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

The Investigation, Design and Excavation of a Cutting in Completely Weathered Granite and Dolerite near Boddington, Western Australia

F.R. GORDON
Director, Soil and Rock Engineering Pty. Ltd., Perth
and
D.M.A. SMITH
Associate Director, Soil and Rock Engineering Pty. Ltd. Perth

SUMMARY. On the Cable Belt overland conveyor route that links the Worsley Alumina Refinery to the Boddington Mine Site, a 30m deep cutting was constructed by earth moving equipment in completely weathered granitic and doleritic rocks. A geotechnical investigation, comprising reconnaissance mapping boreholes and seismic refraction traverses, revealed a deeply weathered and lateritised profile of kaolinitic clays and sandy silts of granitic origin intruded by weathered doleritic dykes containing montmorillonitic clays and silts. The weathered profile is characterised by a relatively uniform spread of iron and aluminium sesquioxides throughout most of the cutting. The oxides have cemented together kaolinitic clay minerals, and have bonded these aggregations into a framework to give very high undisturbed strengths. The cutting was designed with batters of 60^{o} (to the horizontal) and 5m wide access and maintenance berms 8m vertically apart, and was constructed with minor modifications to the design. The cutting has already been subjected to the design 1 in 100 year rainstorm.

1 INTRODUCTION

The 'Deep Cut' is the name given to a cutting located some 10km from the Worsley Alumina Mine site at Boddington on the 51km long Cable Belt overland conveyor to the Refinery near Worsley. The cutting is some 150km south-southeast of Perth.

The cutting was part of major site and earthworks necessary to maintain the design alignment and profile of the Cable Belt conveyor through the hilly terrain southwest of the mine site. The works included the construction of 10 bridges to a maximum height of 30m, 37 earthen embankments to a maximum height of 22m and 32 cuttings of which the 'Deep Cut' was the deepest.

The cutting is approximately 430m long, 13m wide at the bottom and is up to 30m deep. It is one of the deepest cuttings made to date (1982) in the Southern Hemisphere and is excavated in totally to completely weathered rocks.

Soil and Rock Engineering Pty. Ltd., was commissioned by Cable Belt (Australia) Pty. Ltd. to design the cutting. The construction contract was let by Raymond Engineers (Australia), the Contractor for Worsley Alumina Pty Ltd, to MacMahon Constructions Pty Ltd.

2 GEOLOGICAL SETTING

The geological setting is similar to that of the Worsley Alumina Refinery site described by Gordon (1984a). The cutting is made in weathered Precambrian banded or segregated porphyritic granites and pegmatites, dipping 20^{o} to the north-east and intruded by dolerite dykes striking obliquely to the cutting and dipping at 60 to 85 degrees to the south. Shears are present at the margins of the dolerite dykes and shears with similar orientations also disrupt the weathered granite rock mass with slickensided planes. Faults at low angles of dip and striking parallel to the dykes are also present.

The banded granite rocks are totally to completely weathered and lateritized to depths of up to 50m. The model of weathering is the Plateau type as defined for the Refinery site (Gordon 1984(b)). The ground water level is approximately 50m deep, and the mobilization and diffusion of the cementitious iron and aluminium oxides (sesquioxides) appear to be more significant and uniform than at the Worsley Refinery site (Gordon and Smith, 1984).

The steep topography and an eroding ferricrete cap are the result of active denudation from short local tributaries of the Murray River. Although the lower slopes have been cleared for farming, strong stands of the jarrah-marri-karri forrest association are present on the plateau and laterite remnants.

Because of the presence of a large massive laterite cap and lateritic soils, the geological mapping was limited. The presence of major dolerite dykes with margins that were not parallel, a zone of shearing, and joint patterns were established. The surface expression of the geological features is presented on Figure 1 which also shows the 'as excavated' cutting and the site exploration.

