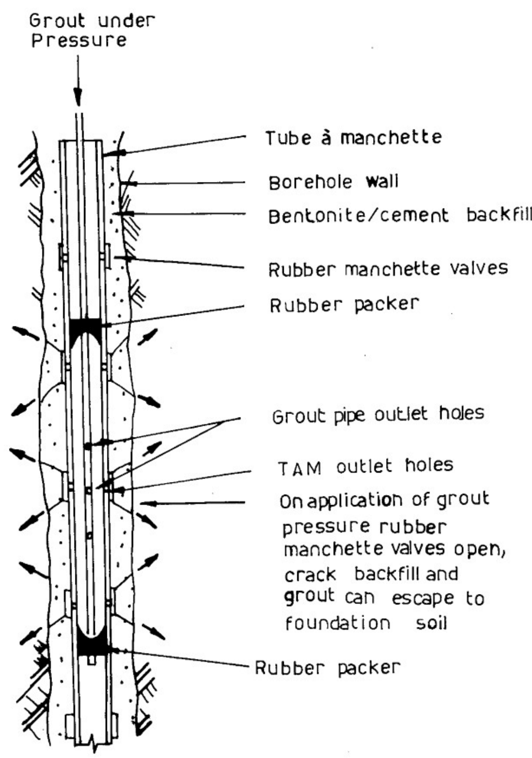

FIG 4 Tube a Manchette Grouting System

During production grouting of bedrock stages, several instances of surface leakage were noted. These occurred when soil depth was significant. Thus exaggerating the rock grouting pressure in relation to the actual rock depth. The grout pressure in rock was subsequently reduced to 15 D. In addition, in particularly soft areas a strengthened "roof zone" was constructed by pre-grouting the surface soils with cement/bentonite grout.

4.7 Injection Volumes

With the reduction in pressures, and the decision not to purposely initiate ground fracture, the usual TAM grouting philosophy, of injecting a fixed volume of grout, was not appropriate.

Instead, cement grouting was carried out to refusal (3 litres/15 minutes) whilst resin grouting was carried out for a period of 200/D minutes. This grouting time allowance was intended to result in zones of equal permeability at different depths being injected with equivalent volumes of grout. Hence soil at depth would be grouted at higher pressure for a shorter time and vice versa.

An upper limit for grout take at any stage was set at 1000 litres.

Refusal flow for the resin grout was set at 1.0 L/m/100 kPa which was calculated as the approximate grout take to a stage with permeability of 10^{-6} m/sec.

4.8 Grout Type Allocation

The initial grouting procedure involved cement/bentonite grouting of all stages, followed by chemical grouting of all stages. It quickly became apparent that:

a) Cement/bentonite takes in soil were negligible.
b) Resin takes in rock, following cement/bentonite grouting, were negligible.

This led to deletion of cement/bentonite grouting in all but the lower two stages of the soil and the deletion of resin grouting in rock. This considerably reduced the number of hook ups required which more than compensated for the cost of possible increased resin takes in the soil.

4.9 Water Testing

Water testing was carried out over two metre stages in open boreholes, initially at a pressure of 5 D kPa using inflatable rubber packers above the stages being tested.

Continual problems, with water leaking past packers and with packers bursting due to over inflating, led to the abandonment of this type of test in soil.

A simple falling head test was developed, using low head in open drill casing. The casing was progressively advanced past the previous drilled level, without using water recirculation. This bedded the casing into the soil. A two metre hole was then drilled past the end of the casing, and the casing filled with water. Leakage past the casing seal was noted in approximately 5% of the tests, however, results were generally satisfactory. The effect of any leakage past the seal would lead to overestimating of permeabilities.

4.10 Gamma Logging

As a possible means of pre-determining the areas of higher permeability, the use of gamma logging was attempted. The gamma log measures the level of gamma radiation emitted by the soil and is carried out within boreholes. The level of radiation from sands is markedly different to that from clays and it was considered that zones of low radiation may indicate sandy areas of higher permeability.

Whilst early work in this regard suggested that some such correllation may exist, it could not be established that the results would be sufficiently conclusive to enable confident interpretations to be made.

5 CONSTRUCTION PHASE

5.1 Construction Programme

The very tight refinery construction programme and very wet winter weather of the region necessitated the construction of the main embankment for the Refinery Catchment Lake Dam during the summer of 1981/82. This meant that the grouting operation was completed during the winter and spring of 1981. The greatest part of the works was completed during an eighteen (18) week period between 15th August, and 22nd December, 1981.

5.2 Production Statistics

Final extent of work on Refinery Catchment Lake Dam was as follows:

Drilling overburden 23,300 metres
Drilling rock 3,437 metres
Grout hook-ups 25,640 No.
Permeability tests 2,485 No.
Cement 207 tonnes
Bentonite 39 tonnes
Resin grout 123 tonnes

To complete this extent of work in the time available required double shift operation. Work was arranged on the basis of ten, twelve hour shifts per week. A total, on site input of 82,000 man hours was involved in the operation.

5.3 Logistical Problems

Refinery Catchment Lake Dam works coincided with a very high level of specialist geotechnical contracting activity throughout Australia causing a shortage of experienced personnel. Peak work force was nearly 100 with most requiring some specialist skill. This necessitated a considerable extent of on site training. Site Manager and works foremen were provided from overseas.