3 SEISMICITY

An analysis was made of arcuate geological structures defined by stream patterns in the South West Seismo-Tectonic Zone located some 30 to 100 kms to the east of the cutting (Gordon, 1971). Although seismic events are sparse compared with the activity in the Meckering-Calingiri-Cadoux zone, the lineaments provide evidence of former faulting that could be reactivated at any time. A design earthquake of M_L 6.8 at an epicentral distance of 40 km was adopted. This could produce an acceleration at this site of the order of 0.09g.

4 FIELDWORK AND LABORATORY TESTING

Following geological reconnaissance mapping, six boreholes were drilled to depths between 10m and

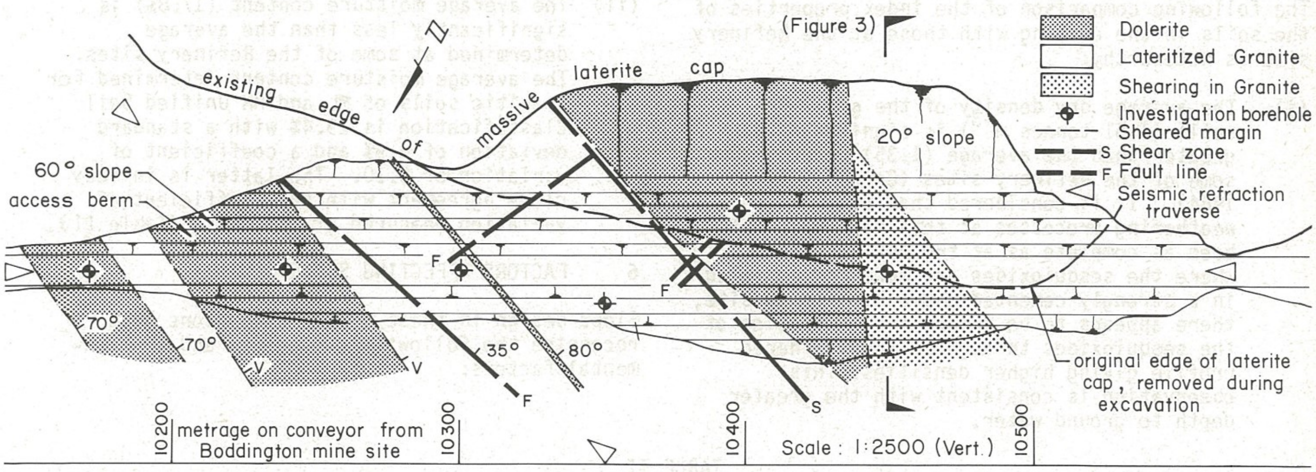

Figure 1. Plan of 'Deep Cut' showing geological features and locations of exploration stations

30m. Sampling in 62mm diameter, thin-walled tubes and standard penetration tests were carried out at 1.5m intervals in all boreholes. Their locations are shown relative to the geological surface features in Figure 1.

Two seismic refraction traverses 385m and 440m long were carried out. (Figure 1) Two-way shooting at 10m centres was used in each traverse.

The laboratory test programme consisted of the determination of Atterberg limits, bulk density, pocket penetrometer values, triaxial compression and falling head permeability testing.

5 DISCUSSION OF RESULTS

The geological reconnaissance and fieldwork revealed three lateritized soil types within the proposed cutting. They are summarised in Table I.

No groundwater was encountered.

The seismic refraction results indicated a two-layer model. The average seismic velocities for the upper layer varied from 600 to 900 m/sec. This range is consistent with a partially saturated and extremely weathered material. The second layer was present approximately 20 to 30m below the proposed invert level of the cutting and was characterised by average seismic velocities ranging between 3000m/sec and 6500m/sec.

The index and strength properties of the granitic and doleritic soils are summarised in Table II.

The engineering behaviour of these soils is strongly dependent on their mode of weathering and the bedrock type. The geological and environmental influences on the weathering processes of similar soil types encountered at the Refinery site have been presented in a separate paper by Gordon and Smith (1984). The soils at this site are characterised by high strengths and low compressibilities and despite their cohesive origins and soil classifications they behave, in geotechnical engineering context, as cemented granular soils. Their high natural strengths are a function of the abundance of cementitious aluminium and iron oxides (sesquioxides) that have accumulated throughout the profile. The sesquioxides have coated the surfaces of the aggregated clay minerals thereby modifying the plasticity properties of these soils. The low Atterberg limits are diagnostic of the small specific surface areas of the clay aggregations. The soils have an open-voided and possibly honeycombed structure comprised of clay aggregations to silt and sand size. The aggregations are firmly underpinned by the cementitious sesquioxides that also provide a framework for the three dimensional structure.

TABLE I

GENERALISED SOIL PROFILES AND DISTRIBUTION

Generalised Soil Profile	Distribution (Metrage)
1. Dense to very dense sandy SILTS, becoming more clayey with depth and ferruginated, are present to a depth of at least 30m. These soils are the weathered products of a banded uniformly-grained granite and are light brown in colour from the presence of gibbsite and goethite minerals surrounding the kaolinitic clay aggregations. Faults and shears are present with no cohesion across the planes.	10,124 to 10,156 10,186 to 10,202 10,257 to 10,345 10,359 to 10,384 10,440 to 10,554
2. Hard clayey SILTS and silty CLAYS, iron and aluminium enriched and segregated, extend to the depths investigated. These soils are weathered products of dolerite and have relict joints. Core stones are present at depth and sesquioxide cementations become stronger in the upper layers.	10,156 to 10,186 10,202 to 10,257 10,345 to 10,359 10,384 to 10,440
3. Massive, fractured, and boulderised laterite CAPROCK overlying sandy GRAVELS extend from the surface to depths of approximately 5m. These materials are totally weathered and overlie the very stiff to hard ferruginated sandy clayey silts.	10,290 to 10,520

The following comparison of the index properties of the soils in the cutting with those at the Refinery site is noteworthy:

(i) The average dry density of the granitic soils (1.51 tonnes m^{-3}) is significantly greater than the average (1.35) determined at some of the Refinery sites (Gordon & Smith, 1984). It is considered that the weathering processes at this site have not been as complete as at the Refinery site, where the sesquioxides are more concentrated in a strongly cemented caprock. At this site, there appears to be a more even diffusion of the sesquioxides throughout the weathered profile giving higher densities. This observation is consistent with the greater depth to ground water.

(ii) The average moisture content (17.8%) is significantly less than the average determined at some of the Refinery sites. The average moisture content determined for granitic soils of ML and MH Unified Soil Classification is 29.4% with a standard deviation of 8.9% and a coefficient of variation of 0.30. The latter is in very close agreement with the coefficient of variation measured at this site (Table II).

6 FACTORS AFFECTING SLOPE DESIGN

Slope design in these ground conditions must recognise the following geological and environmental factors:

TABLE II
Properties of Granitic and Doleritic Soils

Soil Property (Units)	Soil Type	No. of Tests	Range	Mean	Standard Deviation	Coefficient(3) of Variation
Dry Density (tonnes.m^{-3})	Granite	47	1.18 - 1.73	1.51	0.13	0.09
	Dolerite	8	1.18 - 1.51	1.38	0.10	0.07
Moisture Content (%)	Granite	42	8.0 - 27.4	16.8	4.9	0.29
	Dolerite	8	23.0 - 38.3	29.3	4.7	0.16
Liquid Limit (%)	Granite	42	41 - 74	49.0	6.7	0.14
	Dolerite	6	55 - 91	72.3	12.2	0.18
Plasticity Index (%)	Granite	42	8 - 41	15.0	5.9	0.39
	Dolerite	6	8 - 46	31.3	13.3	0.42
Degree of Saturation (%)	Granite	3	42 - 69	60	16	0.27
	Dolerite	4	36 - 66	52	13	0.25
Cohesion (kPa)	Granite	5 (1)	118 - 165	144	19.0	0.13
	Granite	50(2)	107 - 157	132	17.7	0.13
	Dolerite	22(2)	135 - 157	148	6	0.04
Angle of Internal Friction (degrees)	Granite	5	21.3 - 27.4	23.0	2.9	0.13
Permeability (m/sec)	Granite	3	$3x10^{-8}$ to $5x10^{-9}$	$3.5x10^{-8}$	$3.4x10^{-8}$	0.97