This skilled labour shortage, the wet winter weather and the very short construction period posed significant logistical problems for the Contractors and the successful completion of the contract on time was evidence of their efficient organisation.

5.4 Construction Techniques

The use of the Tube-a-Manchette technique made it possible to allow the drilling operation to proceed largely independently of the grouting works. This permitted for maximum flexibility of effort. Various methods for all aspects of the work were tried and/or considered in an attempt to optimise production. Basically, the most successful methods developed may be described as follows:

Production Drilling - a truck mounted Edson rotary top drive rig was used to drill overburden and place temporary steel casing to rock. Conventional air track rigs were then used to drill rock and, after placement of Tubes-a-Manchette, withdraw casing.

Permeability Test Drilling - because permeability tests were necessary in 2 metre stages (downstage) through the overburden the actual water test represented the bulk of the time spent on this operation. For this reason a drill rig which could be moved between holes during the testing was necessary. To reduce the set up time involved, a specially modified air track with rotary head was used for the bulk of this work.

Cement Grout Mixing and Pumping - most cement/bentonite grout was mixed in a central batching plant and pumped via steel lines to mobile holding tank and pump units. All pumping was carried out with Mono Pumps.

Resin Mixing and Pumping - resin grout was mixed in central batching plant and delivered along the grout curtain line by a pressurised reticulation system, whereby the grout was available at maximum injection pressure at any required location. Grout flow was tapped from the pressure line to a manifold system from which individual hole connections were made. Return lines, from each hole, connected via a main return line to the central batching plant. In this way a large number of individual hole connections could be made concurrently from one pump. Generally, it was possible to grout on up to ten holes simultaneously.

6 RESULTS

A total of 896 pre-grouting and 1438 post-grouting permeability tests were completed at the RCL Dam Site. The results of these are summarized in Figure 5.

In general, natural foundation permeabilities were very low with the highest recorded permeability being 1×10^{-4} metres per second. Less than 10% were higher than 1×10^{-5} metres per second.

Permeabilities were noted to be, on average, slightly higher over the central section of the valley and this led to the installation of an additional two rows of grouting over 200 metres of the curtain.

Final permeability test results showed that the extent of more permeable foundation areas has been dramatically reduced and the overall average permeability has been reduced by a factor of around five times.

Due to the inherent inaccuracy in the permeability test method used, particularly when attempting to measure post-grouting permeabilities in a single row curtain, these results are considered conservative and true post-grouting permeabilities are likely to be even lower.

Filling of the reservoir began in May, 1982 and over 15 metres of water were stored by August, 1983. Instruments in the dam and foundations are being monitored.

At the time of writing, piezometers are still showing residual effects of construction pore pressures and seepage collection systems are not yet fully operational, thus, meaningful comment on dam performance is not yet possible. Indications are that the seepage to date is well within design expectations.

7 CONCLUSIONS

The experience gained on this major grouting project has indicated that soils with average permeabilities as low as 10^{-6} metres per second can be satisfactorily grouted using low viscosity grouts, in this case a tannin based resin.

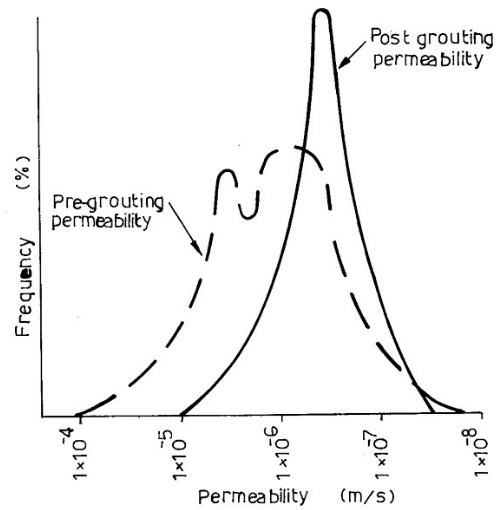

FIG 5 Permeability Test Results

Application pressures are critical to the success of grouting in these soils as ground fracture appears to be detrimental to permeability, particularly in zones where the pre-grouting permeability is already low.

8 REFERENCES

BJERRUM, L. NASH, J.K.T.L. KENNARD, R.M. and GIBSON, R.E. (1972). Hydraulic Fracturing in Field Permeability Testing. Geotechnique 22, No. 2, 319 - 332.

BLIGHT, D.F., COMPSTON, W. and WILDE, S.A. The Logue Brook Granite age and significance of deformation zones along the Darling Fault Scarp. Annual report of the Geological Survey of Western Australia, 1980.

BOWEN, R. Grouting in Engineering Practice. London, 1975.

GHD-DWYER (W.A.) PTY. LTD., Worsley Water Management, Refinery Catchment Lake Dam, Design Report. Raymond Engineers, 1982.

GIDIGASU, M.D. (1976) Laterite Soil Engineering. Amsterdam. Elsevier Scientific Publishing Co.

GORDON, F.R. (1964) Geological Investigation at Wungong Brook Upper Dam Site. Annual Report of the Geological Survey of Western Australia for 1964.

GUTTERIDGE HASKINS & DAVEY PTY. LTD. Worsley Water Management Stage 2 Investigations, March 1980 10 Vols. Reynolds Australia Alumina.

SKEMPTON ET AL (1963) Grouts and Drilling Muds in Engineering Practice. London, Butterworths.