NOTES:
1. These results were determined from unconsolidated, undrained, triaxial compression tests.
2. These results were estimated by dividing the pocket penetrometer results by 3.5. Where the soils were too hard to test, a pocket penetrometer result of 550kPa was adopted.
3. The coefficient of variation is the ratio of the standard deviation to the mean.

TABLE III
Parameters for Stability Analysis

Soil Model	Generalised Description of Soil Model	Design Parameters			
		Bulk Density (tonnes.m^{-3})	Cohesion c (kPa)	Angle of Internal Friction Ø (deg.)	Seismic Coefficient x g.
A	Ferruginated and partially saturated sandy SILTS, clayey SILTS and silty CLAYS of granitic and or doleritic origin.	1.9	125	21	0.09
B	Sands, pisolitic laterites, cobbles and boulders to 5m, overlying partially saturated	2.0	0	35	0.09
	SANDS, clayey SILTS and silty CLAYS of granitic and/or doleritic origin	1.9	125	21	0.09

(i) the rock mass consisting of totally to completely weathered granite intruded by dolerite dykes and pegmatite veins and pods;

(ii) relict joint planes that are present in the dolerite dykes;

(iii) the unfavourable jointing and dip where the cutting intersects the massive laterite sheet and the possibility of block gliding into the cutting;

(iv) possible stormwater percolation through the upper permeable profile (fractured caprock) and the influence on (iii);

(v) weak bands of soil or sheared zones with slickensides in the weathered granite and marginal to the dolerite dykes;

(vi) the rainfall pattern - 1000mm per year of which 85% is received in winter; and

(vii) the seismic loading.

7 SOIL MODELS FOR STABILITY ANALYSES

From the generalised soil profiles presented in Table I, two soil models A and B were selected. (Table III). Model A was selected for the analysis of the generalised profiles 1 and 2 while model B was chosen to analyse the stability of generalised profile 3. (Table 1).

The design parameters for Model A and the second layer of model B approximate the 35th percentile of the soil strengths measured in the laboratory.

Because of the heterogeneity of the fractured caprock layer towards the western end of the cutting, it was decided to assign gravel properties to the entire stratum (Layer 1 of Model B, Table III).

Detailed studies including Camkometer testing have been carried out on similar soil types at the Worsley Alumina Refinery with the following range in results (Smith 1984 (a) (b)):

(i) peak shear stresses varied between 214 and 806 kPa (average 429 kPa) and were mobilised at strain levels between 0.7 and 2.0%; and

(ii) residual shear stresses varied between 53 and 408 kPa (average 234 kPa).

No Camkometer tests were carried out at the cutting. From the results of the index testing (Section 5), it would appear that the soils at this site contain a greater concentration of sesquioxides throughout the profile below the caprock and this is supported by the deeper colouration of the exposed faces. As the soil strength is primarily a function of the concentration of the cementitious sesquioxides, then it follows that these soil types are likely to have higher peak and residual strengths than the Refinery soils.

On the basis of the foregoing, it is anticipated that in excess of 95% of the soils exposed in the cutting would have engineering properties significantly greater than the design values. (Table III).

The long term behaviour of slopes in lateritised soils is different than that for slopes in sesquioxide-free and temperature-zoned, saturated soils of similar Unified Soil Classification. In the latter, the natural strengths are, to a degree, a function of the excess pore-water pressures generated by the excavation processes. With time, the negative pore water pressures dissipate and these soils undergo a strength loss. In the partially saturated lateritised soils at this site, the negative pore water pressures are either non-existent or dissipate immediately on excavation and their strength is predominantly a function of sesquioxide cementation. This form of ferruginisation is resistant to weathering processes.

8 DESIGN PHILOSOPHY

A deep cutting containing a conveyor system is not required to meet the rigorous safety standards required of an excavation accommodating a roadway or a railway line where human life is at risk. Nevertheless, any major disruption to the conveyor system could cause consequential production losses of significant size to the Refinery operation. The deep cutting is a vulnerable bottleneck as no alternative routes can be constructed in the event of failure. Also any major earth movements could render the entire cutting liable to further movements and a dangerous place to work. The cutting was assigned an importance category rating of 2 (Ministry of Works, NZ, 1973). This is relevant to free-standing structures at least 6m high in locations where replacement would be difficult or costly and/or where other consequences of failure would be serious.

9 METHOD OF ANALYSIS AND RESULTS

The stability analyses was carried out with a computer programme, (STABL) that uses a limit equilibrium solution, based on the modified Bishop Method of Slices. The effects of seismic loading on cut stability were pseudo-statically modelled:- an acknowledged conservative technique preferred for its simplicity (Seed, 1966).

The results of the analyses for batter slopes of 60^{0} and 75^{0} in ground conditions defined by Model A, are illustrated in Figure 2. Superimposed is the design safety factor of 1.5. For excavations to depths of 24m, which will be the case along approximately 50% of the cut, slopes as steep as 75^{0} will satisfy the imposed stability criteria. Where the excavations are deeper, the batter slopes will need to be flattened to approximately 60^{0}.

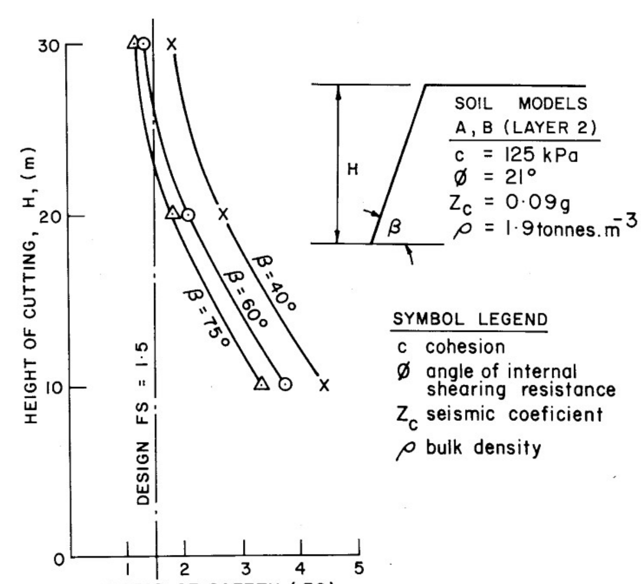

Figure 2. Summary of stability analyses

The most likely mode of instability of the gravelly and laterite caprock in the upper 5m of Model B is by block or wedge gliding along surface(s) softened and lubricated by storm water run off that had percolated down joints in the laterite.

10 DESIGN FEATURES

1. Batter slopes of 60° below the horizontal were recommended in the granitic and doleritic soils. It was recognised that the slopes may need to be flattened or stabilised at the margins of the doleritic dykes and in shear zones where relict rock joints with little cohesion would probably be present. The extent and degree of shearing and faulting and relict joint planes were determined from site inspections, that were an integral part of the design phase.

2. Maximum slopes of 30° to the horizontal were recommended in the fractured caprock and gravelly strata.

3. Access berms, 5m wide at 8m vertical intervals, were constructed along the cutting and at the interface of the laterite caprock/pisolitic gravels and the kaolin-laterite zone soils on the south side of the cut. The design functions of the berms were to provide access to slope maintenance crews to facilitate drainage and if necessary retard slope-wash and block movements (Figures 3 and 4).

4. Spoon drains were to be provided at the back of the berms to facilitate slope drainage. When the berms were completed, the drains were installed in the centres of the berms.

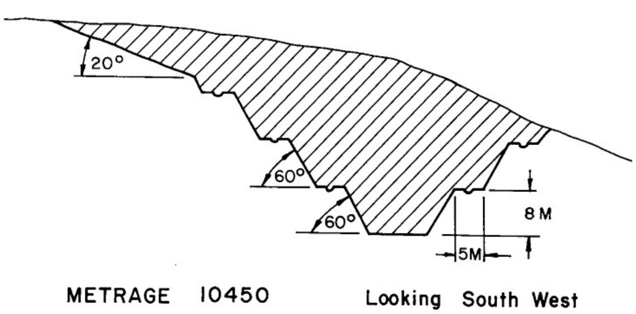

Figure 3. Typical cross section of the cutting

11 CONSTRUCTION INSPECTIONS

1. The cutting was constructed entirely with earth-moving plant. The only rock encountered in the cut centre consisted of dolerite core-stones having a maximum dimension of 1m.

2. The cutting revealed a lateritized profile of exceptional size and clarity (Figure 4). The totally to completely weathered granite rock mass with four dolerite dykes was traversed by 45 to 85 degree south-dipping shears that retained a central discontinuity or opening. Low angle faulting had also disrupted both the granite and dolerite rock masses.

3. In the zone where the prevalent 110 degree striking shears have intersected other shears and joints, some unstable wedges and planes were present. A section 30m long on the lower berm of the north face was stabilized by draping with cyclone wire mesh.

4. Four dolerite dykes with disrupted margins obliquely intersect the cutting and dip at 60 to 85 degrees to the south (Figures 1 and 4). Relict jointing in the dykes allowed a few blocks of highly weathered rock some minor relaxation into the cutting.

5. Pegmatite pods and bands are present throughout and these are more susceptible to weathering and slope wash movements than the surrounding rock mass.

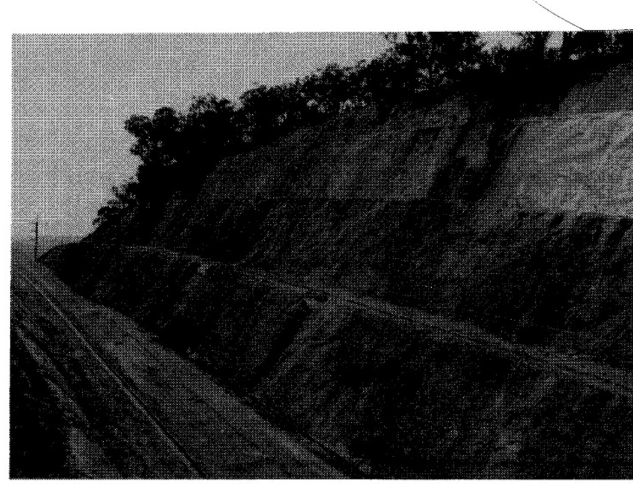

Figure 4. South wall showing weathered profile, dolerite dyke in centre

6. Modifications to design batters were made locally in the upper ferruginous gravelly materials and in sheared zones that were deficient in sesquioxides. In these more permeable zones, leaching processes had removed the sesquioxides with 250mm of the shear.

7. The 60 degree sloped surfaces were initially graded or planed with a grader blade mounted on a D6. The planing produced a highly polished surface.

8. In the period from the 20th to the 22nd of January 1982, the just-completed cutting was subjected to the 100 year rain storm when 198 mm of rain fell in some 40 hours. No structural failures or major falls occurred. Surficial erosion in the form of slab slides, debris flows, cracking and rilling removed some 90 mm from the previously glazed batter surfaces over approximately two-thirds of the cutting. It is considered that the surface may have been highly stressed as a consequence of the blading.

9. The Cable Belt conveyor was placed close to the low side of the cutting with the access road and powerline on the high side (Figure 5).

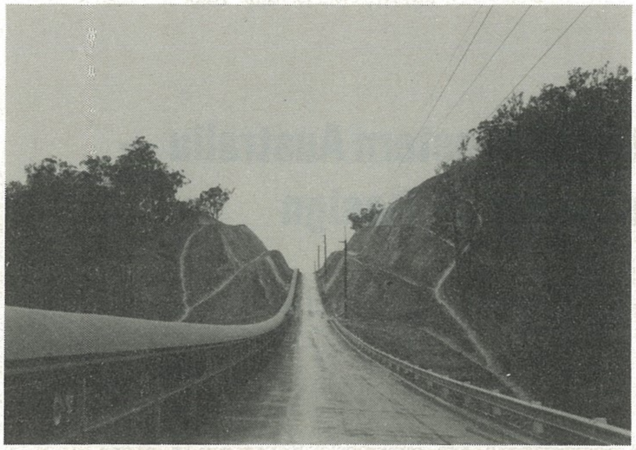

Figure 5 Photograph of completed cutting

12 CONCLUSIONS AND RECOMMENDATIONS

From the information presented in this paper, the following conclusions have been reached:

1. A deep, steeply-sided cutting was successfully excavated in totally to completely weathered Precambrian banded porphyritic granitic and intrusive doleritic rocks. The cutting has already been subjected to the design 1 in 100 year rainstorm.
2. The cutting was in the main excavated as designed with side slopes of 60^0 and access berms (5m wide) at vertical intervals of 8m.
3. The weathered products of granitic rocks exposed in the cutting are in the form of kaolinitic clays and silts that have been coated and cemented by sesquioxides as part of the lateritisation weathering process. The products of the steeply-dipping intrusive dolerite dykes are ferruginated montmorillonitic and kaolinitic clays and silts. These soils are the products of weathering in the semi-tropical environment existing at the time of lateritization.
4. The cementitious sesquioxides have diffused more evenly throughout the weathered profile than in the weathered profile of similar rock types at the Worsley Alumina refinery some 40km south west of the cutting. The sesquioxides had been transported through the profile over distances in excess of 50m. This distance is significantly greater than has been reported for the weathering of similar rock types in different environments in other parts of the world.
5. The selection of geotechnical properties for use in slope design should take into account the characteristically high natural (i.e. undisturbed) strengths and the susceptibility of the cemented and brittle soil structure to sampling disturbances. Otherwise, slope design in lateritised profiles will be very conservative.
6. The cutting is susceptible to surficial erosion during heavy downpours. There is a need for routine inspections by suitably qualified personnel and co-ordinated maintenance operations to ensure an uninterrupted service life.

13. ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance and co-operation of Worsley Alumina Pty Ltd, Raymond Engineers (Australia) Pty Ltd and Cable Belt (Australia) Pty Ltd without whose permission this paper could not have been published.

14. REFERENCES

Gordon F.R. 1972 Earthquake Risk in Western Australia Ann. Rept. Geol. Survey West. Aust., 1971.

Gordon F.R. 1984a. The Distribution and Engineering Properties of Precambrian Igneous Rocks at the Worsley Alumina Refinery Site. 4th ANZ Geomech. Conf Perth.

Gordon F.R. 1984b. The Laterite Weathering Profiles of Precambrian Igneous Rocks at the Worsley Alumina Refinery Site. 4th ANZ Geomech. Conf. Perth.

Gordon F.R. and Smith, D.M.A. 1984. The Interaction of Geology and Geotechnology. 4th ANZ Geomech. Conf. Perth.

Ministry of Works NZ (1973). Retaining Wall Design. Notes. Issue C. July (1973).

Seed, H. B. 1966. A Method for Earthquake Resistant Design of Earth Dams. Jnl S.M.F.E. SM1. Jan 1966

Smith, D.M.A. (1984) (a) Compressibilities of Lateritized Granitic Soils at Worsley. 4th ANZ Geomech. Conf. Perth 1984.

Smith, D.M.A. (1984) (b) Settlement Characteristics of Lateritic Soils. 4th ANZ Geomech. Conf. Perth 1984.